UNIVERSITÉ
DE GENÈVE
FACULTÉ DE TRADUCTION
ET D'INTERPRÉTATION

CONFLICT MONITORING AND GOAL MAINTENANCE IN CONTINUOUS COMPLEX TASKS

MULTITASKING IN INTERPRETERS AND ORCHESTRA CONDUCTORS

Thèse

Présentée à la Faculté de traduction et d'interprétation
de l'Université de Genève
pour obtenir le grade de Docteur en interprétation

par

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ἕν οἶδα, ὅτι οὐδέν οἶδα

(Socrates, attrib., ca. 399 B.C.E.)

I saw, that I did not see

(Bing Translator, 2021)

Abstract

The present dissertation focuses on multitasking abilities in simultaneous interpreters on the one hand, and in orchestra conductors on the other, as both professions require the execution of highly specific and highly complex tasks. The theoretical investigation is two-fold: First, we analyse the cognitive constraints and functions involved in multitasking, notably in continuous multitasking. Here we highlight the central role of context and conflict monitoring and of goal maintenance in the control mechanisms at play, supporting the hypothesis that two control modes, proactive and reactive, interact. Second, we seek to identify the various types of control skills necessary for successful multitasking for the specific purposes of interpreting and conducting, in order to derive possible implications of specific multitasking expertise for the processing of new, continuous multiple tasks.

A behavioural experiment was designed to investigate whether conductors, interpreters, or both, show exceptional proficiency in a concurrent task paradigm compared to a control group. Individual variables potentially linked to higher scores in the exercise were also accounted for and analysed. We investigated the groups' performance with regard to processing speed and the differential involvement of reactive and proactive mechanisms of control reflected in conflict monitoring and goal maintenance measures. The experimental task, administered before and after repeated single-task exposure, was comprised of a visual-verbal 2-back component and an auditory task requiring the maintenance of a covert count of an intertwined series of beeps. The findings suggest that performing continuous concurrent tasks is possible. Consistency in good multitasking performance was observed as well as performance improvements after training. In addition, while the groups' performance did not differ significantly in terms of accuracy, distinct patterns of performance and progression were identified between the expert groups. Interpreters and conductors showed differences in reaction time and post-error slowing, which suggest that they tend to rely on different control modes. Varying degrees of adaptability also appeared between the three groups. Regarding multitasking performance, there appears to be little manifestation of reactive control during performance in the first iteration of the dual task, while in the second iteration participants appear to rely advantageously on some degree of automation and reactive control. This suggests that the proactive and reactive modes of control may play distinct roles in reaching optimal performance at the various stages of training.

Résumé

Cette thèse traite des capacités des interprètes travaillant en simultanée et des chefs d'orchestres, professionnels dont l'activité exige des tâches hautement complexes et spécifiques, à effectuer des tâches multiples. La partie théorique examine principalement deux aspects : tout d'abord, les contraintes et les fonctions à l'œuvre dans un contexte de tâche multiple (« multitasking »), et notamment le rôle essentiel des mécanismes de vigilance face au contexte et à l'émergence de conflit cognitif et des mécanismes de maintenance des objectifs, argumentant en faveur de deux modes de contrôle, réactif et proactif. En second lieu, nous tentons d'identifier les compétences et modalités de contrôle cognitif nécessaires pour assurer le bon déroulement de deux tâches complexes précises, l'interprétation et la direction d'orchestre ; nous cherchons à déduire en quoi l'expertise dans une tâche multiple donnée peut avoir des implications face à l'exécution de nouvelles tâches concurrentes et continues.

Dans la partie expérimentale, nous cherchons à établir si les chefs d'orchestre, les interprètes, ou ces deux types de professionnels, obtiennent des résultats supérieurs à ceux d'un groupe de contrôle au cours d'un test composé de deux tâches continues et concurrentes, utilisant des mesures comportementales. Nous tenons compte de variables individuelles et biographiques susceptibles de contribuer à la performance. L'analyse des résultats des groupes porte sur la rapidité de traitement et sur l'implication respective des mécanismes de contrôle réactif et proactif, à travers des mesures de détection de conflit et la maintenance des objectifs. La tâche experimentale comporte un « 2-back » utilisant des stimuli visuo-verbaux et une tâche auditive consistant à maintenir mentalement le compte de deux séries de bips diffusés aléatoirement. Les participants ont effectué cette double tâche avant, puis après avoir pu s'entraîner dans les tâches séparées. Les résultats font apparaître qu'il est possible de réaliser des tâches continues et concurrentes en même temps. On observe également une constance dans les performances élevées, ainsi que des progrès suite à l'entraînement. En outre, bien que les scores ne diffèrent pas significativement entre les groupes, on discerne des schémas distincts de performance et de progression entre les groupes d'experts. Le ralentissement post-erreur et le temps de réaction des interprètes et des chefs d'orchestres présentent des différences, ce qui suggère qu'ils n'ont pas tendance à s'appuyer sur le même mode de contrôle. Des différences émergent également en matière d'adaptabilité entre les trois groupes. De manière générale, on relève peu d'indices suggérant que les participants font usage de contrôle réactif pendant la

première itération de la tâche multiple, alors qu'ils semblent en tirer parti, ainsi que d'un certain degré d'automatisation, pendant la seconde. Il semble ainsi que les modes de contrôle proactif et réactif aient un rôle distinct à jouer dans notre capacité à réaliser la meilleure performance possible à différents stades d'entraînement.

Dedication

À Maman

À Grand'mère

In loving memory

Acknowledgements

Credit for this dissertation finally seeing the light of day should be widely shared. This has been both a very personal, at times lonely, endeavour, and a truly collective process in many ways, and I am eternally grateful to all of its artisans.

My deep appreciation to my thesis advisor, Professor Kilian Seeber, without whom this day would never have come. I owe you an enormous debt of gratitude for orienting me towards the Graduate Center in New York at the very start of this project, and for seeing it through when its fate hung in the balance; Your rigour in sorting out ideas helped me structure the profusion of data and arguments.

I cannot express the extent of my heartfelt gratitude to Professor Klara Marton, my co-advisor, who made all of this possible. Thank you for providing me with a research home. I felt incredibly welcome at the Cognition and Language Lab and have learnt so much there on the way research can and should be done. Your professional and human qualities are and will remain an inspiration, and I cannot thank you enough for always finding a way to keep encouraging me through all the doubts and difficulties that arose along the years.

There is hardly a fitting word to thank Dr. Laura Keller, who has been the friend and project manager any doctoral student needs and anyone could dream of, taking the time and offering countless advice to help give this dissertation a recognisable shape and keeping me sane. I can safely say that getting to this point would simply not have been possible without you.

I wish to thank the members of my jury, Professors Alexis Hervais-Adelman, Tilo Strobach and Clemens Wöllner, for agreeing to read this thesis and to bring their valued expertise into its discussion; I feel truly privileged. Many thanks also to Professor Lucia Ruiz Rosendo for agreeing to chair this jury.

My fond appreciation to Distinguished Professor Loraine Obler: I was very fortunate to attend your classes and lab, and I am grateful for your insights and your kind interest throughout this process. My sincere gratitude to Professors Fernando Prieto Ramos and Pierrette Bouillon, as Deans of the Faculty, for giving this thesis a chance.

I am indebted to the Swiss National Science Foundation for granting me the mobility subsidy that allowed me to start this project in the best conditions possible, and to Professor François Grin for promoting my application.

I would like to thank the colleagues I had the joy and privilege to work with in the doctoral programs at FTI in Geneva and at the GC in New York. You taught me so much, and discovering the intricacies of cognitive control by your side was a pleasure. I am indebted to all of you, particularly to Dr. Luca Campanelli for graciously sharing your *n*-back code and for your awe-inspiring crash courses in E-prime, R, and mixed-effects modelling, to Zhamilya Gazman, Dr. Deepti Wadhera and Dr. Eve Higby for their numerous insights, and to all those I still like to think of as my labmates, especially Lia Pazuelo, Jungna Kim, Dr. Jungmee Yoon, Yasmine Ouchikh, Dr. Rhona Amos, Eleonore Arbona, and last but certainly not least, my long-time partner in crime, Dr. Carmen Delgado Luchner.

Many thanks to Biruh Mekonnen for creating an ad-hoc program for the sinewave-tracking task – whose data promises fascinating next steps – when E-prime’s continuous multitasking capacities were overwhelmed.

I also wish to express my gratitude to everyone in Vienna who helped me structure my workplan and shut out intrusive thoughts: Michaela Auer, and the team at Wolfgang Coffee, my lab ersatz.

This study would not exist without the participants, whom I wholeheartedly thank for their time and availability to submit themselves to cognitive torture. I will not de-anonymise you here, but I am truly grateful to each and every one of the conductors, interpreters, and controls. I am sincerely grateful to all each and every person who provided me with precious contacts.

Above all, my everlasting gratitude goes to Samar, who comforted, spurred, supported and tolerated me throughout the many and at times painful stages of bringing this thesis to completion, and made all these years worthwhile. I am bracing for your revenge.

To all those who have waited for this day as impatiently as I have: My father Christian, my sisters Cécile and Aude, my brother Vincent, my family, my dear friends, and more generally the subset of humanity who had to put up with me these past too many years, all my apologies and thanks.

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List of abbreviations (frequently used abbreviations in bold)

ACC: Anterior cingulate cortex

ACT-R: Adaptive Control of Thought-Rational model

ANT: Attention network task

AoA: Age of (language) acquisition

AX-CPT: Continuous Processing Task (with A-X cue-probe pairs)

dlPFC: Dorsolateral prefrontal cortex

DMC: Dual mechanisms of control

EF(s): Executive function(s)

EPIC: Executive-process interactive control

ERP: Event-related potential

EVC: Expected value of control

EVS: Ear-voice span

GAT: Guided activation theory

IFG: Inferior frontal gyrus

PES: Post-error slowing

PFC: Prefrontal cortex

PBWM: Prefrontal Cortex - Basal Ganglia subserving Working Memory architecture

PDP: Parallel distributed processing

PRP: Psychological refractory period

RT: Reaction time

SMS: Sensorimotor synchronisation

SOA: Stimulus-onset asynchrony

STM: Short-term memory

WM: Working memory

Part I. Introduction

1 Overview

1.1 General introduction

As the daily pace of life seems to accelerate, research on multiple task performance and its effects on our capacity to complete tasks efficiently and successfully is on the rise. The term *multitasking* itself is used more and more and describes a broad array of parallel activities, like forms of *media multitasking* (Alzahabi & Becker, 2013; Moisala et al., 2016; Ophir, Nass, & Wagner, 2009; Ralph, Thomson, Cheyne, & Smilek, 2014), that is, a series of intertwined but interrupted, more or less demanding activities that are characteristically attended to in a differential manner: Working while listening to music, answering phone calls while writing e-mails, etc. Research in multitasking, therefore, focuses on distinct types of performance (Strobach, Wendt, & Janczyk, 2018): Performance in task combinations which require the sequential processing of each task, i.e., *task switching*; and performance in combinations of tasks which overlap in time, requiring simultaneous and concurrent processes.

This dissertation focuses specifically on concurrent multitasking: The simultaneous execution of two (or more) tasks requiring controlled processes, or a particular type of complex tasks in the sense that such processes are and remain engaged throughout their execution. Tasks are deemed complex when various components require control: walking and chewing gum (famously) cannot be considered a complex task, but driving and carrying out a sustained conversation can (see e.g., Salvucci & Taatgen, 2008; Strayer & Watson, 2012; Strayer, Medeiros-Ward, & Watson, 2013). Complex tasks are called continuous when control is required constantly on one or several accounts. Continuous multitasking is therefore a combination of higher-level tasks, which cannot be reduced to simple stimulus-reaction sequences – like reacting to an auditory or visual cue vocally or by pressing a button – but require the prolonged and simultaneous pursuit of diverging goals. Continuous multitasking has been shown to lead to performance breakdowns in a vast majority of the population (Just & Buchweitz, 2017). Watson, Strayer and colleagues (Watson & Strayer, 2010; Medeiros-Ward, Watson, & Strayer, 2015) have found in repeated instances that only a minority of people (recurrently about 2.4 % to 4 % of various samples) seems to be able to carry out control-demanding tasks concurrently without any deterioration of the outcome.

This raises major questions: Does the brain actually engage in continuous multitasking? If not, how do those who seem to be able to carry out separate continuous tasks concurrently actually succeed? Are they resorting to demanding, but achievable, forms of control? And conversely, if continuous multitasking is a reality in the brain, what conditions allow for it?

To address these questions, we will need to define what these controlled processes are, and what the literature tells us about the way they come into play during multitasking. We will endeavour to form a picture of the mind's capacity, or lack thereof, to treat the demands of multiple tasks in parallel, rather than sequentially, based on different theoretical insights about the nature of control. The experimental part uses behavioural measures; However, insofar as many contemporary studies and theoretical frameworks rest on functional and structural neurological insights, some of these insights will be described in the literature review in order to provide comparability across the theories and across the disciplines studied. The theoretical part will place a particular focus on the cognitive control framework (Miller & Cohen, 2001; Botvinick & Cohen, 2014), including the *expected value of control* (Shenhav, Botvinick, & Cohen, 2013), *dual mechanisms of control* (Braver, Gray, & Burgess, 2007) and *multitasking vs. multiplexing* (Feng, Schwemmer, Gershman, & Cohen, 2014). We will discuss conflict monitoring and goal maintenance as measures of proactive and reactive control (Botvinick, Braver, Carter, Barch, & Cohen, 2001; Braver, 2012; Chiew & Braver, 2017). We will then proceed to explore two specific populations with particular exposure to real-life continuous complex task execution: simultaneous interpreters and orchestra conductors.

We assume that experts in continuous complex tasks, such as conducting and simultaneous interpreting, are used to exerting control in a way that enables the parallel execution of the necessary processes, and that this experience may constitute an advantage in new multitasking situations. A second assumption is that these control processes will differ across expert populations depending on their specific complex task experience. The testing design will control for other variables of interest, such as bilingualism and musicianship, in order to explore how the experts' control patterns may or may not differ from those expected from these populations and look at the relationship between processing speed and successful performance during multitasking.

This thesis will seek to shed light on these assumptions by looking at expert and naive multitaskers in new, specific multitasking situations, and provide suggestions as to how we can learn to multitask and what multitasking expertise may teach us about control.

1.2 Terminology

To describe the simultaneous performance of two or more cognitive tasks, the literature uses several terms: *Multiple task performance* (e.g., Damos, 1984, 1991; Meyer & Kieras, 1997a, 1997b, 1999), *dual task performance* (e.g., Pashler, 1994; Halvorson, Ebner, & Hazeltine, 2013; Liepelt, Strobach, Frensch, & Schubert, 2011; Ruthruff, Van Selst, Johnston, & Remington, 2006; Schumacher et al., 2001; Sigman & Dehaene, 2008), *dual-tasking* (e.g., Bier, Lecavalier, Malenfant, Peretz, & Belleville, 2017; Buchweitz, Keller, Meyler, & Just, 2012; Damos, 1991; Levy & Pashler, 2001) or *multitasking* (e.g., Burgess, Veitch, de Lacy Costello, & Shallice, 2000; Feng et al., 2014; Fischer & Plessow, 2015; Just and Buchweitz, 2017; Salvucci & Taatgen, 2008; Sanbonmatsu, Strayer, Medeiros-Ward, & Watson, 2013). In the present study, the term *multitasking* will be used. Multitasking situations, however, encompass a wide spectrum of tasks whose inherent constraints determine the necessity to process them in parallel and our ability to do so. Where the distinction is possible, the term *concurrent multitasking* will be used when discussing the real-time maintenance of two concurrent tasks requiring continuous control, like concurrent streams of thought (Just & Buchweitz, 2017), while *dual-tasking* will be used to underline situations where such maintenance has not been found to be necessary. *Dual task performance* or *multiple task performance* will refer more generally to the context of simultaneous task combinations without assumptions as to the simultaneity of the processes at play.

As stated in the overview, multitasking research, the study of whether we actually can do two (or more) things at once in a continuous manner, and the examination of underlying mechanisms, has to deal with multiple limitations: Not only those of the human brain, but also the difficulty of accounting for the brain's workings when it comes to tackling complex cognitive tasks, that is, integrated tasks relying on the "use of both controlled (conscious, conceptual) and automated (unconscious, procedural, or strategic) knowledge" (Clark, Feldon, van Merriënboer, Yates, & Early, 2008, p. 579). We will use the term *continuous complex tasks* to describe real-life tasks which cannot be broken down into distinct temporal segments as their components have no clear beginning or end (e.g., Schmidt, 1988) and therefore rely on various overlapping controlled processes without seemingly allowing for their sequencing.

Recently, the term *cognitive control* has increasingly been defined as the ability to guide thought and behaviour based on an internally maintained goal (Miller & Cohen, 2001; Braver, 2012; Satpute, Ochsner, & Badre, 2012; Cohen, 2017). Cognitive control refers to an ensemble of mechanisms that allow information processing and behaviour to vary adaptively from moment to moment depending on current goals, rather than remaining rigid and inflexible (Miyake et al., 2000; Robbins & Kehagia, 2017). Furthermore, it is assumed to come into play regardless of the specific domain (Chiew & Braver, 2017). Although the term *cognitive control* is now widespread in cognitive neuroscience, other terms have also been used in the literature to refer to a similar construct: *executive control* (defined as the ability to select actions or thoughts in relation to internal goals, e.g., Friedman, Miyake, Corley, Young, & DeFries, 2006; Koechlin & Summerfield, 2007), *attentional control* (Baddeley, Baddeley, Bucks, & Wilcock, 2001), or *executive function* in the singular form (e.g., Koechlin & Summerfield, 2007), which has served in cognitive psychology as a near synonym to what is now referred to as "cognitive control" (Cohen, 2017). For instance, executive function is described as “a higher order cognitive ability that controls basic and underlying cognitive function for purposeful, goal-directed behaviour” (Etnier & Chang, 2009, p. 470, as cited in Healy, Ntoumanis, Stewart, & Duda, 2015, p. 2). However, *executive function* is sometimes also used in a broader sense in the context of self-regulation of thought and behaviour, in the domain of education for example. The term (*cognitive) control* itself had long been used in a more restrictive or less specific way in cognitive sciences, until recent inputs from neuroscience and computational models helped to formulate a comprehensive and integrated theory of control and gave the construct flesh and substance, explaining its current popularity. This term will be used in the present study as we will explore implications of this theoretical framework in multitasking contexts.

Control-related mechanisms are generally thought to be influenced by the internal demands of a task and by the specific demands emerging from the combination of tasks at hand (Cohen, 2017). We will use the term *executive functions* in the plural when referring to specific functions and attributes which have been explored and isolated in specific tasks (e.g., Miyake et al., 2000). They are encompassed in cognitive control and shed light on the specific control mechanisms at play.

For the sake of clarity, we will use *attention* in a restrictive sense only, to refer to the selection at the perceptual stage of certain stimuli for conscious processing (e.g., Broadbent, 1958) and to discuss, where needed, specific types of attention such as focused versus divided attention for example. The term *divided attention* refers to situations calling for the conscious selection of concurrent stimuli, but does not include a hypothesis regarding concurrent or sequential controlled processing.

1.3 Structure of the present thesis

Successful multitasking, especially continuous, should not be possible if the two tasks require cognitive control. Certain professional groups routinely carry out complex tasks that require multiple controlled processes. This study investigates the possibility of continuous multitasking and the involvement of specific control mechanisms in a continuous multitasking setting.

In Chapter 2, we review the evolution of theories and research regarding executive functions isolated in the literature and general mechanisms of cognitive control, including hypotheses on capacity limitations and the possibility to multitask. We provide an account of a contemporary theoretical framework for cognitive control and the proposition that control relies on two complementary sets of mechanisms, based on conflict monitoring and resolution on the one hand, and on goal maintenance on the other. We explore the implication of this proposition on our understanding of specific executive functions involved in completing a task and how conflict monitoring and resolution and goal maintenance come into play in a multitasking setting.

In Chapter 3, we review insights from research on cognitive control processes in bilinguals and examine the case of interpreters. We focus on the interplay between proactive and reactive modes of control and propose that conflict monitoring and resolution play a central role in interpreting.

In Chapter 4, we review literature on cognitive processes and control in musicians as well as the implications of motor expertise and ensemble performance on control. We examine the case of conductors and include a picture of the mental processes at play from the viewpoint of the conductors who participated in the study. We propose that relying on goal maintenance is essential for successful conducting.

To conclude the theoretical part, we contrast these two types of multitasking expertise and discuss their possible implications regarding the possibility of skill transfer to new types of continuous multitasking.

Chapter 5 lays out the aims, Chapter 6 the methods, and Chapter 7 the results of the experimental study for which we compared professional interpreters, professional conductors, and controls (non-multitasking professionals) using a paradigm requiring continuous multitasking. A dual task comprised of a visual-verbal *2-back* on the one hand, and of an auditory task involving covert count-keeping of two intertwined tone series (*beep count*) on the other, was administered. The dual task was administered before and after short-term single-task training in the 2-back task. Behavioural measures of conflict monitoring and goal maintenance were analysed.

Chapter 8 relates the findings from the experimental study to the theoretical framework set out in chapters 2 through 5. The results are discussed with regard to cognitive processes during continuous multitasking, differences between the groups, and methodological implications regarding the possibility of accounting for proactive and reactive control in a multitasking setting. We discuss the limitations of the present study in this regard and propose an outlook for the way forward.

2 Cognitive control in concurrent multitasking

To *multitask* means "to perform a number of tasks concurrently" (Oxford English Dictionary, n.d., definition b). In order to understand what this process entails for the brain, its functions and mechanisms, we must define what a task consists of. Multitasking is likely to be more than just the sum of carrying out the various tasks at hand, as it may imply additional processes on top of the ones required for successful completion of any of the individual tasks.

While the terms *task*, *activity*, *action*, and *process* are used without clear distinction in everyday parlance, for the purpose of this dissertation these terms will be used to refer to specific concepts. Although "task" is a generic term, which may apply to notions as diverse as shaving, making a presentation, doing a somersault dive and even writing a book – or, in the cases relevant here, conducting an orchestra or simultaneously interpreting a speech – it is safe to say that none of these involve the same set of processes in the brain or require the same amount of attention. Not only do tasks require different processes, but a task can require different processes from one time and context to the next. For instance, writing a letter calls for different processes than preparing a speech in writing, and so does walking down to the neighbourhood bakery from walking on a tight rope several meters above the ground. Therefore, it is important to present the specific contexts and conditions for each task when examining its underlying processes.

One way of circumventing the complexity of defining this fluid construct of *task* for scientific exploration is to focus, as we will in the present dissertation, on the idea that a task is a set of processes directed towards and subordinate to a goal. This definition, akin to the proposition in Strobach et al. (2018), makes sense from a cognitive point of view. Computational models of human information processing based on findings from functional imaging studies underline the crucial role of goal representations in influencing the processes that guide our behaviour (e.g., Miller & Cohen, 2001; Botvinick & Cohen, 2014). In empirical studies, it has been highlighted that goal neglect or conversely, maintenance, are crucial to task realisation (e.g., Kane & Engle, 2003).

Studying task execution from the perspective of goal-orientedness underlines the relevance of issues pertaining, for instance, to intention, motivation, the ability to focus on a goal, and the possible autotelic operation of certain sets of processes, which should be explored in their relationship to optimal performance.

Understanding a task as inherently oriented towards a goal and sub-served by a number of processes, may help us shed light on the way the brain deals with that hierarchical structure and whether goal-setting can make the brain see a given assignment as one or as separate tasks. In interpreting for instance, while the process can be broken down into subtasks for practice and pedagogical purposes, an interpreter at work will not be paying attention separately to the acts of listening and speaking, much less still to the separate acts of drawing the meaning and intent of the utterance, juggling with the tempo and the cognitive load by arranging items to be rendered in a certain manner, picking the words that offer the best combination of semantic closeness and ease of retrieval and so on. In fact, following so many instructions consciously would probably induce a breakdown in performance. Thus, the interpreter's mind is more often than not consciously focused on simply "rendering the message accurately", i.e., interpreting. Simple instructions focused on intent, such as "communicate", help students who are learning the technique, possibly because it helps them pursue a more integrated goal and better combine complex processes.

Automation of certain coordinated processes has been described as an effect of training or expertise in a given domain (e.g., Moser-Mercer, 2008; Çorlu, Muller, Desmet, & Leman, 2014). It facilitates inter alia the execution of lower-level tasks in a dual-task setting (e.g., Dux, Tombu, Harrison, Rogers, Tong, & Marois, 2009). It may, however, also happen as additional cognitive load is applied to a high-demanding task, as suggested in musical performance (Çorlu et al., 2014) and in WM tasks (Eichorn, Marton, Schwartz, Melara, & Pirutinsky, 2014). This aspect suggests that multitasking beyond dual-tasking may tap into resources and respond to training in a different way than commonly observed in dual-task settings.

Studying the way in which we attend to a goal requires looking into the processes governing attention and the execution of a task from its initiation to its completion (Satpute et al., 2012), from stimulus perception and/or selection, to enhancing relevant processing pathways or attenuating less relevant ones, to maintaining and updating task-relevant information in working memory (WM), to selecting the proper response or suppressing a spontaneous, yet irrelevant one. This is necessary in order to understand the processing constraints with which the brain has to contend when handling a more complex task.

This chapter will therefore focus on cognitive control in goal-oriented behaviour. It will address the scientific literature on control and its nature, the constraints that have been associated with it, and the possibilities to bypass or handle such constraints successfully. We will then take an in-depth look at two core functions of control during complex tasks: goal maintenance, and conflict monitoring and resolution.

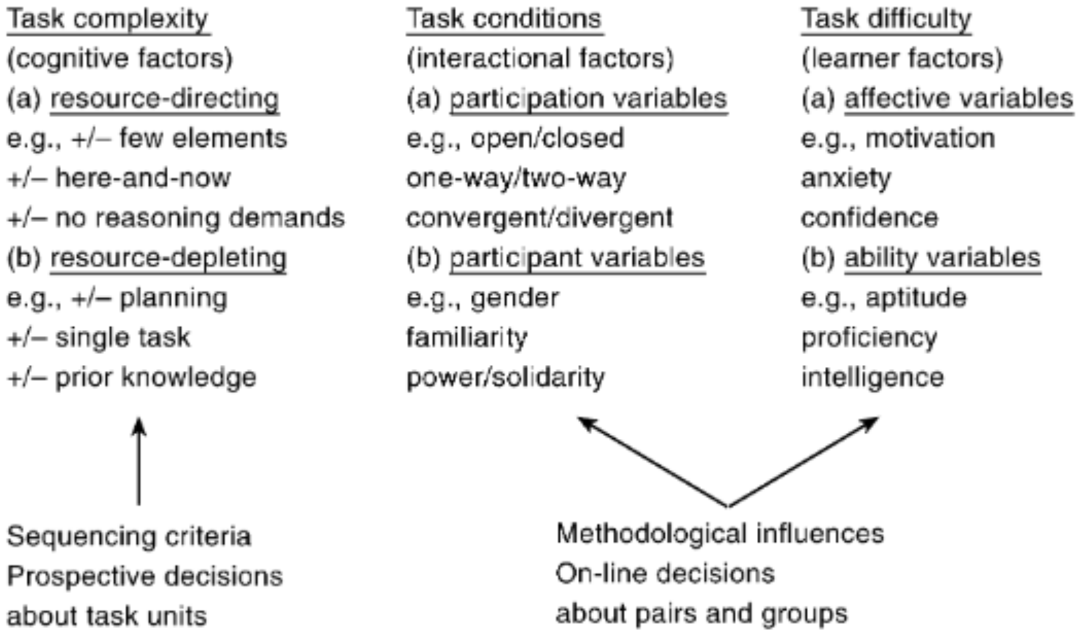
2.1 Tasks, control and executive functions

2.1.1 Task-inherent constraints

When accounting for the demands associated with a cognitive task, different sources of difficulty, that is, factors that require mental effort, need to be considered (Figure 1: Robinson, 2001). Task-inherent factors ("complexity"), performer-inherent factors ("difficulty") and environment-inherent factors ("conditions"). The present discussion of task-related controlled processes will focus on task-inherent factors. We will address individual characteristics as we dive into the nature of control at a later stage.

Figure 1

Robinson's model of task complexity, condition, and difficulty.



Note. Reprinted from "Task Complexity, Task Difficulty, and Task Production: Exploring Interactions in a Componential Framework", by P. Robinson, 2001, *Applied Linguistics*, *22*(1), p. 30. Copyright 2001 by Oxford University Press.

The simplest task paradigm is the simple reaction time (RT) task: there is one type of cue, and one type of response. Whenever the cue appears, a response is required. Introducing more cues and responses transforms the paradigm into a choice RT task, where different cues call for different responses. According to Hick's law (Hick, 1952, as cited in Welford, 1968,

p. 61), the slowing observed with each cue added to the paradigm occurs on a logarithmic scale. The speed-accuracy trade-off reflects the decision process (see review in Heitz, 2014) as well as adjustment to greater cognitive demands, as the task moves on the spectrum from simple to complex and thus calls for one or more controlled processes. In addition, another task-inherent source of constraints is the nature of the stimuli and responses, that is, the task modality and potential structural interference likely to overwhelm our physical (perceptual and motor) capacities. An auditory task calling for a verbal response will be simple as long as stimuli and responses do not overlap.

By the same token, multiple task situations can differ considerably as a function of the tasks at hand. Their temporal characteristics and degree of structural compatibility will determine the amount of interference between the tasks: Shadowing (echoing an auditory stream) while simultaneously copy-typing (typing visually presented text) is a task set relatively easy to learn, whereas reading aloud and simultaneously taking dictation comes with considerable difficulty (Shaffer, 1975). A generally observed phenomenon is that response time (RT) is shorter when the response in one task is structurally compatible with the response in the other task, while a slow-down occurs with structural incompatibility (e.g., Koch & Prinz, 2002; Lien & Proctor, 2002; Logan & Schulkind, 2000; Koch, 2009). Beyond the assumptions – discussed in section 2.2.1.2 – of Wickens' Multiple-Resource Theory (MRT) model (2004, 2008) regarding the nature of resources involved in task completion, the MRT model recapitulates the four structural dimensions of interference in dual task settings. Wickens, Sandry, and Vidulich (1983) manipulated a continuous visuo-motor tracking task by adding a concurrent discrete task involving either visual or auditory stimuli and requiring either manual or vocal responses. When the secondary task contained visual stimuli or required manual responses, interference was increased. Interference is therefore assumed to decrease when two tasks are processed using different stages (perceptual/cognitive and response), codes (spatial vs. verbal coding) and modalities (such as vision and audition for sensory/perceptual modalities, or manual and vocal for motor/response modalities).

Studies investigating multitasking performance are not always easily comparable as they rely on diverse task paradigms and many of them are dual-task rather than continuous paradigms. In a dual-task paradigm, two concurrent simple or choice RT tasks are administered, for which responses have to be as fast and accurate as possible. In some studies, investigating the cost of additional processing between a single and a dual task condition, the tasks are presented at the same time, with the instruction to give equal priority to both (e.g., Liepelt et al., 2011). In such instances, the tasks administered are structurally compatible (i.e., auditory and visual stimuli, and motor and verbal responses). Examples are discrimination tasks using tones and faces (Dux et al., 2009) or circles with different colors (Dux, Ivanoff, Asplund, & Marois, 2006, Schumacher et al., 2001) or number and tone discrimination tasks (Sigman & Dehaene, 2006, 2008). Other studies manipulate the timing of the tasks: the psychological refractory period (PRP) paradigm (Telford, 1931) is a dual-task paradigm which consists in presenting stimuli-response sequences for two simple tasks concurrently, and varying the asynchrony between stimulus presentation (stimulus onset asynchrony or SOA) (see Pashler, 1994). The tasks can also present various degrees of structural compatibility (e.g., stimuli of different rather than identical modalities, or corresponding rather than different spatial mapping between stimuli and responses). Task paradigms that are more continuous include, for instance, a dual listening comprehension task (Buchweitz et al., 2012), and driving while either having a cell-phone conversation (Strayer & Johnston, 2001) or performing an operation-span task, which calls on working memory updating (Medeiros-Ward et al., 2015).

Automatic, or automatised tasks like for instance counting, are executed faster than complex tasks that rely on controlled processing (Schneider & Shiffrin, 1977). When a task is complex, various executive functions are involved. Multitasking is also constrained differently as a function of the complexity of the two tasks involved, that is, the degree to which each of them relies on cognitive control and the specific executive functions which come into play.

2.1.2 Executive functions in single tasks and task combinations

Whenever we pay attention to something, our prefrontal cortex (PFC) becomes active bilaterally, focusing attention, allocating resources, coordinating information and scheduling cognitive tasks (Koechlin & Summerfield, 2007). The information necessary to complete a given task is thought to be stored in working memory (WM). As conceptualised by Baddeley and Hitch (1974), WM divides the notion of a unitary temporary buffer referred to as short-term memory (STM) into a construct that includes both the active maintenance and manipulation of goal-relevant information during the performance of a given task. Daneman & Carpenter (1980) define WM as a processing component dissociated from the storage component (STM). WM has also been conceptualised on a functional rather than structural basis as a central resource for cognitive processes (Just & Carpenter, 1992; Engle, 2002), or as the activated state of information in long-term memory (Anderson, 1983). Measures of WM have been strongly associated with a number of verbal abilities (Daneman & Carpenter, 1980). Another salient feature of WM is that it is limited in capacity – i.e., there is an upper limit to the content made available – and appears to be noticeably constrained when it comes to switching from one task to the next. Interference-based theories (e.g., Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Van Dyke & Johns, 2012) propose that interference, rather than resource limitation and decay of the information available over time, is responsible for the lack of durability of items held in WM. Therefore, while a number of models posit that controlled mechanisms responsible for maintaining these items work by strengthening or refreshing them, Oberauer et al. (2012) propose that these mechanisms can operate by removing interfering items. Other models (e.g., Lemaire & Portrat, 2018) suggest that both time-based decay and interference need to be counteracted and that both types of mechanisms coexist to preserve WM content. In any case, the focus has shifted from the amount of information which can be stored to the quality (strength, distinctiveness) of the actual representations active in WM, especially when it comes to verbal processing and retrieval (Van Dyke, Johns, & Kukona, 2014). Beyond the sheer issue of WM capacity, the mechanisms presiding over the selection, use, allocation and regulation of the information in WM, are of interest here.

The construct of WM comprises an executive system to fulfil these functions. From the start, Baddeley & Hitch (1974) postulate the existence of a Central Executive to allocate the necessary information to subsystems that act like repositories: the phonological loop for verbal-acoustic processing, the visuo-spatial sketchpad for mental image manipulation, and the episodic buffer, added later to the model. The episodic buffer (Baddeley, 2000) provides for the integration of short-term and long-term memory and allows us to retain and manipulate a limited amount of information from diverse domains in temporally and spatially sequenced episodes. This makes the temporary storage of material possible beyond the capacity of the phonological loop, accounting for instance for our ability to better recall words when they can be meaningfully chunked in a sentence or to repeat long prose passages (see Christoffels, 2006).

Baddeley (1986) proposes a broad role for the Central Executive, responsible for the control and regulation of cognitive processes. He suggests that the central executive may be similar to the Supervisory Attentional System (SAS) proposed by Norman & Shallice (1986; Shallice, 1988) in their model of attentional control of behaviour: a superordinate set of productions (i.e., condition-action rules) that control the state of WM and thus the execution of behaviour. Baddeley then proceedes to propose that the Central Executive is not a unitary element and does not serve a single function (Baddeley, 1996). The proposed functions of the Central

Executive are the following: coordination of two tasks; switching of retrieval strategies (e.g., in random number generation); selective attention and stimulus inhibition; and the temporary activation of long-term memory and retrieval of information stored there.

In subsequent literature, executive functions (EFs), the question of their unity and/or diversity, and their relation to WM capacity have been further explored (Miyake et al., 2000; Oberauer, Süß, Wilhelm, Werner, & Wittman, 2003). Oberauer et al. (2003) propose a model of WM capacity that is subdivided, on the basis of a structural equation analysis of customised tasks, into three main functions. Concurrent storage and processing, assessed with complex span tasks; relational integration (renamed from "coordination"), the ability to build new relations between elements, thus creating structural representations; and supervision, which is more independent from WM than the others and refers to the control of cognitive processes by goal representations. Supervision includes several sub-functions, namely distraction prevention, setting response criteria and shifting between task sets. Their findings, in terms of the diversity of the functions and their closeness to the WM capacity construct, were consistent with those of Miyake et al. (2000) who focused on three EFs frequently posited in earlier literature: shifting, updating and monitoring, and the inhibition of prepotent responses. They integrate shifting between mental sets and task- or attention-switching and for testing purposes do not differentiate between updating and monitoring. A latent variable analysis of the respective set of tasks assumed to engage these specific cognitive processes suggested that the three latent variables do share some underlying commonality (termed "common executive function"), but that they are also clearly distinguishable.

The identified construct of inhibition was further broken down by Friedman and Miyake (2004) in a successive factor analysis of performance in diverse tasks: Prepotent response inhibition refers to the ability to deliberately suppress dominant, automatic, or prepotent responses. Resistance to distractor interference is defined as the ability to resolve interference from external information that is irrelevant to the task at hand. Resistance to proactive interference is the ability to resist memory intrusions from previously relevant information that has become irrelevant to the task. Whereas prepotent response inhibition and resistance to distractor interference seem to tap a shared inhibition capacity, resistance to proactive interference appears to rely on a distinct process (Friedman & Miyake, 2004). Miyake and Friedman (2012) suggest that with finer-grained and thus more appropriate tasks, it would be possible to further break down the isolated and tested executive functions into component functions: Updating, for instance, is composed of monitoring, active maintenance, and item addition and deletion. In fact, testing, isolating, and delineating these functions remains a challenge (e.g., Marton, Goral, Campanelli, Yoon, & Obler, 2017; Paap, Anders-Jefferson, Zimiga, Mason, & Mikulinsky, 2020).

Specific tasks have been assumed to require distinct EFs, based on their underlying schematics and on the observed patterns of brain activation associated with their performance. Appendix A provides a short description of the tasks used by Miyake et al. (2000), Friedman and Miyake (2004) to isolate and specify these functions, as a very large body of subsequent literature uses or discusses a number of similar tasks to conceptualise cognitive control. Other tasks used in the literature to test EFs and mentioned in the present theoretical review are also described in Appendix A.

As Satpute et al. (2012) underline, the assumption when using such tasks is that the type of conflict they involve is to some degree similar to the conflict experienced when trying to resist any impulse outside of the lab, and that therefore these tasks engage the same neural systems as goal-directed behaviour in other contexts. However, Miyake and Shah (1999), Miyake et al. (2000) and Friedman and Miyake (2004) insist on the issue of task impurity, which they try to circumvent by focusing on commonalities within specific task sets, irrespective of their concrete object.

These specified EFs appear to be underpinned by concrete biological constraints. Biological models such as the *Prefrontal Cortex - Basal Ganglia subserving Working Memory architecture* (PBWM: O'Reilly & Frank, 2006) have been used to develop computational models of EF tasks. Chatham et al. (2011), for instance, were able to simulate the hypothesised processes of the *n*-back task, which requires participants to respond to probes that are identical to probes presented “n” items prior (see Appendix A) and requires WM updating. They tested aspects such as the neural representations underpinning the gating processes associated with updating or the performance patterns under various levels of dopamine. The same computational model reproduced the relationships entertained by specific functions with each other and generic cognitive ability (Miyake & Friedman, 2012), highlighting the biological underpinnings of observed behaviours. Regarding generic EF capacity, manipulations of model parameters influencing the strength of representations in the PFC affected performance in the modelled tasks across the board and seemed to suggest that individual differences in the assumed common EF rely on goal-maintenance mechanisms, which influence lower-level processing (Miyake & Friedman, 2012). According to the model, EFs – whose role is to help stop prepotent responses, resolve interference, update WM, shift mental sets, and coordinate multiple tasks (e.g., Baddeley, Kopelman, & Wilson, 2004) – enable goal-directed behaviours (Chatham et al., 2011). Positing that the "common EF" factor reflects goal maintenance in the PFC, Munakata et al. (2011) further specify Friedman and Miyake's (2004) distinction between types of inhibition: First, directed global inhibition, where the role of PFC areas is to maintain the abstract information suggesting when to inhibit the function of the target region. Second, indirect competitive inhibition, where PFC neurons directly excite goal-relevant processing areas and allow them to better compete with alternative pathways, which are thus indirectly inhibited.

Not all of the functions highlighted come into play in single-task settings. Some are discretely applied according to the task at hand. Others, however, are needed and can be investigated specifically in the context of task combinations. Miyake et al. (2012) stress that dual-tasking can justifiably be explored as an EF, or that higher-lever and more complex functions like planning might encompass the individual EFs studied. The specific role of EFs during multitasking appears to be far from marginal. In a study involving individuals with brain injuries, Burgess et al. (2000) using structural equation modelling found evidence of three WM-related constructs underlying multitasking: retrospective memory (defined as remembering the rules governing the task), planning, and prospective memory (following the plan, knowing what needs to be done). Theorists of EFs have also reflected on their involvement in a multitasking context for coordination purposes, as discussed above (e.g., Baddeley, 1986, 1996; Oberauer, 2003; Chatham et al., 2011).

Multiple-task performance is consistently characterised by the fact that it affects the way the individual tasks are executed, either by changing the task outcome (overwhelmingly for the worse) with respect to single-task condition, or by modifying the individual tasks' component processes. Just and Buchweitz (2017) underline that performing two tasks concurrently can take a different psychological form than simply executing the processes associated with each task, as additional mechanisms and phenomena can come into play in multitasking. For instance, the auditory task of listening to words over the phone impairs performance in a visuo-spatial task, such as multiple object tracking (Kunar, Carter, Cohen, & Horowitz, 2008). Conversely, doodling while listening to a voice message over the phone was shown to improve focus and message recollection over taking note of the target information (Andrade, 2010). The deterioration or modification of performance in a multitasking setting is a product of juggling task-specific processes and interference in structures or processes engaged in more than one task at once, but may be related to a greater necessity of coordination, possibly calling for the additional involvement of executive processes.

However, it appears that the structural characteristics – that are domain-dependent – and the intrinsic demands of the respective tasks are essential in determining the executive processes needed to ensure the successful completion of complex tasks. Simple response-time dual task paradigms (see Just & Buchweitz, 2017) require attention switching and likely draw on coordination mechanisms (Liepelt et al., 2011; Strobach, Salminen, Karbach, & Schubert, 2014) that appear to be more or less transferable across tasks depending on their characteristics. In other instances (Miyake et al., 2000), more continuous multiple tasks, like combining a continuous visuo-motor tracking task and an auditory-verbal reaction-time task, while not inherently complex, did not allow to isolate a specific "dual-tasking" function, suggesting a complex interplay of various functions in that type of context.

2.1.3 Summary: Executive functions and multitasking

Across accounts regarding the role and structure of WM (Baddeley, 1986, 2000; Chatham et al., 2011; Engle, 2002; Just & Carpenter, 1992; Oberauer, 2003; Oberauer et al., 2012), WM-related EFs are essential to ensure timing and coherence of the various processes on which a task relies. While EFs all rely on some common component, they are involved in distinctive manners in various tasks (Miyake et al., 2000; Friedman & Miyake, 2004; Oberauer, 2003). In multiple task situations, interference between the tasks is highly dependent on the task characteristics but needs to be resolved without detriment to the respective tasks. It is unclear whether dual-tasking or multitasking are themselves EFs (Miyake et al., 2012) that are separate from those which intervene at the task level (like shifting, in the case of dual-tasking). It is also unclear to what extent these EFs depend on a more general, common form of executive control that is inherently dependent on goal representations, associated with specific neural networks (Chatham et al., 2011), and to what extent they are linked to the selection of relevant and the inhibition of irrelevant processes (Munakata et al., 2011). This in turn raises the question of the possibility of pursuing competitive goals simultaneously at all.

Cognitive control theories offer global accounts of goal-related human behavioural patterns. The following sub-chapters explore the literature on this unified construct of cognitive control, looking for a framework in which phenomena associated with multitasking can be best accounted for.

2.2 The capacity debate and its implications on multitasking

The present study is based on a functional theory of cognitive control (Miller & Cohen, 2001; Botvinick et al., 2001; Braver et al., 2007; Feng et al., 2014). However, today's research on the issue of multitasking still heavily revolves around the nature of the limitation on multitasking performance and the debate between some version of a central or a distributed limitation hypothesis. It appears therefore necessary to provide a detailed overview of the salient theories that have shaped that debate.

Research seeking to provide an account of how the brain exerts control relies to a large extent on dual-task settings or multitasking (Meyer & Kieras, 1997a), precisely because these seem to push our ability for cognitive control to its limit and therefore help provide an understanding of the constraints that apply. Jaeggi et al. (2003) stress the effectiveness of the concurrent-task paradigm as an experimental tool to investigate control processes and the limits they encounter, since one of the main functions attributed to cognitive control is the distribution of attentional resources to different simultaneous processes. When control is involved, the observed deterioration between single-task and dual-task performance ranges from slowing and/or accuracy loss to downright breakdown (Just & Buchweitz, 2017). Based on this picture, three main constraints are suggested in the literature: Capacity limitations, that is, the assumption that there is a ceiling in the "amount" of control which can be exerted at any given time; timing issues, that is, the assumption that certain processes central to the completion of any task requiring control involve an inevitable delay; and structural constraints, based on the idea that certain physical "resources" (a term which is not always further specified, but which can be considered for the sake of simplicity to refer to processing nodes) can accommodate only a limited number of active processes. These limited resources, however, can be central or peripheral. These hypotheses are also compatible with one another (see Hazeltine, Ruthruff, & Remington, 2006, and Halvorson, Ebner, & Hazeltine, 2013, for a review). They will be explored in the next section.

2.2.1 Limited-resource and flexible-resource accounts of control

2.2.1.1 The central bottleneck hypothesis: Background and models

Multitasking theories rely heavily on the notion of capacity limitation, and the primary aim of research in this field has been to investigate and explain dual-task interference. These efforts started with empirical data showing longer RTs associated with shortened intervals between stimuli (Telford, 1931, Craik, 1948; see Meyer & Kieras, 1997a, for an extensive review), first suggesting the existence of a psychological refractory period (PRP) estimated to lie at 500ms, during which the second stimulus could not be processed. This observation plays a central role in theories of capacity limitation, together with the “attentional blink” – an accuracy cost in detecting the second of two visual targets presented at an interval of 200–500ms (Raymond, Shapiro, & Arnell, 1992). An abundance of studies have used the PRP paradigm, manipulating stimulus onset intervals (see reviews in Meyer & Kieras, 1997; Hazeltine et al., 2006) to shed light on the locus – and partly on the nature – of interference between two tasks, and therefore on processing limitations.

The "single-channel" hypothesis was formulated on the basis of the PRP phenomenon (Welford, 1952): When someone is engaged in a task, any mental process for a subsequent task has to be put on hold, globally affecting the chain of processes between stimulus perception and response. Indeed, behavioural observations of numerous stimulus-response combinations (auditory-motor or visual/verbal, in any combination and order; see Pashler, 1994, for a review), including continuous visual-manual tracking tasks, confirm that the secondary task is delayed by a duration equivalent to the time lapse between perception and reaction (Sternberg, 1969). Therefore, there seems to be an incompressible amount of time, during which stimulus identification, response selection, and movement preparation occur for each task.

However, contradictory observations of inferior delays between two distinct responses exist, notably in dual auditory-manual tasks (e.g., Karlin & Kestenbaum, 1968; see also Van Selst & Jolicoeur, 1997). Such observations suggest that the bottleneck may not comprise central processing stages globally, but be more limited and specific, and located either at the beginning (perception), middle (response selection informed by stimulus recognition) or end (motor production) of the process. These hypotheses are also known as "early selection" – in the first case – or "late selection" theories.

An influential early-selection theory is Broadbent’s (1958) "filter model" of a perceptual bottleneck, where attention acts like a central, capped filter, which limits information processing from the start. All incoming stimuli are stored and analysed in a sensory buffer (a "short term store") and filtered by this selective attention unit. This idea is based to an extent on observations of dual listening or shadowing tasks. However, subsequent research (Deutsch & Deutsch, 1963; Treisman, 1969; MacKay, 1973; von Wright, Anderson, & Stenman, 1975) refutes such observations and points to the possibility to extract information, like one's own name, from an unattended parallel auditory stream. System limitations accounting for the existence of a PRP and of multitasking-induced performance breakdowns have therefore been investigated at later stages of task execution. The response-selection bottleneck model (Smith, 1967; Welford, 1967, 1968; Pashler, 1984, 1990, 1994) suggests that while short-term memory is able to accommodate multiple stimuli, response selection is restricted to a single task at a given moment, meaning that subsequent response selection options have to "queue". This model accounts for the reduction of the PRP when responses are covert, or for the increase of the PRP depending on stimulus-response compatibility in the first task, like the correspondence of a motor response to a visual signal (e.g., Broadbent & Gregory, 1967). The response-selection bottleneck takes response conflicts into account: For instance, dual-task costs and PRP are increased in the presence of dual manual responses, including when the movements of both hands do not interfere with each other. This suggests a common set of processes specific to manual responses (Pashler, 1990). Yet, observed simultaneous response-selection processes indicate an even later locus for the bottleneck (e.g., De Jong, 1993; Keele, 1973). Using simple and choice reaction-time tasks as second tasks with different onset intervals in order to compare the observed RTs and the PRP, the authors cited conclude that serial processing occurs at motor initiation level and thus requires task prioritisation. However, these theories do not satisfactorily explain the fact that some tasks can be performed faster on their own than if they are given priority and simply followed by a second task, a case where a specific bottleneck should not apply (Broadbent, 1982; Neumann, 1987).

To resolve such contradictions, Kahneman (1973) conceptualises attention (in a broad sense, akin to the contemporary notion of control; see Cohen, 2017) as a limited resource, which nevertheless fluctuates in capacity. In that view, cognitive effort depends primarily on the demands of current activities, but does not necessarily suffice to meet those demands. This paradigm offers a differential account of control: Control becomes divisible and can be allocated by degrees, with near-full focus at high levels of task difficulty; it becomes selective with regard to perception and/or performance; and it can be controlled as a function of current intention or longer-term dispositions. This theory encompasses general limitations on task performance based on task difficulty and competition, but it also allows for a fluctuating point of interference, and notably, for fluctuating capacity. This framework is able to accommodate accounts of attention elasticity, divisibility and flexibility. The elasticity of the attentional capacity refers to the adaptation of the amount of effort allocated to a given task (as illustrated for instance by the fact that pupil dilation changes with increased or decreased effort exertion in a dual task paradigm with an auditory-verbal task requiring computing and a visual recognition task, when RTs remain stable; Kahneman, Beatty, & Pollack, 1967). Attention flexibility and divisibility – the fact that attention can be allocated to more than one process at a time and to varying degrees – are evidenced by the ability to attend to different extents to two tasks, like one continuous visual-manual tracking task and one visual-manual choice RT task (Navon & Gopher, 1979), with a gradual performance trade-off between those tasks.

Some neuroimaging studies have reinforced the idea of a ceiling on the amount of possible activation in the brain at any given time: Newman, Keller and Just (2007) highlight the "underadditivity of multitasking activation" in support of this assumption. For one single task requiring a certain amount of activation in some nodes of the brain, and another single task recruiting in turn a given amount of activation in specific nodes, the perfect additivity of the two tasks might be expected to recruit the sum of the corresponding activation for each. However, performing both tasks simultaneously typically activates substantially less than that sum, even when the recruited brain networks for each task (e.g., spatial processing and auditory language comprehension) hardly overlap (see also Just et al., 2001). This suggests that both tasks share activation constraints. Dux et al., (2006, 2009) and Tombu et al., (2011) pinpoint cortical centres whose activation is required by both tasks in a wide variety of dual-task settings, and towards which central processes seem to converge. They highlight a specific network that temporarily limits a variety of operations. This network involves the left inferior frontal junction (IFJ), the insula (bilaterally), and the superior medial frontal cortex (Tombu et al., 2011; Garner, Tombu, & Dux, 2014). According to Dux et al. (2006, 2009), the processes that seem to be concerned by this limitation range from perception encoding to response selection, suggesting a "unified central bottleneck", of which the left IFJ is a key area of interest. The central bottleneck posited can possibly account for phenomena such as the PRP, as well as the attentional blink. Crucially, an improvement in dual-task performance is observed with training, and the improvements are associated with faster processing in the identified bottleneck (Dux et al., 2006, 2009).

However, unitary resource theories do not specify the actual possible points of structural or processing interference between tasks, (whether at the level of attention allocation, in WM, or at a more peripheral level), or how the processing capacity is distributed (Meyer & Kieras, 1997a). It is also unclear whether or to what extent processing capacity is allocated to information processing, structural differentiation, task assessment, workload perception, or the control of outcome (i.e., "crosstalk" between task outcomes). Kahneman (1973) looks beyond attention capacity limitation to analyse multiple-task performance and suggests that both central and peripheral structures, responsible for sensory reception, memory storage and movement production, may be involved. This allows for possible structural interference (i.e., overlapping pathways) in addition to capacity interference (i.e., the exhaustion of attentional capital); but Kahneman contends that capacity limitation will induce interference in any case, even with tasks requiring different perception or response mechanisms.

In sum, the central bottleneck hypothesis suggests that a number of central operations are limited in processing capacity in a given neural complex. One common component of all the cognitive theories mentioned so far is that they view control as constrained by one limited pool of processing capacity. In a plethora of studies of various dual-task conditions, researchers conclude that the observed costs can be attributed to the need to delay central processing for one task, when another task occupies the central mechanism (see reviews in Pashler & Johnston, 1998; Lien & Proctor, 2002; Lien, Ruthruff, & Johnston, 2006). This in turn implies a bottleneck effect whenever the timing between the two tasks calls for simultaneous central processing.

The phenomena described above can indeed be explained by the existence of a central cognitive processing unit that is domain-general, and can be flexibly involved across tasks and processing stages, but has limited capacity. However, Meyer & Kieras, (1997a) suggest 3 different possibilities to explore in addition to this “unitary resource theory”: 1) the existence of diverse information-processing bottlenecks, triggered as a function of the task context (De Jong, 1993, 1994); 2) a fluid bottleneck susceptible to strategic programming; 3) the absence of a bottleneck. Cohen (2017) sums up the various possibilities regarding the nature of the actual "resource" whose capacity limitation is suggested. Such a theory would imply a cap in neural activity and energy consumption (a metabolic limitation), or in the number or extent of representations that can be actively maintained concurrently for task completion (for instance, in WM; a structural central limitation), or in computational power; or functional limitations on the way representations are maintained. However, considering the essential role that control fulfils in human behaviour, the amount of metabolic resources in the brain allocated elsewhere, and the computational power of the PFC, Cohen considers these ideas less than compelling.

2.2.1.2 Control as a flexible resource: Backgrounds and models

Kahneman (1973) formulates two predictions regarding interference between concurrent tasks, which derive from the notion of limited capacity: First, the limited capacity is central, therefore interference will be observed whether or not the two tasks share perception or response mechanisms. Second, the amount of interference will partly depend on the "load", that is, cognitive demands, imposed by each task. However, in contrast with these predictions, a second task performed in a PRP paradigm is not always affected by the cognitive demands associated with the primary task (e.g., Wickens, 1976). In addition, structurally similar tasks carried out concurrently are often found to show more interference than less similar tasks (e.g., visual-motor tracking is more easily combined with an auditory-vocal task than with the same exercise in an auditory-manual condition in McLeod, 1977; or there are differences in visual-manual versus visual-vocal tasks, Levy & Pashler, 2001). Therefore, scholars such as McLeod (1977), Allport (1980; Allport), and Wickens (1984, 1991) suggest that performance breakdown in a multiple task situation may be attributed to structural interference more than capacity interference, namely, that some peripheral mechanisms for sensory or motor mechanisms are constrained and that competition may occur at those levels rather than centrally.

For instance, interference can be reduced between two tasks when the structural requirements (e.g., stimulus or response modality) for different conditions in one task are changed, even when the level of difficulty is kept constant or increased. Thus, McLeod (1977) combines a continuous manual tracking task with a mental arithmetic task at various difficulty levels, where arithmetic difficulty had no influence on the tracking, suggesting independent processes and multiple processors rather than a single one. In fact, load-related interference theories presented in the previous section are also challenged when performance in a given task remains unchanged in spite of an increase in the required cognitive load for the concurrent task. By the same token, instances of "perfect time-sharing" during complex, but structurally different tasks like piano sight-playing and speech shadowing (Allport, 1980) seem to go against theories based on capacity limitation, as they point to structural crosstalk as the source of constraints (Wickens, 1984)[1].

Multiple-resource theories (Allport, 1980; Allport, Antonis, & Reynolds, 1972; Navon & Gopher, 1979; Wickens, 1983, 1984) seek to better account for the relationships between central and peripheral processing, assuming that specific processes draw distinct sets of pools of resources, with separate and divisible capacity, which is allocated flexibly according to the task at hand. Therefore, limitations in dual-task performance result from a competition

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[1] “Perfect time-sharing” remains, even now, a bone of contention between proponents and opponents of a central bottleneck theory (see e.g., Tombu & Jolicoeur, 2004).

between tasks for these specific resources: Two tasks drawing on the same resources can be executed simultaneously (i.e., in dual-task condition), but with a lesser rate of progress than in single-task condition. Conversely, simultaneous execution is possible without interference in the case of tasks requiring compatible, (i.e., different) sets of resources. Observations from a comparison between dual-task conditions exemplify this. Multiple-resource theories not only suggest that shadowing and copy-typing (e.g., Schaffer, 1975) make use of non-overlapping representations and processing pathways – one auditory-phonological-verbal, the other visual-orthographic-manual – but propose separate capacity sources (e.g., Wickens, 1983, 1984) between and within processing stages, codes and modalities (see section 2.1.1.). This implies that truly simultaneous performance of two given tasks will be impossible when the same basic processors are shared; and conversely, that pairing each of those tasks respectively with a task that does not require any of the same basic processors can in principle result in parallel performance without mutual interference (Allport et al., 1972). Multiple-resource theories do accommodate a number of observations that challenge the unitary-resource hypothesis, like the cases discussed above, where the processing capacity required by a given task is less relevant for performance than interference at perception or response level. However, these theories leave the description of the postulated specific resource sets open and possibly infinite (Meyer & Kieras, 1997a). Furthermore, they struggle to explain cases of irreducible performance depletion when distinct modalities of perception and response are involved (e.g., Pashler, 1990, 1994), and thus fail to entirely disqualify the bottleneck hypothesis.

2.2.1.3 Computational models of cognitive control

On the basis of these multiple-resource theories, which suggest that the constraints do not lie so much in the nature than in the object of control, i.e., the processes themselves, and that control intervenes precisely to regulate possible conflicts (Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; Botvinick & Cohen, 2014; Cohen, 2017), several models were proposed to try to overcome the theoretical challenges and to offer comprehensive predictions for controlled behaviour. The models seek to account for the broadest range of performance and therefore, like multiple-resource theories, do not rest on an assumption of general-purpose limited cognitive capacity. Therefore, when progress is made in several parallel tasks, it has to be monitored and coordinated to manage priorities and avoid for instance the conflicting simultaneous use of physical sensors or motor effectors (Meyer & Kieras, 1997a). These systems are based on computing architectures where conditional rules are defined, which are expressed according to the degree of activity of representations in WM (Botvinick & Cohen, 2014).

Among these models, Anderson’s (1983) unified model of higher-level cognition, the ACT* (Adaptive Control of Thought) and later (1993) ACT-R (Adaptive Control of Thought-Rational) models based on the production system framework (Newell & Simon, 1972), applied contemporaneous rules of artificial intelligence to simulate human information processing. The ACT* allows to predict specific processes like the direction of attention and behavioural control, and is best known for theorising declarative and procedural memory. In addition, Anderson’s models adapt the three stages of motor skill acquisition modelled by Fitts and Posner (1967) to cognitive skills: cognitive, associative, and autonomous skill acquisition, with progressively reduced reliance on declarative processes. Norman and Shallice (1986) model controlled processes on the basis of a set of production rules, which govern the state of WM and, in so doing, the execution of behaviour. The Supervisory Attentional System thus described is later assimilated by Baddeley to his Central Executive (Baddeley, 1993). These models rely on operation properties and syntax, not the semantic content of the representations, making them "symbolic" models of cognition, though further revisions of the ACT-R have sought to establish correspondences with biological mechanisms in the brain (Anderson et al., 2008).

Since the late 1990s, a number of models have sought to shed light on how multiple component tasks can be managed and coordinated. Salvucci (2005) and Taatgen (2005) both posit and test a model of general executive specifically involved in managing dual-task conditions, including continuous multitasking. Salvucci's "general executive" is based on a queuing mechanism that is temporally aware and manages current task goals. The model hypothesises that goal representations are guided in part by reasonable heuristics of multitasking behaviour (Salvucci, 2005), meaning that a form of learning is needed and takes place in the process. Salvucci's computational model is conceived within the framework of Anderson et al.'s (2004) ACT-R model, which encodes step-by-step sequences of thought and action in the form of computational script. However, the representations described in the model also seek to account for patterns of human behaviour beyond multitasking situations. Indeed, this highlights the question whether such a general executive capacity is involved in multitasking specifically, or if multitasking rather reflects the workings of cognitive control generally.

Meyer and Kieras (1997a, b) design a comprehensive computational model of executive cognitive processing: the EPIC (Executive-Process Interactive Control) architecture. The model emphasises the relevance of strategy use in the involvement of cognitive control and assigns a prominent role to production rules governing a task (Meyer & Kieras, 1997a). The model includes various executive processes to adjust to task instructions or instructions derived from the current context. These processes exert various forms of control to maintain priorities and coordinate progress between concurrent tasks. They do so, for instance, by inserting and deleting task goals in WM, directing the gaze where needed, sending selected responses, or preparing for the anticipated motor responses. In contrast to the idea of a Central Executive (Baddeley, 1986) or Supervisory Attentional System (Norman & Shallice, 1986), executive processes do not depend on a separate mechanism but rather entail a separate set of production rules which do not modify task-level production rules, but coordinate them via WM manipulations. Executive task scheduling is therefore based on strategies and, importantly, susceptible to practice. The various observed PRP phenomena are explained by a flexible "strategic response-deferment" to delay selected task responses as needed. The strategic response deferment is based on a processor with infinite capacity to test and apply production rules simultaneously, which in turn introduces timing constraints on the flow of information based on strategies. The EPIC theory accounts for the capacity to adjust to task priority instructions by offering alternative response-transmission modes, allowing responses to either be stored temporarily in WM (deferred mode) or to be sent directly to their motor processors (immediate mode) (Meyer & Kieras, 1997a). The model assumes an inevitable serial constraint on controlled processes.

More recently, Salvucci and Taatgen (2008) have sought to expand the EPIC model and integrate ulterior findings into a single computational theory of *threaded cognition.* The main differences between the expanded model and EPIC are twofold. First, threaded cognition introduces a serial procedural resource, while the EPIC model allows multiple parallel rule firings. Second, the new model departs from the idea of rule-based executive processes to manage resources and resolve resource conflicts, instead proposing that the brain has a basic ability to perform multiple concurrent tasks and that this ability does not require supervisory or executive processes (Salvucci & Taatgen, 2008). In their view, a general, domain-independent, parsimonious mechanism like the one proposed by Liu, Feyen, and Tsimhoni (2005) allows for concurrent processing and provides basic resolution of interference between resources. The fact that the numerous instances of multitasking in our everyday behaviour are the result of that basic ability does not preclude that higher-level functions may be involved when we engage deliberately in multitasking (Salvucci & Taatgen, 2008).

Cohen, Dunbar, and McClelland (1990) endeavour to reflect brain function as closely as possible by relying on Parallel Distributed Processing (PDP; Rumelhart, McClelland et al., 1986), a theoretical framework which seeks to account for the vastly parallel architecture of the human mind and to unify neural and cognitive processes in a highly computational framework. By contrast to the production rule framework, used in other models, the PDP adopts a "connectionist" approach, in which mental and behavioural phenomena are thought of as emergent properties of interconnected neural networks. This framework is further developed in Botvinick and Cohen (2014).

2.2.1.4 Origin of control

Remarkably, the latest theories dispense with the idea of an "inner voice" being at the origin of control, a "homunculus" hidden in the brain (Botvinick & Cohen, 2014). Behavioural choice happens solely as a function of the stimuli encountered, and the associations they trigger. But this raises the question of how, in the presence of certain stimuli, a weaker behavioural response can be selected. Satpute et al. (2012) give the example of somebody with diabetes who is offered an apple. The biased-competition model (Desimone & Duncan, 1995; Miller & Cohen, 2001) integrates these situations in its account of controlled behaviour. The initial assumption is that a given stimulus activates multiple response pathways (eat the fruit, give it, leave it…). In the absence of control, pathways would inhibit one another until the strongest pathway is activated and influences behaviour. For an alternative pathway (in this case: renouncing to eat the apple) to be selected, a goal must be represented and internally maintained, in order to bias the selection of the goal-relevant pathway over any stronger pathway. This is consistent with the account of inhibition in Munakata et al. (2011), and with the ACT-R (Anderson, 1993), which posits goal representations used to guide behaviour. These goal representations are, like intermediate task products, temporarily held in WM.

As we can see, in order to circumvent the idea that something "thinks in our place" in the brain and allocates control, biased-competition theory rests on goal representations as a driving force for control. If goals drive the processes that allow for task performance, these goals need to be activated and retained in memory and linked to specific behavioural representations. Therefore, in the biased-competition theory, the following essential attributes listed by Satpute et al. (2012) subserve several central functions that constitute a control system:

1. A WM, defined as the ability to internally maintain goals and contextual information important for engaging in goal-appropriate behaviour.
2. A means of “adaptive gating” in order to let only goal-relevant information into WM and keep goal-irrelevant information out.
3. A mechanism to select goal-relevant and inhibit goal-irrelevant associations as a consequence of maintaining a goal.
4. A means of determining when control needs to be deployed (Satpute et al., 2012, pp. 52–53).

The system rests on adaptive gating, which allows the neural networks maintaining goal-relevant information active to update it as necessary. Adaptive gating refers to the notion that certain threshold levels of a given neurotransmitter in specific nodes in the brain trigger two distinct mechanisms: one which prevents irrelevant information from interfering with the maintenance of relevant information, and one which allows relevant information to update the contents of WM (Braver & Cohen, 2000; Frank, Loughry, & O’Reilly, 2001; Miller & Cohen, 2001). This function is essential, as it allows the mind to adjust to the demands of the task at hand, and to then move on to treat another task once the first one has been completed. This way, information that has become irrelevant can be discarded and does not "bloat" WM.

To fulfil this gating function, dopamine is a choice candidate (Miller & Cohen, 2001), as it has been found to transmit two sorts of signals ("tonic" and "phasic"), which are thought to work in opposition and have been associated with maintaining information over time irrespective of distractions, or conversely updating the information (Braver & Cohen, 2000; Cohen, Braver, & Brown, 2002). The basal ganglia have been hypothesized to play a specific role in this regard (O'Reilly & Frank, 2006, see section 2.1.2) in emitting gating signals controlled by dopamine activity, with those signals in turn enabling selective updating in the PFC. The gating model has recently been refined, with the addition of an output gate able to determine which active representations in the PFC to use and a mechanism to reallocate WM capacity when representations have become irrelevant (Chatham & Badre, 2015; see Chiew & Braver, 2017).

Such observations support the idea that exerting control may involve an amplification of weaker pathways and/or an inhibition of stronger pathways (Munakata et al., 2011; Satpute et al., 2012). The biased-competition model supposes that weaker associations are amplified in the PFC and, once sufficiently activated, they are able to inhibit the stronger associations (Miller & Cohen, 2001). This is what the guided activation theory (GAT) proposes: task representations, or goal representations, in the PFC exert control by biasing the flow of activity. According to GAT, the PFC is responsible for the active maintenance in WM of critical task information, which is necessary for the execution of goal-directed behaviour when interference from distractors has to be ignored or competing response reflexes have to be overcome to complete the task (Botvinick & Cohen, 2014).

Based on guided activation theories, control is exerted adaptively on the basis of the demands of the task at hand, as signalled by the occurrence of conflict between active representations. Control hence does not intervene where such conflicts are absent and a strong response association exists. This idea casts light on how one and the same task can call for control or not depending on the context, and challenges the discrete mechanisms thus far hypothesised for automated and controlled processes.

2.2.2 Control vs. automaticity

2.2.2.1 Nature of the processes

Certain activities are by nature administered by "primitive" parts of the brain, and are therefore in essence automatic, like breathing, eating, or walking. They are also noticeably easy to combine with other tasks (Hallinan, 2009). Understanding an audible utterance in one’s own native language, for instance, seems to happen automatically. It can be hard to avoid overhearing and understanding something that is being said in a language we master very well, even if we do not actively pay attention to the people or the radio at the origin of the utterance for example. On the other hand, listening to and understanding languages we know less well, can require some attention (e.g., Bidelman & Dexter, 2015).

The first influential distinction between automated and controlled processes is owed to Posner and Snyder (1975), Schneider and Shiffrin (1977), followed by Norman and Shallice (1986); They underline intrinsic differences between the two kinds of processes. On the one hand, automated processes are in essence quick, can happen in parallel, do not draw on attentional resources, are difficult to interrupt and do not suffer from the simultaneous execution of a controlled task. On the other hand, controlled processes are slower, happen sequentially, draw heavily on attentional resources, are easy to interrupt, and do suffer from the concurrent execution of another controlled task. Norman and Shallice (1980) go on to specify different meanings of automaticity: The unaware performance of certain tasks (like walking in the absence of internal or external constraints), the spontaneous initiation and execution of punctual actions (like brushing away an insect from one's arm), and the reflex of drawing one's attention to an environmental change, without controlling the direction of attention. Additional effects of automation are underlined: A collection of processes can be consciously observed without specifically attempting to control them, as in sports, or a task can be performed without interfering with other tasks, bypassing any limitation in processing resources.

To distinguish automated from controlled processes, Shiffrin and Schneider (1977) used a mapping task, where participants were made to look for a given set of letters. In the consistent-mapping condition, the targets were always identical, while in the varied-mapping condition, the targets changed from one trial to the next. After prolonged training (hundreds of trials), no effect of the target-to-distractor ratio was observed anymore in the consistent-mapping condition, whereas in the varied-mapping condition, that ratio remained associated with changes in response time. While this paradigm was instrumental in defining automation and describing its characteristics, it also established automation as the result of intensive training, namely, a change in the internal nature of the task depending on individual experience.

2.2.2.2 Training effects

Indeed, automation appears to exert increasing influence on the performance of a task as the degree of practice increases, as reflected in ceiling accuracy and higher processing speed. More specifically, repeated stimulus-response pairings are associated with progressively stronger automatic processing until that automatic processing is strong enough to be entirely relied upon, avoiding competition for limited central capacity – provided such a central resource is assumed – (Logan, 1988; Ruthruff et al., 2001) and circumventing the need for attention (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980).

Schneider and Shiffrin (1977) conclude that skill acquisition is affected by three factors: the consistency of the target-distractor pattern, the amount of training, and the cognitive load associated with the task. According to this vision, cognitive load can be expected to influence the rate of acquisition; nevertheless, consistent training will, after a sufficient amount of exposure, induce automatic responses irrespective of the cognitive load. This would imply that only consistent task rules and response modalities can be trained. This view further implies that the benefits of training apply solely to the practiced task and cannot be transferred. However, broader training effect patterns have been observed: The automatised processing of one task component can be extended to different stimuli categories (Schneider & Fisk, 1984) or to different task components (depending on their degree of closeness to the original task; see also Cormier, 1987).

The neural underpinnings of an automated process are task-specific associative connections, that is, a "sequence of nodes that nearly always becomes active in response to a particular input configuration" (Schneider & Shiffrin, 1977, p. 2), activating pathways away from brain regions involved in cognitive control and attention (e.g., Chein & Schneider, 2005; for a review of early neuroimaging conclusions on cognitive control localisation see Ridderinkhof, van den Wildenberg, Segalowitz and Carter, 2004).

Training effects in multitasking are associated with decreased activation in these areas responsible for the exertion of control (Haier, Siegel, Tang, Abel, & Buchsbaum, 1992; Petersen, vanMeier, Fiez, & Raichle, 1998; Chein & Schneider, 2005), which is in turn associated with reduced response times. Rypma et al. (2006) associate slower responses, even in a relatively simple reaction-time task, to increased neural activity in the executive control network; In addition, that activity is bidirectional, suggesting a double constraint placed on otherwise swift visual/motor processes by planning and by monitoring. An alternative account for situations in which participants become capable of carrying out two tasks without performance depletion is provided by Dux et al. (2006, 2009). After single-task training in both discrimination tasks used, the delays in response observed in the dual-task paradigm (Pashler, 1994) decrease from 400ms to 40ms while accuracy increases (Dux et al., 2009). However, the authors underline that the reduction in interference costs observed after training does not seem to be due to a diversion of the flow of information processing away from the PFC (towards more task-specific, more implicit processes). Nor is any segregation of PFC into task-specific neural networks observed (to suggest a bypassing of the bottleneck in information processing). In their view, training increases processing speed in a temporally constrained network dedicated to central stimulus-response mapping, and this acceleration (which allows multiple tasks to be processed in rapid succession) is enough to account for the swiftness of trained processes and to produce the appearance of parallel processing. This conclusion is based on a pre- and post-training study of possible regions of interest not showing an increase in activity in these regions with training (Dux et al., 2009). More specifically, following training, the peak of the IFJ activation in the dual task occurs earlier than before training, which indicates that information is transmitted faster (Dux et al., 2009; Tombu et al., 2011; Garner et al., 2014). The authors therefore attribute the multitasking limitations in humans to a mechanistic factor, which is the poor speed of information processing in the lateral PFC, more specifically in the IFJ (Dux et al., 2009)[2]. However, this finding does not definitely corroborate one of three main possible underlying hypotheses. The authors posit that that speed limitation could itself be underpinned by a competition for inferior frontal lobe resources, which is reflected in a competition for central processing resources. Alternatively, the limitation could lie in the computational capabilities of that brain area; or it could be a functional feature, due to sequenced processing introduced as a reaction to interference between the processes involved in the tasks (Cohen et al., 1990). According to all three hypotheses, dual-task or single-task training would facilitate dual-tasking in a given paradigm.

Successful multitasking has also been associated with higher "neural efficiency": Jaeggi et al. (2003, 2007) use this term to refer to reduced magnitudes in brain activation as well as a reduction of the range (spatial extent) of activation. In those studies, Jaeggi et al. use a dual *n*-back task, with 2 different manual responses associated with visuo-spatial or auditory cues. With increasing dual-task difficulty, high-performing multitaskers showed decreased activation in areas of the PFC associated with cognitive control. In low performers, interestingly, activation levels increased. Using fewer resources in the executive network might indicate the ability to perform certain task-specific process in that given situation without strategic control, that is, to automatise them (Just & Buchweitz, 2017). However, low performers may also resort to less effective strategies (Meyer & Kieras, 1997a), leading to higher resource consumption for mediocre levels of performance. Jaeggi et al. (2007) suggest the following: In situations of cognitive overload, like the tested multitasking situation, an efficient strategy would be the ability to avoid superfluous or extraneous brain activation by keeping a form of "cool" and focusing on crucial elements of the task at hand. This could be compared to certain traits and activation patterns observed in expert airline pilots compared to novices (Peres et al., 2000). Another type of change observed in a multitasking situation (Just & Buchweitz, 2017) is an increase in synchronisation (relative to the single task) between the various task-related brain areas. The task used was a dual comprehension task requiring

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[2] The IFJ is located in the lateral PFC region, which is assumed to be involved in cognitive control, and more specifically in active goal maintenance (Lamichhane, Westbrook, Cole, & Braver, 2020). It is unclear, however, whether or not the superior medial frontal cortex highlighted as part of the central processing network in Tombu et al. (2011) extends to the (dorsal) anterior cingulate cortex (ACC), a structure thought to be central in conflict monitoring (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004; Botvinick & Cohen, 2014).

continued focus (Buchweitz et al., 2012), where participants had to listen to two people speak at the same time (one in each ear). Successful performers showed modifications in the relative timing of activation between specific nodes.

Additionally, some extremely specific task conditions appear to lift some of these observed constraints on multitasking. These tasks, which structurally involve the least demands, are called ideomotor compatible tasks. Ideomotor compatible tasks seem to bypass any assumed bottleneck by resorting to strong stimulus-response associations, like for instance visually presented directional arrows (left or right) requiring a manual response (shifting a joystick in the corresponding direction), or an auditory-vocal task in which the letters *A* or *B* were presented aurally and required shadowing (Greenwald & Shulman, 1973; Schumacher et al., 2001; Hazeltine, Teague, & Ivry, 2002). However, such tasks and instances of "near-perfect time-sharing" (Schumacher et al., 2001) have recently come under scrutiny, as doubts arose with regard to whether they really allow for the engagement of parallel processes, away from the assumed bottleneck (see Hazeltine et al., 2006; Halvorson, Ebner, & Hazeltine, 2013), or if they involve such short central processing stages that the bottleneck is not saturated and remains "latent". With very short response times, which generally indicate short central stages, it is difficult to distinguish between a latent bottleneck and parallel response selection (Hazeltine et al., 2006; Lien et al., 2006). Importantly, as exemplified by this issue, it is difficult to distinguish serial from concurrent processing, and therefore, to draw conclusions on the sequential character of control or, on the contrary, to establish whether control supports parallel processing. The validity of any claims in that respect would depend on our capacity to observe processes with sufficient temporal resolution (Cohen, 2017). More generally, the idea that automation is the solution to control-related constraints, coupled with the observation that paying attention to processes that are usually not attended to tends to radically modify the characteristics of their execution, has led to conceptions of automation and control as two mutually exclusive constructs built in opposition. However, the picture might not be so clear-cut.

2.2.2.3 A control-automaticity continuum

The distinction in nature postulated between controlled and automatic processes has been reconsidered by several frameworks. The Soar architecture (Laird, 2012; Laird, Newell, & Rosenbloom, 1987), hierarchical in nature, proposes different levels of real-time processing, from lowest (and fastest) to highest: the first level in the model simulates perception, encompassing sensory WM input and motor commands; the second, “reactive” level still entails bottom-up, parallel, automatic processing depending on the current state of WM; the third "deliberative" level uses knowledge from the previous level to sequentially propose, select, and apply an action. With learning, these choices can be “chunked” (i.e., compiled) to allow for parallel processing. Such processing can thus typically arise from practice and skilled task execution. When the knowledge from the lower levels is incomplete or uncertain, problem-solving algorithms are triggered to resolve impasses, such as those generated by conflicts between simultaneously selected but incompatible actions, as can happen in dual tasks. In EPIC, Meyer & Kieras (1997a & b) suggest that once specific production rules for particular task combinations are established, more complex processing can take place to schedule tasks concurrently with a minimal lag between conflicting events. Thus, a major advantage bestowed by practice to expert performers of dual tasks may be provided by a strategy shift at the executive level: Whereas a possible spontaneous strategy for novices involves scheduling the tasks and thus suspending one of the two altogether to eliminate potential conflicts between sensory, motor, or processing resources, this approach undermines their ability to multitask smoothly. EPIC (Meyer and Kieras, 1997a & b) or ACT–R (Anderson et al., 2004) have been used in multitasking models (for a comprehensive review see Salvucci, 2005) with the objective of understanding how a specific task combination is rendered possible, such as fighter jet piloting (identifying an object on the radar while deciding on one's trajectory and following it) or air traffic controlling (guiding various planes while monitoring landing conditions). These models are based on individual task models, which they then seek to integrate in a specific combination. They have been tested using aggregate performance in the task, but are not applicable to other task combinations. Consistent with the effects of practice that they propose, these models rely on multitasking control mechanisms that have been specialised and fine-tuned for a specific task or task combination, or as it were, "customised executives" (Salvucci, 2005). Therefore, these multitasking architectures suggest heavy task-dependency and an impossibility of skill transfer.

Differences in modality pairings, too, may yield differences in automation between various combinations of stimulus and responses (Hazeltine et al., 2006), in turn influencing how practice can modulate the degree of automation beyond the effect of exposure to repeated patterns mentioned earlier (Shiffrin & Schneider, 1977). For instance, many observations suggest that it is easier to establish "direct routes" between visual stimuli and manual responses, than between visual stimuli and vocal responses. This might be due to manual movements often relying on vision in everyday behaviour. Hazeltine et al. (2006) suggest that when such direct routes are not established, response selection cannot occur solely on the basis of automated processes, even after several practice sessions. Moreover, practice is widely considered to lead to performance change due to a transition from controlled processing to automatic execution, but that transition happens progressively rather than abruptly, suggesting a gradation in the level of automaticity achieved (Logan & Etherton, 1994).

Cohen et al. (1990) also propose a continuum of automaticity. Cohen and colleagues' PDP model, based on the Stroop task (see Appendix A), suggests that a pattern of activity within neural networks can act as an explicit task representation and provides insight into the type of control exerted in the PFC (Botvinick & Cohen, 2014). The model thus seeks to account for automaticity and the role of control without supposing mechanisms for control that are of a distinct nature, thereby placing automation and control on a continuum determined by the strength of the connections in processing pathways: Weaker associations require greater control. Learning occurs as associations are strengthened, and practice can modulate the absolute strength of pathways, and therefore reliance on control. In addition, the extent of the involvement of control also depends on the relative strength of the competing processes (Botvinick & Cohen, 2014), and therefore on their relative position on the continuum (Cohen, 2017): To allow a weaker task-relevant pathway to compete with a stronger but task-irrelevant pathway, top-down support is exerted.

The suggested continuum with regard to the involvement of control offers fascinating implications regarding the way control may work: It means that control can be exerted with varying intensity. Indeed, the modulation of control intensity is investigated further (Shenhav et al., 2013) based on the observed influence of a specific neural network involving the dorsal anterior cingulate cortex (dACC) on cognitive control (Miller & Cohen, 2001; Botvinick et al., 2001; Botvinick, Cohen & Carter, 2004). In accordance with findings in the literature on ACC function, the regulation of control is found to be associated with "motivation", or stronger engagement on the basis of current incentives (for a review see Shenhav et al., 2013). This points to a reward-based mechanism for control, a theory that we will discuss next.

2.2.3 Summary: Implications for task-switching versus continuous multitasking

The various theories and propositions regarding capacity limitations in controlled processes often contend with the question of whether the limited capacity for control can be shared between two processes, allowing them to proceed in parallel, or whether it has to be allocated to each in turn, making task-switching a requirement. If controlled processes are by nature constrained temporally, limited quantitatively as to the information load they can deal with, and forced to happen serially as a consequence of both these limitations as discussed above, then only automatic processes can occur in parallel with others. This conclusion has come to define control in opposition to automaticity (see Cohen, 2017). In this case, automatisation of at least one of the two tasks is the only way to achieve multitasking, and to do so in the manner least likely to harm performance. Numerous examples of acquired motor coordination, which is highly automatised with training (e.g., Çorlu et al., 2014) come to mind: This type of automation is instrumental to satisfactory musical performance as it frees controlled resources to be allocated to the actual interpretation of a given piece.

However, the observed temporal constraints could also be attributed to central processes not being allowed to operate in parallel, whether they share a common mechanism or not, because they are scheduled serially in order to avoid the expected cost of crosstalk (Meyer & Kieras, 1997a; Hazeltine et al., 2006). Hence, influential theories of dual task performance diverge when it comes to the implications of observed limitations and costs: Depending on the school of thought, these limitations are explained by structural constraints, namely shared processes in the cognitive architecture, or by strategic constraints, that is, executive scheduling of task operations. As we have seen, some tenets of structural constraints usually posit central mechanisms with limited capacity, whereas proponents of strategic constraints usually do not attribute the costs that scheduling seeks to avoid to central limitations, but rather to a competition for peripheral, sensory or motor-processing resources. Theories that do not rely on a single limited resource endeavour to account for processing capacity being allocated in a differential manner according to task and context. We will now explore their implications.

2.3 Control as an emergent property of task execution

We have seen in previous sections a review of the limitations hypothesised in most of the literature on controlled processing. Many of these accounts share a common feature: they view control either as one or a collection of finite resources. This means that exerting control not only imposes limitations on the processes that are attended to, but depletes these resources or binds them to a set of processes and therefore entails the risk of leaving other processes unattended (see review in Kool, Shenhav, & Botvinick, 2017). But if – as recent theories suggest – control is deployed adaptively in the form of increased transmitter signals in response to crosstalk in shared representations in the mental environment (Botvinick et al., 2001), then control fluctuations do not reflect a limitation (Cohen, 2017): Forcing sequentiality in the activation of these representations is the very purpose of control (Feng et al., 2014).

It is therefore important to note that the constraints associated with control do not depend on the "amount" of control requested to successfully execute a given task. Fluctuations in control, then, are not attributed to the impossibility to exert control, but rather to a form of computation resulting in an expected benefit in not exerting it (Botvinick, 2007).[3] Control works by enhancing signals in specific, selected pathways against habitually predominant pathways, in order to support a given a course of action. There is a cost involved, precisely because control entails a choice of specific pathways over others (Kool et al., 2017). To put it very bluntly, it is as if control, due to its very nature, were susceptible to fear of missing out on the options it does not select (Kurzban, Duckworth, Kable, & Myers, 2013). The cost of control could also reduce incentives to introduce crosstalk in the shared representations, for instance by following concurrent goals (Feng et al., 2014).

This section will explore in more detail the cost entailed in exerting control. We will then move on to look at the circumstances that can facilitate the selection of one course of action over others; the effectiveness of purely reactive control, in the face of similar expected rewards, would be limited. Since expected rewards are attached to goal-serving task representations, the idea that control is goal-oriented is central and its implications in multitasking settings will be discussed further in section 2.4.

2.3.1 The expected value of control hypothesis

In the neuroscience of cognitive control, the ACC is associated with a multiplicity of functions ranging from conflict and performance monitoring to action selection and reward processing (e.g., Botvinick et al., 2001; Cohen, 2017). Cohen and colleagues (2013, 2017) propose a single function underlying these various mechanisms: the allocation of control based on an evaluation of its expected value. The Expected Value of Control (EVC) hypothesis is formulated by Shenhav et al. (2013). It goes beyond the broad relationship with motivation hypothesised until then for the ACC and proposes that the ACC (more specifically the dACC) is specifically responsible for the adaptive adjustment of control to task demands.

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[3] Several hypotheses on the nature of control have been proposed regarding those benefits. One, for instance, is that exerting control for too long entails a biological risk in accumulating certain substances (peptides) that are generated in the process and are harmful for the brain in the long run (Holroyd, 2016).

Behavioural data from simple reaction-time decision tasks, such as a speed-accuracy trade-off after errors, also called post-error slowing (PES), support adaptive adjustments in control (Botvinick et al., 2001). Botvinick et al. (2001, 2004) attributed these effects to a mechanism that monitors the conflict generated by errors and/or interference, and which uses this information to adjust the intensity of task-relevant signals in order to maintain task performance. The specifics of conflict monitoring will be discussed further below. The EVC model sets these observations in a wider context and posits that the purpose of these adjustments lies in optimising the allocation of control.

Although the EVC hypothesis, derived from a model based on Stroop task data, does not claim to offer a comprehensive theoretical framework of cognitive control (Shenhav et al., 2013), it lays the basis for attributing an essential three-fold role to control: the management of lower-level information processing mechanisms ("regulation"), the choice and intensity modulation of the control signal emitted ("specification"), and the monitoring of current circumstances in order to unfold adaptively ("monitoring"). A distinction is made between the (ACC-served) decision process that allows specifying the control signal, and the implementation and regulation of that signal to modify task-relevant processes, which are based on distinct neural substrates (regulation is associated with the inferior PFC). Kool et al. (2017) propose adding a fourth function to this set that would precede monitoring: the evaluation of individual events and objects or states in the environment ("valuation").

It is assumed that control fulfills all the functions above in order to adapt optimally. This assumption is based on analyses of simple decision-making tasks and behavioural data suggesting that, for a given task, there is an optimal speed-accuracy trade-off as well as optimal representations ("initial bias"), which maximise rewards for the task conditions at hand. Moreover, individuals seem to adapt their behaviour to approximate these optimal parameters (Botvinick & Cohen, 2014). For instance, Yu, Dayan and Cohen (2009) analyse the optimal intensity of attention allocation to the target stimulus in the Flanker task[4], showing that by adjusting the intensity of attention based on conflict monitoring within trials, near-optimal conditions can be reproduced. The model was able to reproduce observed behavioural data.

According to the EVC hypothesis, a cost-benefit analysis of the involvement of control has to be carried out for reward optimisation. Indeed, when control is invested in one task, chances of rewards associated with that task increase. However, due to constraints that come with

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[4] The task is described in Appendix A.

allocating control, these chances have to be measured against the loss of rewards associated with other tasks in the context at hand ("opportunity cost") (Shenhav et al., 2013; Cohen, 2017).

These insights regarding the inherent cost of control do not, however, completely invalidate the hypothesis that there may be inherent constraints on performance associated with control allocation. There may also be a cost of control attached to the crosstalk from multiple tasks. The EVC hypothesis and the models based on the emergent nature of control do not preclude control-associated performance costs. However, it should be underlined that control intervenes precisely in situations that involve conflicting pathways. It is hence difficult to disentangle the effects of control from the properties of the situations calling for it (Feng et al., 2014). That being said, it appears that tasks are supported in the brain by neural representations that serve multiple purposes and can be used for more than one task, both sequentially and at once, and that crosstalk arises from the simultaneous recruitment of these representations for different purposes. Feng et al. (2014) refer to this phenomenon (the allocation of a mechanism or a set of representations to multiple purposes) as "multiplexing": For instance, phonological representations can be used to encode aurally presented words, but also to read words out loud. An additional source of crosstalk is the competition between stronger and weaker pathways in stimulus and response processing (Botvinick et al., 2001, 2004; Botvinick & Cohen, 2014). In turn, control is involved in reinforcing signals in given pathways to solve the conflict, and this is likely to restrict the number of competing processes which can be used at once (Meyer & Kieras, 1997; Botvinick et al., 2001). However, these restrictions presumably apply at the level of local and task-specific representations (e.g., visual or phonological), rather than applying as capacity constraints in a single, central control resource as theorised for instance by Pashler (1994) (Feng et al., 2014). Feng et al. use computational simulations based on the neural network competition hypothesis and conclude that even small amounts of crosstalk can have considerable negative effects on performance. They suppose that control therefore imposes a cost in that it prevents this sort of "multitasking" in order to avoid performance decrements, instead promoting multiplexing as a way to allow efficient and flexible processing (Feng et al., 2014; Kool et al., 2017).

This account of the differential task-related and control-related costs offers a framework within which constraints in multiple local "resources" and a certain imposed seriality can be reconciled without assuming a limitation in the capacity for control itself. It also accommodates neuroimaging findings showing both serial and parallel processing within a cognitive task, with parallel response processing observed, as well as an apparent "bottleneck" effect around the decision-making stage (e.g., Sigman and Dehaene, 2008).

However, it should be also taken into account that the parallel activation of shared neural representations can be beneficial for the execution of a task (Cohen, 2017). Musslick et al. (2016) extend the findings of Feng et al. (2014), similarly based on PDP and neural network simulations, to identify additional factors influencing the relationship between pathway overlap and parallel processing capability. In so doing, Musslick et al. find that multiple-use representations offer more efficient (i.e., fewer) connectional patterns, higher speed, and better generalisation during learning. Still, there is tension between these advantages and the costs of parallel processing, as with increased overlap (multiple use) of representations, processing tends to become serial and rely on control mechanisms to avoid crosstalk. This tension is thought to reflect the constraints on multitasking performance and underlie the trade-off between automatic and controlled processing. Thus, the observed shift from controlled to automatic processing with learning could reflect a transition from reliance on interactive and general-use representations to independent and specific representations (Cohen, 2017). Musslick et al. (2016) further highlight the potential trade-off in multitasking settings between the learning advantages bestowed by shared neural representation between tasks and the crosstalk generated.

These insights into the potential cost of control help shed light on the suggested "opportunity cost" (Cohen, 2017, p.7) entailed when exerting control, as well as the mechanisms presiding over its allocation. These reveal, in turn, how some individual differences in cognitive control could be articulated, and provide accounts for observed behavioural phenomena intuitively associated with its exertion. For instance, beyond the hypothesised internal cost of control (manifest e.g., in increased RTs), it is subjectively experienced as costly when we engage in it, as illustrated in the Stroop task (Cohen, 2017): While it feels effortful to name the colour "green" if the word written in green represents the name of another colour, naming the colour "green" in any circumstance not calling for control does not. Kool, McGuire, Rosen and Botvinick (2010) point to a natural tendency to avoid having to exert control, the "law of less work". They are able to isolate this tendency from participants' behaviour in a series of experiments involving visuo-vocal "demand selection tasks" (p. 169) – a recurring choice between two alternative courses of action associated with higher or lower demand. Specifically, participants could choose according to their own preference from two visually presented decks of cards, one of which – unbeknownst to them – consisted of mostly congruent trials, while the other proposed more rule-switching. Avoidance of control demand (i.e., the participants favouring less shifts) was clearly identified as a frequent pattern of behaviour, and analysis of result patterns showed that this was distinct from error avoidance. Kurzban et al. (2013) attribute the sensations associated with mental effort to the estimated opportunity costs. Phenomena such as fatigue or boredom play a role in allocating signals away from task-related pathways to alternatives associated with higher benefits. Motivation, by contrast, can be seen as the appreciation of the expected rewards: It appears to play a crucial role in energising control-dependent signals (Kouneiher et al., 2009). According to Cohen (2017), there are promising perspectives in investigating effort as the index of the opportunity cost of control, and motivation as "the system's 'willingness to pay' the cost of control" (p. 7). Robbins and Kehagia (2017) stress the importance of considering broader circumstances under which the executive system has to operate ("states"), and that mood, motivation, reinforcement from environmental feedback, or the current point in the sleep-wake cycle, stress and fatigue are not neutral in that respect. Moreover, these circumstances, which fluctuate within individuals, may also vary across individuals and be personality ("trait") dependent.

Pinpointing the role of reward computation as an essential basis for the engagement of control has implications in terms of the role played by task- and goal representations. Indeed, the study of neural substrates indicates that the dACC, associated with context monitoring (Botvinick et al., 2001, 2004; Botvinick & Cohen, 2014) and the "specification" of control signal (Shenhav et al., 2013), has been empirically found to monitor the rewarding value of action sets according to their outcomes (Charron & Koechlin, 2010). It carries out this monitoring function by representing immediate as well as future behavioural goals concurrently, and by driving the recruitment and relative scheduling of processes according to the incentives of pursuing those goals. This in turn is consistent with the EVC hypothesis. In their study, Charron and Koechlin observe that in multitasking settings involving the active, rewarded pursuit of two concurrent goals (using a dual backward letter-matching task), these relative weighting processes were activated in parallel in each hemisphere to allow for the simultaneous and separate pursuit of these goals, whereas seriality was observed in the control of task execution. This is, again, in line with the observations regarding the constraints in controlled processes highlighted above.

The reported findings highlight that control is not a goal per se in the brain, but that it arises from the set of conditions calling for it. We can thus argue that control rests on two main factors, which allow and drive its exertion: conflict monitoring in context and goal maintenance. The next sections will explore these mechanisms.

2.3.2 The dual mechanisms of control hypothesis

Theories of biased competition, adapted gating and the expected value of control reviewed above offer an insight into the part played by conflict monitoring and goal representations in the modulation of control. Indeed, it seems that representations of the task at hand constitute an internal context, which is monitored for emerging discrepancies and either updated as necessary – depending on goal-conducive new information – or maintained in order to limit the effects of interfering information (Satpute et al., 2012; Cohen, 2017).

Control therefore appears to involve a balance between maintaining and updating the internal task context. The observed dual action of dopamine, mentioned above (section 2.2.1.3), and its suggested role in modulating how representations are updated and maintained have led to the proposed dual mechanisms of control framework (DMC: Braver, 2012; Braver et al., 2007). According to this framework, cognitive control can take two forms: proactive and reactive.

Proactive control aims to maintain task goals in order to prepare for future events. Goal-maintenance allows to optimally select task-relevant over task-irrelevant, distracting information at an early stage (Hutchison, 2011). Goal maintenance appears to manifest as sustained activity within the lateral PFC. That sustained activity comes at a cost: It is taxing on metabolic resources and is subject to apparent stringent limitations in the number of active goal representations, that is, representations actively maintained in WM (Braver, 2012). Moreover, proactive control biases the system to selectively attend to goal-appropriate information and to therefore ignore goal-irrelevant stimuli, which makes it less sensitive to changes in stimulus features; It is therefore probably more efficient as a control strategy when high levels of interference are expected than in other circumstances (Burgess & Braver, 2010).

Conversely, reactive control relies on stimulus-triggered transient activation within the ACC (Botvinick et al., 2001, 2004): The conflict detected between competing responses induces the lateral PFC along with other brain structures to retrieve the inactive task goal from memory (Hutchison, 2011). In contrast to proactive control, reactive control appears to free WM and processing resources in the intervals separating the moment in which one intention is formed from the next instance of intention forging (Braver, 2012). Therefore, still in contrast to proactive control, reactive control is not taxing on WM capacity (Hutchison, 2011); reactive control is beneficial when conflict is infrequent, as it triggers an increase in vigilance only when the setting allows it, for instance following the rare incongruent trials in a mostly congruent situation.

Proactive, goal-maintenance-oriented cognitive control thus induces top-down changes in behaviour: Neural activity in lower-order sensory or motor areas is modulated as a function of an individual's goals, resulting in task-relevant representations being enhanced, and/or task-irrelevant representations suppressed (Miller & Cohen, 2001; Gazzaley, 2011). Conversely, bottom-up modulation of behaviour means that sensory input takes the lead and determines mechanisms in higher-order processing areas – a type of modulation on which conflict monitoring seems to rely. The DMC framework assumes that within individuals, situational changes will modify the weighting between proactive and reactive control. According to Braver (2012), even subtle alterations in task demands can result in large alterations in the control strategy of choice.

It has been pointed out that these forms of control might run counter to each other (Chiew & Braver, 2017) and that high proactive control can be associated with reduced reactive control – during the execution of a given task, but also at the level of individual differences beyond a single task (Braver, 2012). First, the computation of a cost/benefit trade-off leading to the use of proactive or reactive control could depend on the "ease" of maintaining goal representations in WM, and therefore on WM capacity (e.g., Kane & Engle, 2003). Second, the level of reward associated with each course of action may differ between individuals, depending on their internal estimation of the value of the various strategies to achieve a given goal. Burgess and Braver (2010) and Braver (2012) therefore suggests a positive correlation between constructs like fluid intelligence – i.e., problem-solving and reasoning ability, a factor of individual variation often highlighted in WM tasks (for a review see Unsworth & Engle, 2007) – and the use of proactive control. Beyond "cognitive" traits, however, even affective factors like personality (e.g., sources of motivation specific to the individual) might influence neural and cognitive activity in support of goal-directed behaviour (Chiew & Braver, 2017): For instance, the tendency to plan ahead or count on external events to steer one’s course of action, on the shorter or longer term.

The intra- and inter-individual implications of these accounts raise two major questions: what are the consequences of reactive and proactive control respectively with regard to multitasking, and what do the assumed sensitivity of both control modes to individual traits tell us about the possibility of multitasking skill transfer? Can personality- or training-induced tendencies influence how control affects the performance of a given task more than, say, a new task combination involving the same task does?

The second question will be discussed more in depth in the following chapters of this dissertation. To address the first question, we will look at two essential mechanisms and phenomena underlying the involvement of control, both reactive and proactive: Conflict monitoring – involving context monitoring – on the one hand, and goal maintenance on the other.

2.4 Resistance to interference and conflict resolution: Conflict monitoring and goal maintenance

2.4.1 Sources of conflict

In order to better understand how conflict demands and triggers control, it is important to look at what conflict is. The literature on control offers a variety of accounts for competing processes when control is engaged, as we have seen in the previous sections, but most of these accounts concur on the type and characteristics of tasks which appear to be taxing on the control system.

Meyer and Kieras (1999) formulate five conditions to optimally decrease dual-task costs when performing two reaction-time tasks: (1) Participants are encouraged to give the tasks equal priority; (2) each task is supposed to be performed quickly; (3) there are no constraints on the temporal relations and serial order among responses; (4) the performance of one task uses different perceptual and motor processors than does the performance of the other; and (5) participants receive enough practice to compile complete production-rule sets for performing each task. By inversion, this list provides a picture of the factors which give rise to dual-task costs, by compelling individuals to manage priorities or avoid the simultaneous, conflicting use of physical sensors or motor effectors (Meyer & Kieras, 1997a), thereby forcing seriality onto the system. In this model, multitasking costs are therefore directly linked with conflicting representations.

In the multiple-resource theories, the EPIC model, and computational models, which all share the same premises, conflict can occur at various stages (see section 2.1.1): Perception (early level), cognitive processes (central level), and response stage. Conflict can arise from the type of modality at hand, sensory (visual or auditory) or motor (manual or vocal). It can also arise from the type of processing required: verbal or linguistic tasks seem to rely on different "coding" processes than spatial tasks do, as we find reflected in Baddeley's distinction between WM repertoires as well (Wickens, 1980, 1984)[5].

In contrast to bottleneck theories (e.g., Hazeltine, Ruthruff, & Remington, 2006), which suggest that crosstalk arises in dual-task situations regardless of whether the stimulus or response categories overlap, and posits a form of concept-independent crosstalk in central stages, the cognitive control framework (Botvinick et al., 2001) proposes that these limitations are purely "computational", that is to say functional, rather than structural, and that they are induced by the fact that certain sets of neural representations are used concurrently for different purposes, giving rise to crosstalk. In both types of frameworks, however, crosstalk in any given neural network critically limits the possibility to multitask and signals a need for control (Botvinick et al., 2001, 2004; Botvinick & Cohen, 2014). This makes conflict monitoring a function and condition of control.

2.4.2 Conflict monitoring

Botvinick et al. (2001, 2004) elaborate a computational model of control, which relies on conflict monitoring to signal and regulate the need for control. This model is described using the Stroop task, which requires that participants resist following a highly automatised script – the urge to read words – in order to follow a weaker association – naming the colour of the ink. Botvinick et al. (2001) refer to studies showing real-time changes in control depending on fluctuations in performance and task demands. In that sense, conflict monitoring goes beyond identifying the presence of conflict, as it also keeps track of the level of conflict and therefore of the level of control required. Botvinick and his colleagues model a core conflict monitoring function for the dACC and observe that activity in that area is responsive to changes in conflict during task performance: For instance, incongruent trials in the Flanker task are accompanied by greater activation if they follow congruent trials than if they come after other incongruent trials. Thus, not only is the conflict generated by incongruency, but the signal is also reactively modulated according to the need to adjust to changes in the pattern of conflict detected (Botvinick et al., 2004; Cohen, 2017).

Viewed from this perspective, conflict monitoring entails reactive adjustments of control, meaning that control is increased or decreased as a function of a change detected in conflict intensity. However, it seems that conflict monitoring may not be purely reactive, as this

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[5] Wickens (1988) adds a fourth possible locus of interference with distinct visual channels.

would not be optimal for error avoidance – and presumably processing speed – with a new computation needed for every trial (Brown & Braver, 2005). The role of the ACC was therefore investigated with regard to the strength of its reactions to diverse contexts: A greater likelihood of errors was associated with a greater response in the dACC, suggesting that conflict monitoring as mediated by the ACC also involves an adjustment to the perceived likelihood of making errors.

Furthermore, observations of dACC activity over repeated trials seem to support the idea that a type of learning is taking place, related to the likelihood of errors (Brown & Braver, 2005). The posited association of the dACC with performance monitoring and adjustment has been investigated empirically. Indeed, imaging studies support the hypothesis that ACC activity influences activity in the lateral PFC and behavioural performance, while studies of patients with ACC lesions show that the experience from previous trials triggers lesser adjustments in control (see review in Shenhav et al., 2013).

Conflict monitoring, therefore, appears to serve as an integrated, complex process encompassing several functions: First, as we have just seen, to trigger control and to determine the degree of its application; second, to maintain an online estimate of conflict-mediated difficulty to modulate that application; and third, to allow a response adjustment to minimise conflict on the basis of that estimate.

2.4.2.1 Conflict monitoring and task difficulty

Taking into account the possible variation in the intensity of control, task difficulty can be estimated as a function of control demand. Shallice and Burgess (1993) identify a high demand for control in the following situations: (1) When a strong response or resisting temptation is required; (2) when the responses are not well learned or novel sequences of actions have to be implemented; (3) when planning or decision making is involved; (4) when correction or troubleshooting is needed; and (5) in situations estimated to entail risk or technical difficulty.

The conflict monitoring hypothesis suggests, as we have seen, the presence of a system in the human brain that responds to conflicts that occur during information processing. Furthermore, this system is activated in circumstances where the given task demands require greater control than is exerted at that point in time. Therefore, there appears to be a direct, online estimation of task difficulty through an indication of the level of competition between potential responses (Botvinick et al., 2001). Yeung, Botvinick, and Cohen (2004) go further in specifying this suggestion: These conflict signals not only serve as difficulty proxies, indicating control demand, but they can, in some cases, lower the need for subsequent error detection. An index of potential errors is generated as a consequence of those signals, and is used as an index of confidence in future responses, when feedback on the outcome cannot yet be received.

As control is adjusted based on the level of conflict in single trials, for instance by reinforcing signals for stimulus treatment in subsequent trials (Yeung et al., 2004), error rates decrease, and response times increase overall. This adjustment has been described as "conflict adaptation" (Gratton, Coles, & Donchin, 1992; Egner, 2017).

2.4.2.2 Learning and adaptation

Botvinick et al. (2001) describe post-error slowing (PES), the observed increase in RT and accuracy after erroneous trials as one of the salient manifestations of conflict monitoring (see section 2.3). PES has been observed and studied for decades (a seminal account is proposed by Rabbit & Rodgers, 1977) and has been interpreted in different although not mutually exclusive ways (Ruitenberg, Abrahamse, De Kleine, & Verwey, 2014).

It seems that adaptation is made possible in the "reactive control" mode and based on conflict monitoring precisely because the dopaminergic effects associated with conflict monitoring are also associated with a greater capacity of modifying neural representations (Braver & Cohen, 2000; Cohen et al., 2002; Botvinick & Cohen, 2014). These authors establish a clear difference between the "parametrisation" of the task processes, which is involved in control, and the learning process. Learning is defined as new information taken in from the environment and giving rise to structural (synaptic) changes. Control on the other hand implies that already established representations are activated and they temporarily adapt information processing parameters to serve the purpose of a given task. This function of control therefore appears to rely on task representations, which have to be monitored for the emergence of conflict.

2.4.2.3 Conflict monitoring and process representation

One of the core functions of control identified in the EVC theory by Shenhav et al. (2013) is monitoring (see section 2.3). The EVC theory proposes a conflict-detecting component of control (isolated in Cohen et al.'s, 1990, Stroop-task model) that depends on monitoring: Information on the current circumstances and their adequacy in serving a given task goal has to be accessed. On the basis of this information, signal specification and regulation are made possible. Shenhav et al. suggest that conflict detection is not the only way in which monitoring allows control regulation, but that response delays, errors, negative feedback or pain are also possible signals for control intensity modulation. Moreover, for control signal specification, the authors argue that external and internal information regarding task choice also needs to be monitored. That information can include explicit instructions and cue-related information indicative of potential reward or risk; but it can also include the realisation that rewards from a current task are diminishing or the recollection of another necessary task. Therefore, even though monitoring comes downstream of the cost-opportunity valuation on which control is based, the role of monitoring is crucial in the emergence and definition of control.

Monitoring for control purposes thus rests on *conflict monitoring* but encompasses *context monitoring*, based on task representations. This may help to explain why monitoring of conflict and task-related processes – manifest in error detection signals – has been associated with WM capacity (Miller, Watson & Strayer, 2012), even though crosstalk-induced conflict detection or reactive control is not assumed to strain WM (Hutchison, 2011; Braver, 2012). Post-error slowing in a choice-RT task and conflict adaptation in the antisaccade task, however, were found to be unrelated to WM capacity variation (Unsworth, Redick, Spillers, & Brewer, 2012). Maintenance of task-related goals, on the other hand, does draw on WM capacity (e.g., Kane & Engle, 2003; Engle & Kane, 2004; Unsworth & Spillers, 2010). The dual nature of monitoring (context and conflict monitoring) thus seems to reflect the dual nature of control (reactive and proactive) and the fine balance between reaction to representational conflict and adjustment of performance in function of a given goal. We will therefore focus first on how conflict monitoring manifests, and subsequently on the goal-orientedness of control and the goal maintenance processes which underpin context monitoring.

2.4.2.4 Manifestations of conflict monitoring: measures

PES is often considered a direct measure of cognitive control (Dutilh, Vandekerckhove, et al., 2012). This because PES is interpreted as increased response caution, linked with the regulation of the control signal (Botvinick et al., 2001). However, several explanations for PES have been proposed and as they are not mutually exclusive, it is possible that more than one of them contributes to the phenomenon (Dutilh, Vandekerckhove, et al., 2012). PES has been interpreted as the emergence of a negative bias towards the erroneous response just executed (Rabbit & Rodgers, 1977); or as a sign of variation in a-priori bias, that is, in the registered task-related information across trials. It has also been suggested that PES reflects non task-related (“non-functional”) behaviour: Attention is distracted because an error was committed (Notebaert et al., 2009), or there is a judgement on the performance inducing a delay in attending to the next trial (Rabbit & Rodgers, 1977; for a review see Dutilh, Vandekerckhove, et al., 2012).

Dutilh, Vandekerckhove, et al. (2012) propose a statistical "diffusion model" to break down the contribution of these possible factors to PES. After applying the model to a lexical decision task based on more than a million trials, the authors conclude from that analysis that the slowing phenomenon appears almost exclusively in relation to increased response caution. This does not preclude that alternative phenomena could apply in some instances (e.g., it is possible for someone to be distracted by an error), but points to the validity of interpreting PES as a sign of self-regulation and cognitive control in the sense proposed by Botvinick et al. (2001). According to these findings, PES points to variations in response thresholds, whereby performers of a task adapt to the task environment: They show more audacity after correct responses and more caution after errors, seeking to reach an optimal condition for that task where they can respond as fast and with as few errors as possible.

In another study (Dutilh, van Ravenzwaaij, et al., 2012), the authors reflect on the standard method used to measure PES, based on the analysis of response times and accuracy. PES is often measured by computing the difference in response time between post-error and post-correct trials; however, this method of measurement does not take into consideration the possible adjustments that participants make to their performance between the beginning and the end of a task. As mentioned earlier, motivation plays a possible role in modulating control, and it can fluctuate; also, conflict monitoring – which PES seeks to assess – serves to gradually adjust control in a way that will adjust both response time and accuracy to satisfying levels. Therefore, arguably, performance and PES are likely to evolve over the course of the task and PES can disappear or be overestimated in the analysis if compared to the general mean of post-correct trials. Dutilh, van Ravenzwaaij, et al. (2012) therefore suggest that when using the standard method, only correct pre-error trials be included for comparison with post-error trials to give the best possible account of PES.

Another possible measure of conflict monitoring is the conflict adaptation effect, where differences in performance are found between intermixed congruent and incongruent trials depending on the congruence or incongruence of the previous – and correct – trial; this has been used in tasks like the flanker, Stroop or Simon task (see Unsworth et al., 2012). A trial following a correct trial of the same type tends to be significantly faster than following a trial of a different type, and this in turn appears to be influenced by the amount of conflict observed on that prior trial.

PES also sheds light on the temporal constraints associated with control. Rypma et al. (2006) suggest that control places a double constraint on cognitive processes. They base their conclusions on a study analysing and gauging the directionality and flow of signals in the brain: Not only does the PFC inform cognitive processes, but it apparently also receives feedback from them, and both operations are time-consuming and place a strain on these processes. It therefore appears that control includes a "verification" of how the processes are implemented. To explain this phenomenon, Cohen (2017) offers that the ability to exert control and maintain goal-relevant information may be distinct from the ability to know when control should be exerted at all, or to what extent it is needed. By signalling a need for control when the goal-relevant pathway is not activated due to competition from a stronger pathway, conflict monitoring may take on precisely that second role.

As we have seen, conflict monitoring is an essential part of control, and the orienting process behind reactive control. However, control specification and regulation also require online comparison between the current performance and the currently entertained goal. Goal maintenance is therefore not only the orienting process for proactive control, it is essential to the exertion of control.

2.4.3 Goal representation and maintenance

According to a by now widespread definition (see section 1.2), cognitive control is inherently goal-oriented. This does not only define the type of situations that can give rise to control; it is also revealing of how control itself operates. The comparison between current performance and an internally maintained goal is essential in order to trigger a need for control (Botvinick et al., 2001, 2004; Botvinick & Cohen, 2014), and to serve the cost-opportunity process underlying it according to the EVC theory (Shenhav et al., 2013; Cohen, 2017). Goal representation and maintenance are therefore critical in those frameworks (Lorsbach & Reimer, 2010). The core function of "monitoring", as we have seen, is in itself dual as it relates to both the monitoring of conflict and context. Context information is seen as essential for the emergence and definition of control, and encompasses all representations of task-relevant information that can bias the processes responsible for task performance (Braver et al., 2007). This includes prior stimulus events and task goals in the form of plans or instructions (Lorsbach & Reimer, 2010).

The internal representation of goals constitutes a backdrop against which processes are selected and enhanced through control regulation. In accordance with the cognitive control framework (Botvinick et al., 2001; Braver & Cohen, 2000; Cohen et al., 2002), Paxton et al. (2008) underline that goal maintenance is therefore critical to cognitive control and necessary to ensure successful response in situations where control is required. They propose a role for goal representations that goes beyond sheer informational content. Goal representations include information on desired outcomes, but also on the actions necessary to reach that goal, which can inform behavioural response and planning. This is thought to be made possible by a form of reinforcement learning, which strengthens associations, taking into account the hierarchy of goals and sub-goals encompassed within a task (Cohen, 2017). In addition, these representations may also guide perceptual processes and the allocation of attention (Paxton et al., 2008). Therefore, goal representations are actively maintained to remain available and influence processes, and the authors propose that these representations govern, in WM, how other representations will be used. This represents a modification of Baddeley's model of WM (which posited a separate Central Executive) and suggests that both storage and control functions can be served by goal representations.

In the cognitive control framework, task-relevant information is represented and maintained in the lateral PFC, which interacts with the dopamine neurotransmitter system (see Lorsbach & Reimer, 2010). The gating function attributed to dopamine (see section 2.2.1.3) in the PFC is assumed to serve precisely the representation and maintenance of goal information in a way that regulates information access and keeps task-relevant representations active (Lorsbach & Reimer, 2010). Miyake and Friedman (2012) posit that generic executive function, the common factor in inhibition, shifting and updating, reflects the capacity to maintain goals and bias lower-level processes from the top down, consistent with the above insights from the cognitive control framework and in line with simulations in a PBWM-based computational model by Chatham et al. (2011).[6] Also, shifting tasks are found to be particularly affected by a manipulation of the length of representation maintenance after goal completion, which is

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[6] Indeed, as highlighted notably by Braver and Cohen (2000), Cohen et al. (2002) and the adaptive gating theory, this aspect of control may be especially susceptible to the two different modes of dopamine release (see Section 2.2.1.3). D2 (phasic) versus D1 (tonic) dominant states underlie respectively higher and lower representational perturbability (i.e., flexibility to change representations). Dopaminergic effects are also observable on more complex tasks of rule formation and planning.

consistent with the idea that the shifting-specific factor is related to the ease of transitioning to new representations in the PFC.

As we have seen earlier, the DMC theory, which draws on the binomial character of dopaminergic activity, suggests that the active maintenance of goal representations is at the core of proactive control (Braver et al., 2007; Braver, 2012). These representations are assumed to be maintained in WM, and the ability to maintain them and exert top-down modulation of processes appears to be linked to WM capacity (Hutchison, 2011; Braver, 2012). Such top-down modulation provides for upstream bias of task-serving processes; that bias makes the system less responsive to stimulus-induced conflict, but offers the advantage of pre-emptively enhancing the signal in task-serving pathways and potentially reducing it in suspected distractor pathways (Braver, 2012). There is, therefore, and as evidenced by the overlap between the common EF and inhibition in Friedman and Miyake's (2012) factor analysis, a link worth investigating between goal maintenance and inhibition.

2.4.3.1 Goal maintenance and inhibition

Goals are used to modulate the competition between concurrent relevant and irrelevant information (e.g., Balota & Faust, 2001). Goal representations are crucial in situations where strong competition needs to be resolved for response selection (Paxton et al., 2008). This is for instance the case when the inappropriate response is dominant and needs to be inhibited: Paxton et al. (2008) use the example of the Stroop task, which requires task goals to remain actively represented in a way that attention allocation and response selection can be biased in favour of the ink colour over the written word. Another example of these situations is when the appropriate response is infrequent in absolute or relative terms, like the need to withhold a response to an infrequent "no-go" stimulus. Thus, by failure of active goal maintenance, behaviour would be guided by prepotent response tendencies and goal neglect would manifest in the fast execution of the incorrect, prepotent response (e.g., Unsworth et al., 2012).

The idea of goal-driven pathway selection is consistent with the proposition by Friedman and Miyake (2004) that there is a link between inhibition of a prepotent response and resistance to distractor interference (see section 2.1.2). Friedman et al. (2008) also propose that inhibition does not tap a specific function: Tasks like the antisaccade task (described in Appendix A), which are designed to test prepotent response inhibition, seem to be associated with the common executive function factor. Resisting proactive interference, on the other hand, is dissociated from inhibition and requires efficient and immediate updating of the WM content

(Oberauer, 2005); we will explore the relationship between representation maintenance and updating further below.

The literature has long supported the view that one of the crucial roles of EFs was to directly inhibit automatised behaviours (for a review see Cohen, 2017), and that this function was supported by the frontal lobe. However, several alternative possibilities have since been considered plausible (Satpute et al., 2012): Control may involve the inhibition of stronger pathways, the amplification of weaker pathways, or both. One of these alternative possibilities has gained weight more recently, which is that inhibition, instead of being directed, is competitive. Control thus selects specific processes and enhances their efficiency to compete with interfering associations (Cohen, 2017). This is the hypothesis in the biased-competition model (see section 2.2.1.3): The weaker pathways reach a level of activation that enables them to locally compete with – that is, inhibit – stronger associations (Miller & Cohen, 2001). Egner and Hirsch (2005) corroborate this hypothesis, using a face-and-name recognition task and isolating activity in face-processing pathways. Activity in those pathways increased when attention to faces was required under interference from name-processing, and did not decrease when attention to names was required under interference from face-processing, suggesting that control works by amplifying rather than inhibiting activity. For a neural system that tends to avoid load (Kool et al., 2010; see section 2.3), competitive inhibition is a potentially preferable strategy, in that the number of processes to enhance is usually limited, whereas the number of possible distractors or competitors in a given situation can be far greater (Cohen, 2017).

2.4.3.2 *Increased relevant sensory perception*

In their account of adaptive gating, Satpute et al. (2012) explain that goal representation is crucial in allowing the selection of alternative pathways over habitual ones. This can occur at the response selection stage but also at other stages of information processing, and the dorsolateral PFC seems to be involved in all these cases. For instance, the study of directed-attention tasks revealed that attentional control can bias the processing of incoming information and requires the maintenance of a target-stimulus representation long enough to influence activity in subordinate pathways; or in the central stages, control can be exerted to regulate signals linked to internally maintained information (Satpute et al., 2012).

Munakata et al. (2011; see section 2.1.2) propose a framework that accommodates both directed and competitive inhibition, based on a differential neural structure of the PFC on the one side, and a number of subcortical regions on the other. The PFC works by actively maintaining abstract representations: Contexts and goals as well as task sets that serve these goals. And these maintained representations initiate top-down excitation of associated, concrete task-related representations. In that respect, the inhibition of competitor pathways is a by-product of this mechanism. However, this does not preclude the direct suppression of other stimuli (including stressors), which seems mediated by the activation of specific nodes in subcortical regions through the PFC, to send inhibitory signals to the area triggered by the stimuli. Thus, the PFC supports top-down activation of relevant processes, which in turn may lead to the local inhibition of irrelevant or distracting processes.

Friedman and Miyake (2008; 2017) and Munakata (2011) suggest that the active goal maintenance in the PFC accounts for the isolated common EF in Miyake et al. (2000), and that this explains why prepotent response/distractor inhibition may be an inherent part of that function (Friedman and Miyake, 2017). Individual differences in common EF may thus be linked to the robustness and use of these goal-related representations, highlighting once again the central role played by goal representations in control. Friedman and Miyake (2017) emphasise findings suggesting that areas of the brain assumed to induce inhibition may in fact be active in monitoring for goal-relevant information and other types of goal-related processing. The authors stress that goal maintenance in memory does not suffice in itself to encompass the global EF of the PFC, but that processes of goal identification, formation, and real-time implementation are crucial to defining individual differences in global EF. This definition also makes for a clearer link between executive function theory and the cognitive control framework: the common EF ability is thought to reflect active goal maintenance and top-down bias, which is the mechanism underlying proactive control. Indeed, Friedman and Miyake (2017) propose that individual differences in common EF ability could be linked to individual biases in the balance between proactive and reactive control.

One of the major questions these insights raise is the degree to which the various mechanisms that allow for the successful pursuit of a given goal are compatible and can be used simultaneously. The cognitive control framework is subserved by two processes, where the PFC represents and maintains goals, and task goal conflicts are treated in the ACC. The idea that control uses the activation and maintenance of task-related representations in WM in order to influence processes and that it also regulates these representations is now widely accepted (Cohen, 2017). Goal maintenance is thus necessary to successfully follow a task rule, but it appears from the literature that the mechanisms underlying goal maintenance differ from and could run counter to the mechanisms underlying the updating of goals as well as task-related representations. This question is all the more salient in a multitasking setting: To what extent can it be expected that WM updating will be possible when the system is geared toward keeping goals active?

2.4.3.3 Maintaining versus updating goal and task representations: Stability or flexibility

Friedman and Miyake (2000, 2017) emphasise that the possibility to isolate EFs does not preclude a degree of common variance between them, that is, that they may be correlated to some extent. However, in line with recent frameworks of dual mechanisms of cognitive control, it appears that at the level of individual traits there may be a trade-off between the ability to switch between tasks (shifting) and the common EF associated with goal maintenance and implementation (Friedman & Miyake, 2017). The authors explain the common variance with global EF with the necessity of selecting and implementing the relevant task set, and the adverse correlations with the necessity of replacing the task sets or task goals as quickly as possible when they are no longer relevant. The speed with which this replacement occurs is assumed to account for individual shifting abilities; but in addition, the strength and level of activation of the representations (a mark of stronger EF) may also make them more resistant to potential requirements to change. This has implications for the control-related effects of mental (in)flexibility.

In a study involving trait ruminators – a textbook profile of mental inflexibility – Altamirano, Miyake and Whitmer (2010) highlight the paradoxical effect of mental inflexibility. An indicator of trait rumination, proposed as a measure of mental inflexibility, showed negative correlations with performance in a letter-naming task requiring rapid rule switching; trait rumination was, however, positively correlated with performance in a Stroop task modified to include rare incongruent items (Kane & Engle, 2003) in order to test active goal maintenance. In line with Braver (2012), the authors hypothesise that there is an individual bias in the balance between goal maintenance and goal shifting. Friedman and Miyake (2017) suggest that, conversely, measures of attention-deficit disorders reflecting weaker goal representations could be positively correlated with the shifting factor[7].

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[7] Some studies suggest that attention-deficit hyperactivity disorder (ADHD) may be related to (perhaps partially, or domain-specifically) altered proactive control (e.g., Sidlauskaite, Dahr, Sonuga-Barke, & Wiersema, 2020). However, Balogh and Czobor (2014) find a pattern of post-error acceleration, or an absence of PES, across studies in participants with ADHD, though it is difficult to draw valid conclusions without an analysis of post-accuracy data, and the pattern could depend on task and attention-deficit type (Shiels, Tamm, & Epstein, 2012).

This paradox raises major questions: What differences are there between the updating of goal representations necessary for task switching, and the updating of other content held in WM for the purposes of task completion, and how does the trade-off between goal maintenance and task-switching accommodate the possibility of this task-related form of WM updating. The distinction provided by Friedman and Miyake (2017) is the following: in order to update tasks, information also needs to be replaced, but other task-relevant information needs to be maintained. Therefore, the isolated "updating" function requires a selection of the specific content to update, but not the "shifting" function which updates the task goal by discarding the previous one altogether.

This stability-flexibility paradox can thus be elucidated by looking closer into the way WM updating works. WM updating tasks require lower-level component processes: storing information, gating information into and out of WM, tracking serial order of incoming/stored information, and selective attention (Chatham et al., 2011). The selective update of representations is assumed to be made possible by fine-tuned dopaminergic gating, in line with the PBWM model (O'Reilly & Frank, 2006): The stability-flexibility dilemma is resolved by selective updating in the PFC, which is enabled by phasic-activity-led targeted adaptation processes in the basal ganglia (Chatham et al., 2011; Chiew & Braver, 2017). The PWBM also provides for biased competition through prefrontal representations which are stabilized through recurrent connectivity and tonic dopaminergic activity, in line with the cognitive control framework.

Taken together, these models provide a framework of understanding for how task-relevant processes can be processed differentially (Chatham et al., 2011; Chiew & Braver, 2017): Task-relevant sub-goals (like an individual target letter in the *n*-back task) need to be updated based on the cues presented, while higher-order goals have to be maintained (like knowing which *n*th letter is the target). Chiew and Braver (2017) use a model adapted from the PBWM to describe the possibility to dynamically shift between reactive and proactive control-led modes, using the example of the AX-CPT (continuous processing task; Cohen, Barch, Carter, & Servan-Schreiber, 1999, see Appendix A). In a continuous series of letters in which X is a target after A and Y after B, "A-Y" interference is attributed to the proactive maintenance of A, and "B-X" interference (in the form of slowing) to the use of reactive control (Braver, 2012). The model can accommodate a hierarchically structured version of the task, where higher-order context (a rule valid for a series of trials) influences context processing at a lower level. In that case, the presence of a given stimulus ("1" or "2") in turn requires the activation or deactivation of a given target sequence (O'Reilly & Frank, 2006).

When it comes to full-fledged switching, the PBWM model provides an account of the fine balance to maintain between flexibility and stability (Herd et al., 2014, as cited in Friedman & Miyake, 2017). Whereas all EF tasks are affected by reducing top-down modulation in the PFC, which suggests an association with global EF as discussed above, weakening the activation of the goal maintained in the model yields results on two levels, leading to greater susceptibility to interference but reducing switch costs.

During multitasking, mechanisms which tend to run in opposition may need to run together, providing a setting where the stability-flexibility paradox comes to light in a stringent manner. This explains why Sanbonmatsu et al. (2013) suggest that the individuals "best able to multitask" may also be the ones "best able to not multitask" (para. 9). Strong goal maintenance allows to suppress distractions and competing intruding goals in order to follow through with the processes necessary to complete each task. However, according to the authors' definition, multitasking requires the ability to switch tasks unhindered by conflicting goals. They associated a tendency to "multitask" in real life (e.g., to use a cell phone while driving, or to media-multitask) with higher measures of impulsive behaviour, but also with lower scores in a task requiring the maintenance of dual task representations in WM. This suggests that the personality traits associated with task-switching are also negatively correlated with the mechanisms underlying proactive control. However, it should be emphasised at this point that the task used to measure multitasking ability is an operation-span task, which is highly linked to WM storage capacity and does not clearly distinguish it from goal maintenance per se. Still, in an earlier study, Ophir et al. (2009) find that frequent media-multitaskers – people who concurrently attend to separate information items or streams of content – show impaired performance in a filtering task (visual judgement with distractors), an updating task (the *n*-back) and a context monitoring task (the AX-CPT), as well as higher switching and mixing costs in a switching task (letter- or number-classification task signalled by a cue preceding each trial).[8] This suggests that individuals who habitually divide their attention between incoming sources of stimuli have a lower threshold of resistance to distractors, do not engage in strong active goal maintenance and do not perform well in tasks involving cognitive control.

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[8] Switching cost is the slowing in trials following a rule change (switch trials) as opposed to trials based on the same rule (non-switch trials); Mixing cost is the slowing in non-switch trials in blocks containing rule changes compared to blocks entirely based on the same rule.

Medeiros-Ward et al. (2015) describe multitasking as complex mental juggling involving the maintenance, switching and updating of two or more goals. They ascribe the fact that multitasking overwhelms our control system in most settings to this plurality of simultaneous functions. The next section will explore how other factors related to the task context can influence our ability to maintain goals and exert control in these extreme conditions.

2.4.3.4 Goal maintenance and task representation: intention, motivation, integration

The need for goal representations to be maintained in order to allow top-down modulation by the PFC could explain why neuroimaging studies suggest a split between the medial frontal cortices of both hemispheres in the presence of two rewarding goals to ensure concurrent reward representations and provide for concurrent goal maintenance in the frontal lobes (Charron & Koechlin, 2010; see section 2.3.). The tasks presented were two intertwined backward-letter-matching tasks. Consistent with these observations, performing a third concurrent task led to a breakdown of performance every time one of the other two tasks had to be resumed, suggesting that frontal function cannot accommodate the pursuit of more than two goals.[9] In addition to emphasising the necessity of limiting the number of goals simultaneously pursued, these findings reinforce the conception of goal-maintenance as a phenomenon associated with perceived rewards. As we have seen earlier, the question of motivation might therefore be crucial in determining the extent to which control is used to enhance signals in task-processing pathways.

We have seen that certain personality traits appear to be associated with certain control biases – and therefore could partially determine the ability to maintain control in a taxing setting such as a multitasking situation. In a more transient fashion, the goal-orientedness of control and its responsiveness to internal and external context (Shenhav et al., 2013) suggest that other context-contributing factors like intention (internal) and instructions (external) may heavily influence how control comes into play in a given task, notably by influencing how the hierarchical structure of a task is conceptualised (Chiew & Braver, 2017).

This may be particularly relevant in a multitasking setting, where an individual is presented with apparently incompatible goals, stimuli and responses to juggle. Halvorson, Ebner, & Hazeltine (2013) and Halvorson, Wagschal, & Hazeltine (2013) propose that explicit instructions and implicit indications can play a critical role in that regard. Meyer and Kieras

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[9] As mentioned earlier, in areas of the PFC associated with dual tasking, no such dichotomy was observed, suggesting a unitary supervisory system for task execution.

(1999) suggest that one of the (necessary, although not sufficient) conditions for optimal performance in a dual-task paradigm is to give the two tasks equal priority; Halvorson and colleagues propose that indicating a priority and varying stimulus-onset asynchrony could indeed signal to the participants that the tasks should be treated as distinct tasks. In one study (Halvorson, Ebner, & Hazeltine, 2013), when stimuli were presented simultaneously rather than in succession for the same two ideomotor tasks, no dual-task costs were observed. The authors stress that temporality is not the only factor at play, but that the conceptual perception of the tasks matters – in the presence of one non-ideomotor task, it is difficult to form a single rule to encompass both tasks. In a second study (Halvorson, Wagschal, & Hazeltine, 2013), participants were asked to execute in parallel a visual-motor task and an auditory-motor task, with one task involving implicit sequence learning. Explicit task perception was also elicited from the participants. Their accounts suggested that the conceptual relationship between both tasks played a crucial role. In this case, implicit sequence learning was only observed when the tasks were perceived as separate, as otherwise the random signal from one task was integrated with the stimuli from the other. Thus, subjective task boundaries can be introduced explicitly or formed implicitly, and they seem to affect how associations are made.

This also seems to apply to how representations are formed and reinforced with training. Freedberg, Wagschal and Hazeltine (2014) investigated the type of cross-task learning that can occur in various dual-task settings, to shed light on the level of abstraction of task-related learning. On the practical side, they found that task integration rested to a large extent on the overlap in both stimulus and response modalities: grouped learning of task combinations was possible only in the presence of such an overlap (combining two visual-manual responses rather than a visual-manual and an auditory-vocal one). Learning therefore seems to involve central processes, which establish associations between sensory and motor modalities. However, by manipulating how conceptually related the two tasks were (irrespective of modality), the authors observed that the task combinations could still be learned to the same degree, an outcome consistent with associative learning unrestrained by stimulus or response modality. This suggests that, depending on the conceptualisation of the tasks, top-down control allows certain associations, which provides for the ability to transfer task-related knowledge to different settings. The authors stress that the emergence of such conceptual relations might depend on the level of practice, and may be susceptible to individual differences. However, even in the presence of concurrent stimuli and responses, top-down processes seem to determine which associations can be formed.

Thus, the way task-relevant stimulus-response information is encoded in WM could reflect the hierarchical conceptualisation of a task combination. This is consistent with propositions by Colzato, Raffone, and Hommel (2006), who suggest the existence of multi-level binding processes, ranging from temporary, context-dependent low-level binding operations to longer-term, higher-level associations, whose role is to influence processing. These bindings formed at different levels could be related to hierarchical task-relevant goals and aided by top-down control. Freedberg et al. (2014) thus propose that the contour of a given task or tasks at hand and the processes that they encompass might depend on how individuals perceive and conceive of them: Certain tasks are learned in specific contexts and are therefore harder to conceptualise independently of that context, but task boundaries might not depend entirely on the intrinsic properties of the task. In that case, the constraints involved in multitasking might be alleviated by forming an apprehensible hierarchical task structure. These insights allow us to complete the definition that opens the present study.

As we have seen, the current conception of how parallel processing is possible at every stage of a performance relies on the constitution of implicit, dedicated structures, or the sufficient strengthening of representations that then preclude a need for control. However, new tasks, notably laboratory tasks, call to a limited – and varying – extent upon already strengthened representations, and cannot rely on pre-established courses of action and task-specific pathways. Therefore, it would appear that new tasks inevitably call for control, and that control will in all likelihood limit crosstalk in the required processes by introducing some form of seriality. In the light of how (goal-oriented) control is assumed to work, goal integration therefore appears to be a way to allow for the successful performance of a complex task. It is possible that when the task is perceived in an integrated manner, subserving processes are managed in a way that does not enhance some to the detriment of others.

2.4.3.5 Manifestations of goal maintenance or neglect: measures

A number of confounds is likely to come into play in various cognitive tasks. Regarding WM, for instance, the common assumption for a long time was that WM is a single resource feeding control. Many accounts dispute this, as we have seen, but the idea can be reconciled in practice with the fact that control depends on goal representations, which need to be maintained in WM (see Cohen, 2017). However, the literature on cognitive control suggests that both constructs need to be distinguished, and that control functions may be related to, but cannot be equated with WM capacity. This has impacts on the choice of tasks and measures to assess these functions.

Kane and Engle (2003) propose a functional account of resistance to interference which is close to the DMC hypothesis as they both distinguish two main factors, but give WM capacity a central, executive role as a combination of short-term memory and executive attention (Engle & Kane, 2004). In this account, WM capacity and task context interact to moderate the strength and locus of prepotent response (Stroop) interference. The measure of cognitive control that the authors propose is therefore confounded with WM span. However, they provide insights into possible measures of goal neglect. They posit that interference arises when one of two phenomena occurs: One, is competition resolution, on which individuals tend to rely more when there is less need for goal maintenance (contexts with few congruent trials). This is reflected in response times, and specifically in PES (see section 2.4.2.4). The other phenomenon is failure of goal maintenance. Such failure – in contexts that call for goal maintenance, that is, situations with predominantly congruent trials – generally shows primarily in accuracy as well as in RT measures, where slowing is indicative of a breach in goal maintenance and the tail of the latency distribution may therefore reflect goal neglect.

A task widely used for the assessment of context processing – regardless of WM storage capacity – is the AX-CPT task mentioned above (section 2.4.3.3). The latest interpretation of AX-CPT results, in the framework of the dual mechanism of control hypothesis, also provides a way of distinguishing the relative influence of reactive and proactive modes of processing.

In multitasking settings specifically, a number of tasks and combinations have been used to study processing. However, it should be borne in mind that task combinations are not equal, as they provide for different grouped structures (see Halvorson, Ebner, & Hazeltine, 2013). Moreover, the risk of introducing confounds increases when combining tasks. This is all the more true for task combinations that require the maintenance of concurrent task representations over time. For instance, Sanbonmatsu et al. (2013) assessed multitasking ability by using the operation span task (OSPAN; Turner & Engle, 1989; Unsworth, 2005), chosen for its difficulty, the likely involvement of the PFC/ACC control network, and the necessity to retain information pertaining to that task while performing another task. However, this measure also depends on individual WM storage capacity. This is not irrelevant, as WM capacity is arguably a factor that contributes to maintaining concurrent goals active. However, the measure makes it hard to dissociate the effect of WM capacity and of control processes. In a subsequent study (Medeiros-Ward et al., 2015), the OSPAN task was used in combination with a driving task to identify good multitaskers.

The level of "difficulty" – and defining what this difficulty entails – also poses challenges in defining multitasking settings. Jaeggi at al. (2007) devise a dual *n*-back task, involving responses to both auditory and visuo-spatial cues that are presented simultaneously. The task generated an exploitable results distribution. A questionnaire was given to participants after they completed the task and the answers provided useful indications on the use of strategies: As could be expected, most participants resorted to a combination of a visual tracking strategy for the visuo-spatial task and to verbal rehearsal for the auditory task. But it turned out that most participants had used other strategies as well, and changed strategies with increasing task difficulty. However, it should be noted that better performers declared having used fewer explicit strategies, and more intuitive problem solving or reliance on automated processes than the low performers. Those mentioned having tried various strategies and strategy combinations for irregular amounts of trials over the course of the task. An explanation consistent with the cognitive control framework could be that conscious strategies may reinforce or bias the top-down control processes unnecessarily, working against the flexibility and adaptability of the control system; and that they may undermine the consistent pursuit of the task goal if they are themselves inconsistent (preventing the establishment of dedicated representations).

Indeed, a study by Medeiros-Ward et al. (2015) using the same task (dual *n*-back; Jaeggi et al., 2007) finds significantly distinct pattern of neural activation between the best performers ("supertaskers") and controls, with the former showing evidence of reduced activity in brain areas primarily associated with reactive control – namely the ACC and frontopolar PFC – suggesting more efficient recruitment in these parts of the control network. However, the behavioural measures did not differ significantly between the two groups, with both performing near chance at the most difficult level (dual 3-back).

Heathcote et al. (2014, 2015) propose a new dual *n*-back for the purposes of multitasking testing, specifically meant to assess "memory multitasking", that is, the ability to perform multiple concurrent operations in memory. The task targets proactive interference resolution, as well as binding between stimuli and temporal concepts (Oberauer, 2005). On the other hand, the task is also designed to reduce the influence of limitations in WM capacity, by limiting the number of items to memorise to four (double 2-back). Also, proactive interference (3-back lures) is maintained at a constant, high frequency, and a response is required for every trial (target or not). A single response is required for every trial, based on the processing of both incoming stimuli (auditory and visual), and a target response is required in the presence of a target in either or both of these stimulus modalities (Heathcote et al., 2014). The approach seeks to test multitasking capacity and (proactive) interference resolution specifically. However, it does not test the constant maintenance of concurrent goal representations.

Testing the capacity to concurrently multitask and the characteristics of control during multitasking remains a challenge. The goal-orientedness of control and the reliance on goal representations to modulate control raise the question of strategy use and sheds lights on why it is often extremely difficult to disentangle the one from the other. It remains unclear how much cognitive control is too much cognitive control, and how much is necessary to prevent interference.

2.5 Summary and implications

Multitasking, in contexts where more than one stream of information is concurrently processed, requires concurrent, online updating of task-related content. Shifting is a more extreme form of goal updating, and it has been argued that shifting is a necessary characteristic of multitasking performance. However, in the absence of external indications other than the respective task requirements, successful continuous multitasking would require, at the very least, a rapid shift back and forth between goals and the rapid and successive retrieval of task-related information. Alternatively, it can be assumed that multitasking involves the continuous maintenance of two goals without systematic necessity – or possibility – to shift in order to allow successful updating of the concurrent tasks. The human brain seems to be able to accommodate both mechanisms, but structural efficiency appears to favour reliance on joint representations and forced seriality when the complex task has not been trained. Testing this aspect is challenging and demands the design of a task set that requires both dual monitoring and updating in order to explore whether the constant maintenance of current goals is possible: Staying on task, as reflected in accuracy measures, would therefore be an indication of continuous maintenance.

The term “proactive control” does not mean that the control signal is defined *in advance* of the task. It refers to on-task control signal definition as modulated in real time by the intention to complete the task and a probabilistic prediction of its constraints. That control signal is also adjusted “reactively” as a function of conflict signals, that is, constraints which do not align with these predictions. Both proactive and reactive modulations may be involved during the completion of the same task. Indeed, it is likely that the analysis of real-time constraints may lead to new predictions (proactive control), inasmuch as these adjusted predictions are useful to the task. It may also appear that there is a higher chance of success with increased reliance on either proactive or reactive control – an adjustment that requires flexibility. Continuous multitasking represents an extreme setting, which is likely to impose constraints on the flexibility of the proactive-reactive control mechanism, and performance is therefore likely to be heavily informed by individuals' bias towards goal maintenance or conflict resolution. It would therefore be relevant to provide measures to account for both phenomena. In a continuous multitasking setting, our assumption is that (conflict-monitoring mediated) reactive control happens at the level of each specific task level to modulate attention wherever a deficit has been detected, while (goal-maintenance mediated) proactive control occurs at a more global level to ensure that both tasks are being performed.

If control's actual role is to single out processes for sequential or dissociated completion in order to avoid interference (Musslick & Cohen, 2019), what would the benefit of exerting control be during continuous multitasking? Our assumption is that it is necessary for successful multitasking to adjust the controlled processing of two (or more) tasks relative to each other. In a continuous multitasking context, successful performance will thus depend on whether control assumes a "switchman" function, i.e., all the control signal is directed to either task, or a "traffic regulation" function, where control signal for both tasks is adjusted dynamically. The temporality of changes in neural activation or maintenance of memory representation may make this phenomenon difficult to ascertain, and behavioural measures are probably not sensitive enough to provide robust indications.

However, a "traffic regulation" function, if at all possible, would likely allow for better performance in both tasks of a continuous multitasking setting by not directing all the attention available away from one given task at any given moment to avoid goal neglect. The possibility of allocating control flexibly is probably affected by the extent to which the hierarchical structure of the complex task has been internalised (see Chiew & Braver, 2017; Freedberg et al., 2014). Also, constraints on control are defined by the constraints set by each component task (i.e., how much sustained attention is necessary to obtain the specific task goal), meaning that in a least-possible-effort/EVC framework, control would be exerted continuously only to the extent to which the tasks absolutely require it. Possible respite would be taken advantage of in "switchman" mode.

Research has shown in several instances that more efficient multitasking, with better performance and reduced multitasking costs, was associated with training (e.g., Chein & Schneider, 2005). In various professions, such as piloting, being able to deal with multiple inputs in situations of cognitive stress is essential (Just & Buchweitz, 2017). This appears to apply to interpreters as well, whose performance becomes more fluid and the rate of errors and omissions is reduced with practice, and to orchestra conductors, who learn to channel a large amount of information in the most efficient, integrated, and clearest way possible towards a multiplicity of musicians.

Studying the particular cognitive constraints and strategies associated with such diverse complex activities as interpreting and conducting, as well as with the underpinning linguistic and musical skills, may help us better pinpoint the processes that come into play in order to allow successful multitasking. This in turn may provide us with tools to understand similarities and differences in the way control operates in multitasking situations. In order to better relate the theoretical views on how control is exerted to the complex tasks of interpreting and conducting, the next chapters will be devoted to an analysis of interpreting and conducting as instances of expert cognitive control.

3 Control processes and multitasking in interpreters

We have seen that real-time multitasking can be considered an extreme cognitive activity and how controlled processes likely come into play. It appears from many studies that the way we exert control is influenced also by individual factors such as experience, training, and habits. For instance, habit- and training-induced myelination[10] is thought to influence processing speed, as well as the degree of neural activation, with possible effects on neural efficiency (e.g., Jaeggi et al., 2007; Neubauer, Grabner, Fink, & Neuper, 2005) and a greater degree of automation in processes that have been rehearsed or repeated. The notion of *neural efficiency* (Haier, Siegel, MacLachlan, et al., 1992), however, is not entirely clear-cut as studies are not univocal about the degree to which less activation actually frees up resources that could be used for other processes. In any case, personal history and training cannot be overlooked when it comes to studying cognitive processes.

Interpreters and conductors are two categories of professionals that inspire a certain degree of awe in onlookers – and reactions such as "I don't know how you do that". Usually, that reaction is not based on the specialised nature of the activity (the fact that it involves an advanced mastery of language, or of music), but rather, on the constraints it seems to place on our capacity to pay attention. Both activities, interpreting and conducting, look to the observer – and may feel to the actor – like they require being actively mindful of several of their component processes as they happen. In our daily lives, we are used to feeling overwhelmed by that kind of situation: For instance, when learning how to drive, we have to break down the various driving situations (say, taking a turn), into all of the motor actions they require (including directing one's gaze to the right places, activating a turn signal, and if driving with manual transmission, shifting gears…). None of these actions are yet practiced enough to stop requiring control or become prepotent in the face of several possible scenarios. However, once driving has become a habit, coordinating and integrating these various actions requires no particular effort, and the drivers' intention is engaged in the activity globally, with enough mental space to adjust one or the other component to the context. By contrast, although many changes in processing – explored below – are observed with practice, several of the simultaneous actions involved in interpreting or conducting seem to individually require control even after long-term exposure and experience.

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[10] Axon insulation through coating by successive layers of myelin (white matter), increasing the speed of conduction in neural networks.

The following chapters will focus on cognitive control during interpreting and conducting, taking into account not only the literature on likely cognitive constraints involved in both activities, but also the possible control-related traits associated with multilingual experience and musical expertise. Indeed, taking into account the possible influence of the skills underpinning interpreting and conducting on control processes may help shed light on how these activities are executed.

It should be noted that interpreting is, at present, a profession with a majority of women, and conducting, still an overwhelmingly male one. For the sake of simplicity, the interpreter and conductor, even when mentioned in the singular, will be referred to as "they" to represent all genders.

3.1 Conflict monitoring and resolution in bilinguals

Not all research on cognitive processes in bilinguals distinguishes explicitly between people who master two and those who master more than two languages (e.g., Chertkow et al., 2010; Poarch & Bialystok, 2015; for a review see Schroeder & Marian, 2017). Neither does it systematically include a focus on the potential differences in language proficiency and exposure between bilinguals (e.g., Luk & Bialystok, 2013; Marian, Blumenfeld, & Kaushanskaya, 2007). The term "bilingualism" and "bilinguals" will therefore be used here in the same way they are used in the literature to refer to people who can use more than one language, except where distinctions between types of bilingualism are specifically discussed.

3.1.1 Bilingualism and cognitive control beyond language

A growing body of research indicates that the various languages an individual masters are simultaneously active in the brain (Kroll, Dussias, Bogulski, & Valdes-Kroff, 2012; Marian & Spivey, 2003a & b; Mercier, Pivneva, & Titone, 2014; Wu, Cristino, Leek, & Thierry, 2013; cf. Costa, Pannunzi, Deco, & Pickering, 2017). It also appears that the choice of the linguistic forms actually encoded and uttered happens comparatively late in the linguistic production process (Hirsch, Declerck, & Koch, 2015; Huettig, Rommers & Meyer, 2011; Levelt, 1989; Levelt, Roelofs, & Meyer, 1999). There appears to be a latency between the cue, or intention to speak and use a language (the preverbal stage), and the actual linguistic production (the verbal stage); models differ regarding the stage at which lexical representations can be activated for one language selectively. While certain models (e.g., Costa, La Heij, & Navarrete, 2006) propose that linguistic competition at the word level occurs and is resolved already at a preverbal stage, others (e.g., Dijkstra & van Heuven, 2002; Green, 1998) suggest that language selection happens as late as at the stage of lexical selection (for a review see, e.g., Kroll, Bobb, Misra, & Guo, 2008). A number of studies involving various methodologies like a picture-word interference paradigm with ERPs (Hoshino & Thierry, 2011), a PRP paradigm (Hirsch et al., 2015) or functional imaging (Reverberi et al., 2015) seem to corroborate the second hypothesis. This points to the co-activation of linguistic systems throughout the production process, and the involvement of language selection and control at the lexical access stage.

The concurrent activation of language systems creates competition and induces a reorganisation of networks in bilinguals as a consequence of managing that competition (Kroll, 2014). There is an ongoing discussion as to whether this leads to more general changes in the negotiation of cognitive competition in multilinguals (see Kroll, Dussias, Bice, & Perrotti, 2015, and Schroeder & Marian, 2017,[11] for a review). The hypothesis that these changes are domain-general rather than specifically involved in linguistic competition (Abutalebi & Green, 2007; Bialystok, 2001) is known as the "bilingual advantage" hypothesis (Peal & Lambert, 1962; see Antoniou, 2019).

This hypothesis has been studied widely: Bialystok, Craik, Klein, and Viswanathan (2004), Martin-Rhee and Bialystok (2008), for instance, suggest an advantage in bilingual children over monolingual children in various non language-related tasks (cf. Arizmendi et al., 2018), though task type and language proficiency influence the differences (see Marton, 2016, for a detailed discussion). Other studies point to advantages in other bilingual populations, notably older adults (Bialystok et al., 2004; Bialystok, Craik, & Freedman, 2007; see also Krashen, 2010). Brain imaging studies suggest that bilinguals with Alzheimer's disease exhibit less symptoms than monolinguals at the same stage (Schweizer, Ware, Fischer, Craik, & Bialystok, 2011; Woumans, Santens, et al., 2015; though Chertkow et al. (2010) find that the effect is restricted to multilinguals as opposed to bilinguals). On average, an Alzheimer's diagnosis seems to be given to bilinguals later than to monolinguals (e.g., Craik, Bialystok & Freedman, 2010). A later onset of dementia or cognitive decline is also reported (e.g., Bialystok et al., 2004; Bialystok et al., 2007; Salvatierra & Rosselli, 2011; Schroeder & Marian, 2012; but cf. Zahodne, Schofield, Farrell, Stern, & Manly, 2014). Other factors like

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[11] Schroeder and Marian discuss the cognitive effect of trilingualism, as modulated by accrued demands on the available linguistic and control system. Salient findings suggest that a cognitive advantage in trilinguals against bilinguals appears to be visible only in older adults. In contrast, trilingualism may present early challenges in very young children, and seems to make no difference in older children and young adults.

the level of education may underlie contradictory findings (Gollan, Salmon, Montoya, & Galasko, 2011; cf. Alladi et al., 2013).

However, a meta-analysis by Hilchey and Klein (2011) as well as later publications (De Bruin, Treccani, & Della Scala, 2015; Lehtonen et al., 2018; Paap & Greenberg, 2013; Paap & Liu, 2014; Paap, Johnson, & Sawi, 2014, 2015, 2016) point to an apparent publication bias in favour of the bilingual advantage as well as a less conclusive picture of bilinguals' cognitive performance compared to monolinguals across the board. A number of studies based on behavioural measures report various effects – and sometimes no effect – of bilingualism on control-related functions (see Cachia et al., 2017, for a review).

Spurred by the heated debate (see Bialystok, Kroll, Green, MacWhinney, & Craik, 2015; Bak, 2016), studies have taken into account the effect of linguistic experience, beyond external factors such as socioeconomic status, to stress differences within the bilingual population (e.g., Prior & Gollan, 2013) and a more nuanced picture is emerging. Specific subgroups like young adults seem to show fewer differences compared to monolinguals in a majority of studies, whereas an advantage tends to be observed in older participants (see review in Valian, 2015a); and determining factors for a potential bilingual advantage such as language proficiency, language use, and exposure to both languages, have been the object of more detailed focus (Goral, Campanelli, & Spiro, 2015; Titone, Gullifer, Subramaniapillai, Raha, & Baum, 2017).

One of the factors frequently discussed in connection with the bilingual language experience is the age of acquisition (AoA). While a number of studies report differences in language representation (e.g., Flege, Yeni-Kamshian, & Liu, 1999; see also the review in Liu & Cao, 2016) and control (see Hernandez & Li, 2007) depending on AoA, a growing body of research points to the flexibility and dynamic character of the language system (Marian, 2008). Language representation and activation are largely modulated by language proficiency (see the meta-analysis by Cargnelutti, Tomasino & Fabbro, 2019) and heavily influenced by the way a bilingual person uses their languages. Therefore, representation and activation patterns can evolve in any direction, including for languages acquired early in life (Higby, Donnelly, Yoon, & Obler, 2020; Köpke & Schmidt, 2004; Köpke & Genevska-Hanke, 2018; Kroll et al., 2015; Schmid & Yilmaz, 2018). And neural structures associated with cognitive control appear to be influenced more strongly by language use than by AoA (see the review in Del Maschio & Abutalebi, 2019). More often than not, this still implies that there are differences in the organisation in the brain between a language acquired earlier or later in life (e.g., Berken, Gracco, & Klein 2017). In other words, even assuming constant language exposure, it is likely that there are differences between an individual's languages as well as differences in the same language between individuals. However, language proficiency and frequency of use (see Luk & Bialystok, 2013) can erase these differences and create new ones.[12]

Such considerations have driven changes in research practices: While earlier studies tended to distinguish between "early" and "late" bilinguals based on AoA, and convenience still makes AoA a frequent discriminating variable, the argument has been made that bilingualism should be treated as a continuous variable to account for its various dimensions (Marian, 2008). This approach, that is becoming increasingly widespread, would also allow to explain variations in language and control networks more conclusively (Sulpizio et al., 2020). Validated tools like the Language Experience and Proficiency Questionnaire (LEAP-Q, Marian, Blumenfeld, & Kaushanskaya, 2007) have been developed to that end.

It is all the more important to determine the participants' specific bilingual language experience as a number of studies stress that bilinguals for whom one language is clearly dominant process input in their dominant language more slowly following production in a non-dominant language than they do in the other direction, and non-dominant (i.e., balanced) bilinguals do not show that difference (asymmetric switching costs: Green, 1998; Meuter & Allport, 1999; for reviews see, e.g., Goral et al., 2015; Van Hell & Witteman, 2009). This points to active inhibition of the dominant language in non-balanced bilinguals. It follows that such inhibition comes into play primarily in contexts where the activation of a less dominant language is required, and that the context of language exposure probably plays a role in the linguistic control constraints placed on individuals.

When it comes to studying the involvement of specific EFs in a task, a series of other central issues needs to be addressed. Starting with that of the experimental task's purity, that is, the question of whether task completion relies on one or more precisely identifiable processes (see Marton, 2015; Marton et al., 2017), task administration (see Schroeder et al., 2016), task reliability (see Arizmendi et al., 2018), and the task's ecological validity (i.e., to what extent it reflects the actual constraints met by the brain outside the lab; see Paap et al., 2020). Blanco-Elorrieta and Pylkkänen's (2018) review of code-switching paradigms finds that laboratory tasks tend to induce additional costs compared to natural contexts due to the participants

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[12] Not only evolving patterns of language use, but also the resulting language control needs, like for instance an increase in inhibition of the L1 (e.g., Linck, Kroll, & Sunderman, 2009) come into play.

having to acquaint themselves with new rules and an unfamiliar environment; Paap et al. (2020) find that Stroop, Flanker and Simon task performances (see Appendix A) relate poorly with one another and with general behavioural inhibition in real life. These factors contribute to the inconsistency of findings in the literature.

Indeed, it is important to stress that the way control is applied in the bilingual mind is not straightforward. When observing neural activity while listening to, shadowing or interpreting from a second language, Hervais-Adelman, Moser-Mercer, Michel and Golestani (2014) conclude that areas underlying nonlinguistic, executive control do seem to be involved in these activities, but to different degrees: "Continuous demands of language control in the multilingual brain, and associated experience-dependent plasticity, could underlie the nonlinguistic, executive advantages that have been observed in bilingual individuals" (p. 4737). This conclusion points to two intertwined factors of variation: Individual differences on the one hand, and the specific activity in which the brain is engaged along with the control demands this entails on the other hand.

3.1.2 Bilinguals and specific control functions

The type of domain-general control functions that may be trained with bilingual language use have been studied widely. We will focus first on behavioural measures of inhibition (resistance to interference), as isolated and described by Miyake et al. (2000) and Friedman and Miyake (2004, 2017), because this aspect is deemed central and has been extensively investigated in the adult populations that are of interest here. We will then present theories of cognitive control in bilinguals, investigate the role of conflict monitoring and goal maintenance and proceed to discuss how current findings relate to generic aspects of control according to recent frameworks (cognitive control: see Cohen, 2017; dual mechanisms of control: see Braver, 2012; Chiew & Braver, 2017).

It is noteworthy that the performance advantage attributed to bilinguals in the various experimental tasks studied is often apparent in the form of shorter RTs, for instance in the Stroop task (Bialystok, Craik, & Luk, 2008; Heidlmayr et al., 2014), in the Simon task (Bialystok et al., 2004; Linck, Hoshino, & Kroll, 2008), or in the Attention Network Test (ANT; Costa, Hernández, & Sebastián-Gallés, 2008; Woumans, Ceuleers, Van der Linden, Szmalec, & Duyck, 2015), or in batteries of cognitive tasks (Marton et al., 2017). However, it is still unclear whether these RTs are indeed indicative of more flexibility in adjusting control processes, consistent with Botvinick et al. (2001) or if, as argued by Hilchey and Klein

(2011), the advantage can be reduced to global processing speed. It is therefore advisable to control for processing speed separately (Marton et al., 2017; Marton & Gazman, 2019). In Marton et al.'s (2017) study, not all cognitive effects of bilingualism were reducible to processing speed. The possible confusion between speed and cognitive control in the literature is also compounded by the fact that although the Stroop, Flanker, and Simon task are often used to measure one construct (inhibition), they each seem to require the resolution of a task-specific form of interference (Paap et al., 2020).[13]

Although a bilingual advantage is not consistently found as discussed above, and although differences between bilinguals and monolinguals may appear on the level of neural activation and not be reflected behaviourally (Marian, Chabal, Bartolotti, Bradley, & Hernandez, 2014), some studies indicate better performance in adult bilinguals in a number of inhibition tasks, supporting the idea that the bilinguals' need to selectively use one language while resisting competition trains cognitive conflict management in a domain-general manner. This includes the Simon task (e.g., Bialystok et al., 2005, 2004; Woumans, Ceuleers, et al., 2015) and the Stroop task (e.g., Blumenfeld & Marian, 2011, 2013; Hernández, Costa, Fuentes, Vivas, & Sebastián-Gallés, 2010), which require the inhibition of a prepotent response. Similar results were also observed in the Flanker task (e.g., Costa, Hernández, Costa-Faidela, & Sebastián-Gallés, 2009; for early bilinguals see Luk, De Sa, & Bialystok, 2011) and the related Attention Network Task (e.g., Costa et al., 2008), which require the inhibition of a distractor (Friedman & Miyake, 2004). In all of these paradigms, the presence of irrelevant stimuli creates conflict, which needs to be resolved through inhibitory control. It is also necessary to switch adequately between trial types (congruent/incongruent) and conditions (e.g., pure or mixed blocks). Resisting interference from irrelevant stimuli requires better selection and recognition of goal-relevant stimuli through goal maintenance in WM. Marton et al. (2017) found better results in bilinguals in switching as well as in a specifically designed task to test resistance to proactive interference, that is, interference from previously relevant stimuli. Resolving conflict accurately then requires WM content to be flexibly updated and made available in order to discriminate between rule-appropriate and rule-breaking stimuli at any given point in time. Prior (2012) also found that bilinguals showed greater ability to suppress inhibition from formerly relevant task-sets, but that in so doing, they incurred higher costs (lag-2 repetition costs), when a previously discarded rule had to be reactivated.

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[13] See also Sommer, Fossella, Fan, & Posner (2003), although that study compares the Stroop and ANT (see below), which do not test the same type of inhibition according to Friedman & Miyake (2004).

As alluded to earlier, within the bilingual population, a domain-general control advantage in dominant bilinguals is suggested – these are unbalanced bilinguals, who have to overcome asymmetrical switch costs. They seem to outperform balanced bilinguals in inhibition tasks. For instance, this is the case in a Simon task (Goral et al., 2015). No advantage was found in balanced bilinguals over monolinguals in the inhibition of interference from proactive and reactive *n*-back lures in Wadhera, Campanelli, & Marton (2018); In that study, successful inhibition of reactive lures was positively correlated with reading proficiency across the board, pointing to the necessity to further dissociate individual factors of variation. There is evidence for balanced bilinguals still needing to clearly separate their two languages, even though they may be exposed to both often. With a bilingual picture-naming task, Festman, Rodriguez-Fornells, and Münte (2010) illustrate the relevance of the amount of bilingual language control exerted in everyday life. They tested bilinguals who did not code-switch against bilinguals prone to code switching and found better inhibition of irrelevant stimuli in non-switchers in a Go/No-Go task as well as in a Divided Attention task.

Successful interference suppression may be associated with strengthening relevant representations and/or limiting activity in the irrelevant channel (see Costa, Santesteban, & Ivanova, 2006). In addition, interference can be anticipated and prevented through proactive control (modulated by the active maintenance of goal-related representations) and/or resolved through early or late reactive control (Irlbacher, Kraft, Kehrer, & Brandt, 2014). Depending on the nature, frequency and variability of interference, it may be more efficient to rely on proactive or reactive regulation of control, modulated by goal maintenance or conflict monitoring. The most frequently used inhibition paradigms do not clearly suggest which of these mechanisms has the highest influence on interference resolution in bilinguals. These paradigms tend to rely on independent trials with cue and stimulus sequence, therefore limiting proactive control strategies and primarily yielding insight on reactive control processes (see also Gullifer et al., 2018).

In order to account for the demands placed by bilingual language use on the cognitive control system, one of the prominent theories proposed is the inhibitory control hypothesis (Abutalebi & Green, 2007; Dijkstra & Van Heuven, 2002; Green, 1998). It focuses on the language-selection mechanism, and the necessity for bilinguals to activate the context-appropriate language and suppress competing non-target language representations at various levels (see De Groot & Christoffels, 2006; Guo, Liu, Misra, & Kroll, 2011). This framework of interpretation is consistent with the above-mentioned reports of better resistance to interference in bilinguals in the Stroop and Simon tasks and lower switch costs (Morales, Gómez-Ariza, & Bajo, 2013). It is also in line with the idea that inhibition is a competitive process, where task-irrelevant pathway suppression and task-relevant pathway enhancement go hand-in-hand (Cohen, 2017; see section 2.4.3.1).

In view of the salient effects of individual bilingual experience on the different control processes involved, Green and Abutalebi (2013) integrate the inhibitory model into the more comprehensive Adaptive Control Hypothesis: They take into account EFs as highlighted by Miyake et al. (2000) as well as the dual mechanisms hypothesis of control (Braver, 2012; Braver et al., 2007) to isolate various control functions and underline the demands placed on these, depending on the interactional context. Differences appear on the basis of whether an individual is interacting within a single-language context (each language is spoken in a distinct environment), a dual-language context (both languages are spoken with distinct interlocutors) or dense code-switching (both languages are spoken with the same interlocutors and usually within the same utterance). The isolated control processes are the following: Goal maintenance; interference control, i.e., conflict monitoring and interference suppression; salient cue detection; selective response inhibition; task disengagement; task engagement; and opportunistic planning. In comparison to monolingual speakers in a monolingual context, even single language use in bilinguals seems to involve goal maintenance and interference control (conflict monitoring and resolution), and dense code-switching appears to call for opportunistic planning only. In other words, dense code-switching is a way to use the most frequent forms in relation to each language and thus to resort to the least demanding processes in the relative absence of obstacles to comprehension. By contrast, dual-language contexts, which are the most constrained, appear to place considerably higher demands on both proactive and reactive control than single-language use, and to also modulate the other control processes involved (with the exception of opportunistic planning). The Adaptive Control hypothesis is therefore made up of two components:

1) Bilinguals modulate linguistic control as a function of the context of a given interaction;

2) this modulation involves domain-general control functions (see also Abutalebi, 2013). Furthermore, both proactive and reactive control mechanisms are put to use.

3.1.3 Proactive and reactive control mechanisms in bilinguals.

Recently, both the adaptive and the dynamic character of bilingual language use have been highlighted (Seo & Prat, 2019). This comes in addition to the complexity of the control processes likely at play depending on the level of linguistic control required (De Groot & Christoffels, 2006). A compelling hypothesis is that language control in bilinguals is hierarchically organised (Branzi et al., 2016) – similarly in fact to cognitive control (see sections 2.4.3.3. and 2.4.3.4) – and that proactive global bias (acting on the language system) as well as proactive and reactive modulation at the local level (acting on lexical retrieval) come into play flexibly (Abutalebi & Green, 2016; see also e.g., Strijkers, Holcomb & Costa, 2011). This is consistent with recent theoretical frameworks for control like the dual mechanisms of control (DMC), which highlight both top-down and bottom-up modulation (Braver, 2012; Chiew & Braver, 2017, see section 2.4).

In their review of the control processes possibly involved in bilingualism, Morales et al. (2013) distinguish between proactive and reactive control processes according to Braver (2012) using the AX-CPT. They highlight increased reliance on both types of control mechanisms in bilinguals in high-demand settings. However, their account of monitoring, including conflict monitoring by the ACC network (see Botvinick et al., 2004; see section 2.3.2.), sets it within a context-monitoring process serving to both set and adjust the task representations. It is therefore interpreted as a proactive process, as in Green and Abutalebi (2013), who also interpret Green's (1998) inhibitory hypothesis in this light. However, Braver (2012) perceives the role of the conflict monitoring functions in the ACC network as one of mediation, serving to regulate the bottom-up reactivation of task goals in a reactive way as opposed to a proactive, top-down bias modulated by task representation. As monitoring – even in a larger context-monitoring view – implies adjustments to the control signal level initially set as a function of the perceived goal, we can argue that it does constitute a reactive mechanism. It is triggered as a function of the degree of activation of the repressed language forms. In a competition context, this reactive mechanism thus serves to optimise the regulation of control signals for better efficiency (see section 2.3.2). The mechanism's reactive nature is still given if the comparison of the current stream of incoming stimuli with the task goal gives way to further control adjustments and ultimately modifies the goal representations themselves to engender new anticipatory, top-down control bias. This is in line with the conflict monitoring model (Botvinick et al., 2001), according to which reaction to conflict in the ACC can be viewed "as part of a more general monitoring function, according to which the ACC responds to a variety of events, all indicating that attentional adjustments are needed to optimize performance or avoid negative outcomes" (p. 626). In fact, this function can be viewed as an integrated demand-based decision-making system

(Botvinick, 2007). In a follow-up behavioural and ERP study, Morales, Yudes, Gómez-Ariza, and Bajo (2015) equate better conflict detection in bilinguals, as associated with ACC functions[14], to stronger reactive control mechanisms.

A number of studies stress that the degree to which monitoring is required may characterise the link between bilingualism and cognitive control (Abutalebi et al., 2012; Costa et al., 2009; Hernández et al., 2010): The general RT advantage in bilinguals seems to not only be modulated by their ability to resolve conflict, but also by the amount of monitoring required in a given setting (see also Bialystok et al., 2004; cf. Prior, 2012). However, group differences in monitoring disappear once processing speed is controlled for in a study using a specific monitoring paradigm and in which PES was measured (Marton et al., 2017), though this calls for clarifying the links between overall RT and PES. Costa et al.'s (2009) conclusion is supported by bilinguals' RT advantage over monolinguals becoming significant in a high-monitoring version of the Flanker task, where incongruent trials appear less frequently, modifying the expectations of what the next trial would be (worse odds for incongruent trials). Cachia et al. (2017) also discuss differences in monitoring efficiency as evidenced by RT differences in the Flanker task in monolinguals and bilinguals, while taking into account individual variations linked to anatomical differences in the ACC considering the importance of the ACC network in conflict monitoring (Botvinick et al., 2001, 2004; see section 1.3.2).

Monitoring mediates (reactive) adjustments to the control signal and the inhibition of interfering signals is a phenomenon attesting to such adjustments. In numerous instances, bilinguals have been found to show comparatively high levels of both. This does not, however, preclude their reliance on proactive control[15]. Green's (1998) inhibitory control model or La Heij's (2005) account of cognitive/language-related control already included the idea that processing was directed a priori by task schemata. Indeed, bilingualism has been associated with a higher degree of inhibition of return[16] and attentional blink, interpreted as indicators of better goal maintenance (Colzato et al., 2008; cf. Hernández et al., 2010).

Proactive control in bilinguals is also discussed in a recent metastudy on code-switching and the switching advantage in bilinguals (Blanco-Elorrieta & Pylkkänen, 2018). The authors

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[14] For ERP signals (error-related negativity ERN and N2) associated with ACC functions, see Yeung, Botvinick and Cohen, 2004; Botvinick et al., 2004; Yeung and Cohen, 2006.

[15] This is logical in any case as the DMC model points to a tendency in one or the other direction, not to mutually exclusive mechanisms. Maintenance of goal representations is a basic requirement, also for subsequent comparison (i.e., conflict detection).

[16] A slowing effect observed in detecting a visual target shown at the same location as a previous random distractor after more than 300ms.

point out that, provided the (natural) context allows bilinguals to code-switch, they do so as a way to avoid effort (consistent with Green & Abutalebi, 2013). It is argued that a bilingual advantage in switching is limited to those who have been largely exposed to contexts of frequent switching accompanied by outside constraints (interlocutor-determined), that is settings requiring top-down control mechanisms for language selection. Calabria, Baus, and Costa (2019) describe the role that the proactive and reactive control mechanisms posited in the DMC framework are expected to play in bilinguals as follows: The activation levels of the various languages is managed a priori by proactive control, before specific lexical items are activated. In turn, transient interference between languages, for instance in the time window in which a language switch occurs, is resolved through reactive control. Calabria et al. (2019) suggest that proactive and reactive mechanisms appear to be at work across various domains of control, whether linguistic or not; However, due to the high demands involved in the bilingual language context, these mechanisms are expected to cooperate more flexibly, and actually domain-generally, in bilinguals.

The present study is concerned with behavioural measures and does not claim to investigate neural networks and functions related to the successful execution of linguistic processes and, more generally, of simultaneous, continuous dual tasks. Such endeavours go beyond the scope of this dissertation. It appears, however, relevant to highlight selected contributions of neuroimaging studies to the current understanding of the processes at play, especially as this provides reference points for the investigation of processes particular to interpreters further below. We will therefore briefly take a look at two specific networks with which bilingual language control has been associated.

One network involves the pre-Supplementary Motor Area/Anterior Cingulate Cortex (pre-SMA/ACC), prefrontal cortex and the left caudate nucleus, which are linked to the following processes: Monitoring of the eventual choice of a specific language, signalling of errors, and inhibition of the unintended language (Abutalebi & Green, 2007; Green & Abutalebi, 2013).[17] Reverberi et al. (2015) stress that this network appears to be involved in resolving competition between languages during the execution phase as opposed to the intention phase. The ACC is activated in bilinguals when they perform either linguistic or non-linguistic conflict tasks (e.g., Branzi et al., 2016; Cachia et al., 2017). This further suggests its involvement in the network associated with conflict monitoring, both generally and domain-

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[17] Again, here the first interpretations of the monitoring function encompassed both reactive and proactive mechanisms ("eventual choice"). It is not the case anymore later.

specifically. As we have seen (section 2.4), the DMC framework (Braver, 2012) predicts that reactive control will be associated with the engagement of conflict monitoring regions such as the ACC and regions involved with associative activity (in the posterior cortex or medial temporal lobe). These patterns of activation reflect the detection of interference or associations, which also transiently reactivate task goals represented in the lateral PFC. By contrast, that region is expected to be maintained active when proactive control is involved (see also Irlbacher et al., 2014).

This duality of mechanisms is also highlighted when it comes to language control. The second language control network is linked to selecting and maintaining prospective intentions and seems to be activated while setting up and updating the preparatory steps to speak a given language (Reverberi et al., 2015). Goal maintenance linked specifically to language use at a given point in time involves the parietal lobes bilaterally. Interference suppression appears to involve the left interior frontal gyrus (IFG) and dorsolateral prefrontal cortex (DLPFC) regions (Abutalebi et al., 2016, Cachia et al., 2017) associated with proactive control (Braver, 2012; Seo & Prat, 2019).

Other models based on neurological findings exist and they broadly overlap, like the Conditional Routing Model (Stocco et al., 2014) which also ascribes a specific role to the caudate and putamen for rule selection; Recent models highlight changes with growing language exposure (Grundy et al., 2017; Pliatsikas, 2020). DeLuca, Segaert, Mazaheri and Krott (2020) attempt to reconciliate existing models and provide an integrated overview of cognitive adaptations across the variety of bilingual experience: These adaptations allow, on the one hand, to adjust to specific, high control demands, which are reflected in increased, strategic reliance on proactive control; On the other hand, they also increase efficiency in handling existing demands, which is reflected in increased reliance on reactive control. Importantly, recent findings suggest that early versus late L2 acquisition is a predictor of control mechanisms (Gullifer et al., 2018), behaviourally and as reflected in neural representations: Late bilinguals seem to rely more strongly on proactive than on reactive control, and the opposite is true for early bilinguals. All these insights suggest that linguistic and domain-general control networks largely overlap (see also Calabria, Costa, Green, & Abutalebi, 2018; Hayakawa & Marian, 2019; Hervais-Adelman et al., 2014, Hervais-Adelman, Moser-Mercer, & Golestani, 2015; Rodríguez-Pujadas et al., 2013), and further illustrate the intertwined processes at play.

3.1.4 Summary

The Dual Mechanisms of Control hypothesis (Braver, 2012; Braver et al., 2007; Chiew & Braver, 2017; see section 2.4) suggests that factors arising from an individual's unique experience and personality influence the tendency to rely on proactive or reactive control. This may contribute to the inconsistencies in the literature regarding control processes in bilinguals (Seo & Prat, 2019). Bilinguals do not exist in a vacuum and their cognitive profile is shaped by a multitude of experiences, which warrants a focus on individual differences (Valian, 2015a, 2015b; Costa et al., 2014). Differential control mechanisms also come into play in bilinguals' language use, probably depending on individual experience, and are likely to underpin a possible advantage, or lack thereof, depending on the context at hand. These factors further underline the necessity to account for within-bilinguals variables and to assess the type of mechanisms underpinning task paradigms when testing cognitive control.

It would thus appear that in a number of cases some processes requiring cognitive control are executed with more ease in bilinguals (as evidenced by shorter RT and sometimes higher accuracy), and that bilinguals show evidence of enhanced control responses in imaging studies. They can therefore be expected to show better performance in complex tasks. However, beyond the differences induced by other biographical characteristics, bilinguals' advantages in processing appear to be predominantly shaped by their specific language experience. We will focus on the case of simultaneous interpreters in the following section.

3.2 Task components, cognitive constraints, and control mechanisms in interpreting

There is little doubt that simultaneous interpreting (SI) is a form of multitasking: It is characterised by the fact that comprehension and production, which happen mostly in succession in everyday language use, are constrained to happen simultaneously (Christoffels et al., 2006). Cognitive constraints are visible; [18] They manifest for instance in the deterioration of performance after some time on task (see review in Seeber, 2015b), and these cognitive constraints do not seem to disappear even once interpreting technique has been mastered, as indicated by the number of errors still routinely made by experienced interpreters (see, e.g., Kopczyński, 1994).

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[18] Early research on interpreting (Barik, 1973) indicated that interpreters sometimes use pauses in the original speech to densely produce content; It would be interesting to see if such a tendency is less observed now, as students are encouraged in the course of simultaneous interpreting training to try and keep a regular pace if possible.

In addition, it is important to keep in mind that the way SI is carried out, the demands involved, and the associated control processes are not constant, but are modulated by a number of factors (e.g., Gerver, 1976), some of which have been highlighted above in the literature review on bilingualism. These factors are supported by impressionistic evidence among interpreters, and not all of them have been investigated in that population, but the following sections will explore the available literature in relation to interpreters' cognitive processes. Firstly, there are task-related factors, situational and intrinsic, such as the sound quality (a factor with renewed relevance nowadays with the rise of remote interpreting, which relies on digital platforms), the difficulty of the source material (including, but not limited to, register, syntax, density, speed, delivery, accent, degree of predictability contained in intonation…; see, e.g., Mead, 2015a; Seeber, 2015b), typological proximity between source and target language, and directionality (i.e., working into or from one's more proficient language). Secondly, there are interpreter-related factors, situational or intrinsic, such as preparation, familiarity with the subject-matter, familiarity with the speaker, familiarity with the listeners' expectations, trust in the boothmate,[19] motivation, stress, fatigue, early or late bilingualism, patterns of language use and exposure, and relative proficiency in the languages at hand.

While the first interpreters, recruited to meet a new need, were highly proficient balanced bilinguals, subsequently trained interpreters differ in their language background, the number of languages that they use in their work and their relative proficiency in those languages. The interpreter's language classification is described within the context of the profession, and often in the literature on the discipline, as a function of how they use the languages (see, e.g., AIIC, 2012). As a consequence, these working languages lack benchmarking in absolute terms for research purposes (Ferreira, Schwieter, & Festman, 2020). As a rule, interpreters work into the language in which they are the most proficient, that is, their L1 ("A" language). A language used as a source language only (passive language) is called "C" language. A language that can also be used as a target language (active language) from the A language is called "B" language[20]. It is, of course, possible to have more than one C, B and even A language.

The present study focuses on SI expertise in interpreters because of the complexity of the task and the real-time nature of the processes involved. While "simultaneous with text", i.e., SI

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[19] For an account of teamwork in interpreting, see Chmiel (2008).

[20] For an attempt to account for the language proficiency levels related to the interpreters' working languages, see Loiseau and Delgado Luchner (2021).

with a visual support, which can help auditory processing but also requires attending to and may constitute a competing input (see Seeber, 2017) is a more and more frequent working modality, we will focus on "pure" SI in the present analysis, and will also refrain from investigating the case of bimodal interpreting from and into a sign language (see e.g., Macnamara & Conway, 2016). SI as a task has not changed over the past decades, much as the technology has (Keller, 2018), although constraints have been added with the multiplication of read speeches (whose text is, more often than not, not provided to interpreters), faster speeches, accents (Seeber, 2015b), and all possible combinations of those factors.

The present review endeavours to provide an overview of the SI process. A brief historical account is provided in Appendix B in order to provide context regarding the evolution of the interpreting task. Starting with scientific insights on the task, the review below will go on to focus on the cognitive processes and constraints involved in SI and their possible implications regarding the exertion of control in real time during interpreting as well as control habits in interpreters.

3.2.1 SI: Processes and models

During SI, the interpreter is busy listening to the source speech, transmitted via earphones, and producing a different linguistic version of the same speech into the microphone. In order to do so, they start interpreting shortly after the speaker and endeavour to follow at a similar pace. However, interpreters vary in the delay they feel most comfortable with. That delay is sometimes called EVS, that is, ear-to-voice span, and also known as *décalage* or (time) lag. On average, it amounts to five words, or 2s (see Gerver, 1976; Christoffels, 2006), though it is sensitive to individual variation (Timarová, Dragsted, & Gorm Hansen, 2011) and to various factors such as experience (Timarová et al., 2014) and difficulty (Chernov, 1994). The lag is influenced by, but also modulates the amount of information that has to be kept in WM before processing, and as such cognitive load and cognitive processing (Timarová et al., 2015). Depending on the circumstances, more or less leeway is left for a lag, placing added constraints on the way SI is carried out (see review in Chmiel et al., 2017). For instance, television interpreting constitutes a particular technique and a special case in that presentation needs to fulfil certain criteria and the interpreter is required to finish at the same time as the speaker at any cost, and anticipate as best as possible the end of the intervention (see, e.g., Straniero Sergio, 2012). In most conference settings nowadays, interventions happen in rapid succession and the interpreter has limited margin to extend the speech duration. That is all the more true when the interpreter serves as relay for colleagues in other booths who do not understand the original language, as happens most frequently in institutions with large linguistic regimens.

SI as a task has been studied and broken down into suggested components numerous times in order to better understand the processes at play, for pedagogical reasons and for research purposes. Only recently has the activity been treated as a form of bilingual language use (e.g., Dillinger, 1994) and control, albeit an "extreme" one (e.g., Hervais-Adelman et al., 2014; Obler, 2012; van de Putte et al., 2018; Woumans, Ceuleers, et al., 2015). At the turn of the century, the study of interpreting started to emerge as a research paradigm of its own within the study of complex cognitive processes, and to explore various links between cognitive theory and interpreting (Köpke & Nespoulous, 2006). Interpreting is described as an "extremely complex task", whose various components require attention, rely on WM and are executed with temporal overlap and under speed requirements (de Groot, 2011, p. 326). This aspect makes it difficult to isolate the various control processes at play, keeping in mind that their combination in real time probably either requires additional processes, such as coordination (Matthews et al., 2000; Moser-Mercer, 2010), and/or modifies control exertion for each task component. In addition, as highlighted in the introduction to this section, other factors come into play.

Certain processes can be isolated: For instance, when the source language is an active language of the interpreters', they may sometimes forget to activate their intended target language (or to stop working) and start "interpreting" the source language into the same language, paraphrasing rather than repeating the content (see Anderson, 1994; De Bot, 2000), only to realise their mistake when the incoming and outgoing sounds do correspond. It appears that the other processes involved in interpreting are taking place in this simultaneous paraphrasing exercise, including message recoding, except for the activation of the target language (see also Christoffels & De Groot, 2004). Over the history of interpreting studies, SI task components have been described by many researchers (e.g., Christoffels et al., 2006; Christoffels & De Groot, 2004; Gerver, 1975, 1976; Goldman-Eisler, 1972; Hervais-Adelman, Moser-Mercer, & Golestani, 2011; Keller, 2018; Moser, 1978; Moser-Mercer, Frauenfelder, & Künzli, 2000). Taken together, these authors identify the following components, emphasising the fact that some of the processes overlap and that additional processing steps occur as previous steps are continued with new content (the order below therefore does not represent an absolute sequence):

- Perception (of verbal information) – (continuous) monitoring + context maintenance and anticipation of original content
- Storage – maintenance of (verbal) information
- Retrieval (at various hierarchical linguistic levels)
- Transformation – decoding and recoding, encoding subsequent input – language and modality switches
- Transmission (production) – (continuous) monitoring + maintenance and anticipation of produced content.

Some of the major SI models, therefore, comprise an account of perception and memory as well as storage systems involved at the various stages, and processing, verbal decoding/encoding, and output mechanisms. We will first briefly review influential models of interpreting with respect to the domain of research upon which they build; As the present work focuses on simultaneous processing and the exertion of control, the subsequent discussion of specific SI models will be confined to the analysis of those (and related) aspects.

Theoretical models of SI have been constituted throughout the years on the basis of contemporary cognitive models. Early SI models, developed in the 1970s (e.g., Gerver, 1976; Moser, 1978) attempt to provide information processing accounts, that is, a theoretical representation of SI as a combination of steps and functions to be considered in its entirety and complexity. These are set within the frame of cognitive psychology, building on early WM theories (Baddeley & Hitch, 1974) and in the case of Moser (1978), language comprehension and production theories (Massaro, 1975). In addition, several partial models endeavour to account for WM in interpreting: Daró & Fabbro (1994) adapt Baddeley's (1990) and Mizuno (2005) adapts Cowan's (1995, 1999, 2000) WM model to interpreting. While the information processing accounts – the first prominent theoretical models of SI – provided a longitudinal section of the various stages involved in SI that is sequential by nature, subsequent models endeavoured a cross-section of the competing linguistic and/or cognitive processes involved. Gile's (1985, 1995, 1997, 1995/2009) Effort Models, often used as a reference in subsequent research, constitute a special case. The framework they provide is pedagogical in nature and does not make claims based on findings and cognitive constructs derived from the literature, but rather provides a practical, subjective account of processing capacity modularity during the interpreting task, discussed with reference to at the time still influential theoretical insights regarding the allocation of attentional resources (e.g., Kahneman, 1973). Ulterior accounts of interpreting take theories in linguistics (e.g., Kitano, 1993, for a machine-based programme) or psycholinguistics findings into consideration. Chernov (1987/2004) situates interpreting processes in a context of limited information-processing capacity and highlights that the role of probabilistic predicting is central to interpreting, making the density of the original speech a determining factor (Chernov, 1994). Setton (1999) proposes a hybrid Cognitive-pragmatic model partly based on Levelt (1989), calling on relevance theory (Sperber & Wilson, 1986/1995) and seeking to integrate interpretive theory[21] (Seleskovitch & Lederer, 1986) as well as insights from information-processing accounts; the model posits that increased proficiency and other changes related to SI are not attributable to improvements in the coordination of processing capacity, but rather to resourceful use of knowledge and pragmatics. Grosjean (1997; 1997/2000), Paradis (1994, 2000) and Christoffels and de Groot (2005) model language interaction during interpreting within a connectionist (i.e., activation-based) framework. Grosjean's language-mode paradigm proposes a continuum of language activation modes between bilinguals and monolinguals, and suggests a distinction between language systems, which are co-activated in interpreters to the same extent as in bilinguals at the higher end of the continuum ("bilingual mode"), and language processing (i.e., input and output) mechanisms, whose activation is uncoupled, allowing to selectively inhibit the source language output during interpreting ("monolingual mode"). In Paradis' account, based inter alia on insights from neurolinguistics, activation is differential, with higher activation thresholds for the least used language. This places demands on the cognitive system when the default balance needs to be superseded, as is the case in an interpreting context. Paradis further provides an account of the superimposed layers of sequential language-processing phases involved during interpreting. Christoffels and de Groot propose a hierarchical view of activation, from more global to more local levels (see section 3.1.3). Seeber (2007; 2011; 2017) and Seeber and Kerzel (2012) draw on cognitive sciences and multiple-resource theory to focus on cognitive load; Dong and Li (2020) endeavour to model the relationship between language control and processing control in interpreting. Recent research also relies on neuroscientific accounts of cognition, language control and cognitive control in a bilingual context (e.g., Elmer, 2016; Hervais-Adelman et al., 2011, 2015; Rinne et al., 2000).

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[21] Interpretive theory (French: *théorie du sens*) is a pragmatics-based, pedagogy-oriented approach of interpreting, which suggests that the core of the activity and its main difficulty lies in "deverbalising" the incoming speech, that is, representing units of intended meaning at non-lexical levels, and "reverbalising" it into the target language.

As domain-general cognitive research and research on cognitive aspects of interpreting developed in parallel, the bulk of the literature on interpreting-related cognition deals with accounts of memory and processing capacity. We will therefore start by providing an overview of these findings; Results from studies in the literature regarding control functions specifically will then be reviewed in the next section.

Early SI models (Gerver, 1976; Gile, 1997; Moser, 1978; Paradis, 1994; Setton, 1999) often attribute a central role to memory systems in interpreting, especially WM, and seek to clarify the role of working, short-term and long-term memory, mirroring contemporary research. WM capacity specifically, and its relationship to performance, is the focus of many studies involving interpreters, in line with literature suggesting a crucial role of WM capacity in language comprehension in the presence of additional cognitive demands (Just & Carpenter, 1992). A number of these studies find better performance in expert interpreters versus controls in verbal WM tasks (e.g., Babcock & Vallesi, 2017[22]; Bajo, Padilla, & Padilla, 2000; Chmiel, 2018[23]; Christoffels, de Groot, & Kroll, 2006; Padilla, Bajo, & Macizo, 2005; Signorelli, Haarmann, & Obler, 2012; Stavrakaki, Megari, Kosmidis, Apostolidou & Takou, 2012; Tzou et al., 2012; Yudes, Macizio, Morales, & Bajo, 2013). Other studies show no clear difference between groups (e.g., Köpke & Nespoulous, 2006; Liu, Schallert, & Carroll, 2004) or no better performance with more interpreting experience (Timarová et al., 2014). Other studies focus on verbal memory capacity (e.g., recall of word lists) in conditions of articulatory suppression, as speech production is expected to block the rehearsal process of incoming verbal information (Christoffels, 2006; Christoffels & de Groot, 2005), affecting recall after SI (Daró & Fabbro, 1994). There, findings suggest that interpreters are able to successfully resist phonological interference (Bajo et al., 2000; Padilla, Bajo, Canas, & Padilla, 1995; Padilla, Bajo, & Macizo, 2005; Yudes et al., 2013); In Köpke and Nespoulous (2006), however, an advantage in free recall after articulatory suppression was observed in novice, but not in experienced interpreters.

To some extent, the mixed findings in WM tasks seem to be related to the type of task at hand, that is, whether pure WM capacity was tested (using e.g., simple span tasks) or whether processing and item manipulation was also involved, as in the case of complex span tasks or reading span tasks for instance (Köpke & Signorelli, 2012; Timarová et al., 2014): Interpreters tend to perform comparatively better in the first type of tasks. A meta-analysis by

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[22] The verbal WM advantage does not extend to the other forms of WM tested here.

[23] An interpreter advantage in verbal WM (reading and listening span) was found only for L1, not L2.

Mellinger and Hanson (2019) suggests a working memory capacity advantage in interpreters compared to various other professions as well as a relationship between proficiency in interpreting and working memory capacity. However, this is far from systematic (see Chmiel, 2018). For instance, interpreters seem to better recall nonwords within complex span WM tasks (Signorelli et al., 2012; Stavrakaki et al., 2012) or otherwise perform better in complex span tasks, which involve concurrent operations (Christoffels et al., 2006; Yudes, Macizo, & Bajo, 2011). These contrasting patterns of results runs somewhat contrary to the assumption that interpreters rely on actively maintaining content in WM due to interference as well as processing WM content for example for verbal comprehension. In addition, when better results were observed in interpreters in WM tasks, the setting did not always allow to draw conclusions as to whether SI trains WM generally, or in L2 tasks more specifically due to accrued L2 proficiency (Amos, 2020), or whether individuals with high WM capacity are naturally selected to become interpreters (Köpke & Nespoulous, 2006, actually find a better listening span in novice interpreters than in all other groups; but the results are qualified by the age pattern of the expert group). Studies comparing performance in WM tasks before and after interpreting training (Chmiel, 2018; Nour, Struys, & Strengers, 2019) do not provide a clear answer to that question, though Babcock (2015) and Babcock, Capizzi, Arbula, and Vallesi (2017) report improved performance in simple span tasks. Moreover, an interference-based rather than purely capacity-based view of WM might better account for the highly varied findings in WM tasks among interpreters. The relative ease of processing units of retrievable information commonly referred to as “chunks” (Miller, 1956) may not be so much a matter of number of units that WM can structurally hold (see e.g., discussion in Cowan, Rouder, Blume, & Saults, 2012; see also Seeber, 2011). Strengthened representations that are less sensitive to interference (Morton & Munakata, 2002) can also explain interpreters’ greater reported ease in exercises requiring, for instance, that they remember sequences of letters, when these on occasion form acronyms that the interpreters have become familiar with through the course of their work (e.g., Henrart & Van Daele, 2017).

Additionally, a number of methodological issues have been raised regarding the mixed findings, such as the lack of time constraints (Moser-Mercer, 2010) in comparison to interpreting, as well as issues independent of the testing paradigm, such as sampling and measurement considerations. Interpreting experience, for instance, can be a problematic variable: It can be confounded with age (e.g., Köpke & Nespoulous, 2006; Yudes et al., 2011), which is also a factor and needs to be controlled. Furthermore, as highlighted by

Timarová et al. (2014), experience, when measured in years, may not yield a correct comparative picture of the number of days interpreters have spent on task. The most prevalent sampling issue related to studies on interpreting, however, is sample size, as professional conference interpreters are a relatively small subset of the bilingual population and as such not easy to recruit in sufficient numbers; The problem is compounded when interpreters with a specific language combination need to be recruited for testing (e.g., Christoffels et al., 2006). In addition, the profession counts a majority of freelancers, which does not facilitate recruitment. Even when it comes to testing students, class sizes in this discipline are smaller than in many others.

Beyond the issue of WM per se, the notion of limited processing capacity is central to most accounts of the interpreting process. Gile's Effort Models and the "tightrope hypothesis", which proposes that interpreters mostly work near cognitive saturation, are compatible with unitary resource control and capacity limitation theories, which no longer provide an undisputed account of phenomena that can be explained in terms of interference. However, the intuitive, pedagogical series of models, which describe subjective effort allocation during interpreting, does illustrate the diverse constraints placed on the system in the presence of non- or less automatised processes during comprehension and production. As such, it can be used to helpfully highlight issues related with directionality for instance, (e.g., comprehension constraints in a C language or production constraints in a B language), and the risks of multiplying such constraints. This serves as an illustration of the fact that control, at least linguistic and possibly more generally cognitive, is not required uniformly across interpreting contexts. For instance, Obler (2012) stresses that the strategies developed at various hierarchical processing levels by interpreters to work into different directions are not necessarily interchangeable. Costa and Sebastián-Gallés (2014) recall that the use of a less proficient language recruits more brain areas associated with control, indicating more effortful processing.

Moser's (1978) model introduces, inter alia, an emphasis on processing speed, as the time constraints in interpreting make it a decisive factor when it comes to decisions to correct production for example. The notion of processing speed as a key factor to alleviating the load on short-term memory and allowing decisions based on monitoring is germane to limited resource theories, and the hypothesis that processing speed is of the essence in order to mitigate the effects of the bottleneck in controlled information processing in a dual-task setting (e.g., Dux et al., 2009). However, an advantage for processing speed in interpreting also fits in with other theoretical frameworks and the possibility of underlying factors such as automation (Shiffrin & Schneider, 1977) or pathway strengthening (Cohen et al., 1990). The speed of information transfer between memory systems is also viewed by Christoffels (2006) as a possible candidate underlying successful SI in the presence of articulatory suppression and interference. The issue of processing speed in interpreting is somewhat difficult to delineate, as time management while on task plausibly rests on strategies that are task-dependent to a high extent (see Meyer & Kieras, 1997a). In addition, multiple processes are involved. Speed of lexical access, for instance, which is likely linked to mechanisms such as reduced inhibition (Babcock & Vallesi, 2015), has sometimes been found to be higher in interpreters than in other bilinguals (Bajo et al., 2000; de Groot & Christoffels, 2006; Stavrakaki et al., 2012; but cf. Christoffels et al., 2006; Woumans, Ceuleers, et al., 2015), though this may also depend on the degree of closeness between the task at hand and the skills required in SI (Santilli et al., 2019). It is also suggested that speed of lexical access seems to increase with interpreting experience (Bajo et al., 2000; Ibáñez, Macizo, & Bajo, 2010).

In functional models of SI, Seeber (2007, 2011; Seeber & Kerzel 2012) endeavours to do justice to the multiple constraints placed on SI by competition in real time at various levels, using Wickens's computational multiple resource theory models. Based on the shared resources and structural domains identified, these models formulate specific coefficients for each source of conflict in given activities, allowing for an attempt to quantify the cognitive load associated with it. Seeber (2011), adapting Wickens's (2002) conflict matrix template, identifies the following demand vectors that are shared in interpreting by listening and comprehension processes on the one side and production and monitoring processes on the other: The auditory verbal perceptual vector, and the auditory verbal cognitive vector. A third vector, the verbal response vector, is used only for the production/monitoring component, but it involves the same (verbal) code format as in the perception and cognitive stages of the listening/comprehension component of interpreting; Additionally, the vocal modality of that response vector presents a conflict with auditory processing. While current theories of cognitive control have moved away from a conception of control as a resource or pools of capacity for control, they are evolved from, and remain compatible with, multiple-resource theories (see section 2.2.1.2 & 2.2.1.3) in pointing to interference as the origin of the demand for control. In a study specifically devoted to concurrent multitasking, let us zoom in and attempt an account of those processes involved in SI on which separate, simultaneous demands are placed.

3.2.2 Cognitive processes during interpreting

Interpreters are bilinguals, and interpreting is a specialised form of bilingual language use, but it remains to be seen to what extent it draws on the same control mechanisms and calls on specific ones. This section will review accounts of various processes which are comprised in the interpreting task and investigate their implications in light of the competition and time constraints involved in interpreting. Beyond placing constraints on verbal WM, SI involves the simultaneous perception and production of speech; This requires that attention be switched or divided between languages and between the processes required for input and output (Hervais-Adelman et al., 2014). In a first step, we will look into the separate control demands involved in speech comprehension and production; Then, we will look at the overlap of these processes as well as the necessity of external and self-monitoring, and what that entails for the control processes coming into play.

3.2.2.1 Discourse comprehension

The first subtask of the interpreter is to adequately perceive and understand the incoming message. In a context free of competing inputs, speech perception and comprehension, especially in the L1, have long been assumed to be largely automatic, since hearing, in the same way as vision, is an immediate sense. However, a large number of variables modulate the automaticity of language comprehension, making it more or less easy to combine with additional tasks. Language proficiency is one of them (see Abutalebi & Green, 2007; Vandergrift, 2006). Krizman, Marian, Shook, Skoe, and Kraus (2012) provide a picture of enhanced and more automatic sensory processing (modulated by subcortical changes) in highly proficient bilinguals, associated with improved control functions, suggesting strengthened interaction between sensory and cognitive systems.[24] Language comprehension has been recently, and fruitfully, investigated in terms of top-down and bottom-up processing at various hierarchical levels (see de Groot, 2011; for a comprehensive review, see Amos, 2020). These respective processes also factor in our ability to process speech in noise, and appear to be modulated by language proficiency (Kim, Marton, & Obler, 2019). Fedorenko (2014), in a review of neurological findings on language comprehension and cognitive control, offers as a path for further investigating the idea that networks involved in language

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[24] Similar findings exist in musicians: see section 4.1.1.

processing might support a bottom-up strategy of language comprehension, while control-related networks might allow for a top-down, predictive strategy. Studies (Grüter, Rohde, & Schafer, 2014; Pérez, Hansen, & Bajo, 2019) have investigated proactive and reactive aspects of processing and control during language comprehension in bilinguals. Grüter et al. formulate the "Reduced Ability to Generate Expectations" (RAGE) hypothesis, which suggests different modes of processing between L1 and L2. L1 reading comprehension relies primarily on predictive processing, while L2 comprehension is more reactive and relies on a posteriori integration. Brain activity patterns during L1 and L2 sentence comprehension appear to corroborate this hypothesis (Pérez et al., 2019). It is proposed that reactive control, consistent with a DMC framework, is parsimonious, which makes it possible (or necessary) to rely on this mechanism in the face of high task demands. In a dual-language context, this would imply that an individual can primarily activate the proactive control network during L1 comprehension, but would possibly shift modes to apply reactive control during L2 comprehension instead. Additionally, incorrect predictions during L2 comprehension seem to trigger accrued control (Dell & Chang, 2014), which is thought to reduce future errors by reinforcing the correct prediction. This provides an insight into learning processes through which the top-down activation of accurate predictions can be facilitated.

In interpreters, an eye-tracking study found that interpreters predicted more than translators during an interpreting task (Amos, 2020; Amos, Seeber, & Pickering, 2022), suggesting more top-down processing in that group; However, the prediction pattern of interpreters did not appear to change with training, which could suggest either that top-down processing is modulated primarily by language proficiency, or that a high ability to predict (Pöchhacker, 2011), and possible domain-general tendency to resort to proactive control, may be part of the non-linguistic qualities, which facilitate the acquisition of interpreting skills (and success in entrance exams).

It appears from the above insights that in monolinguals and highly proficient bilinguals, top-down, a priori control processes are activated that also allow for efficient prediction of the incoming content. In an interpreting context, this is crucial, as the necessity to remain temporally close to the speaker and syntactic differences between languages sometimes makes anticipation (i.e., the rendition of content in advance of its confirmation) necessary (Seeber, 2011). Predicting linguistic content with a degree of certainty activates the corresponding representations prior to its utterance in the incoming speech, and interpreters can therefore prepare – and sometimes produce – their rendition on that basis. The ability or ease to do so is dependent on a number of factors, notably language proficiency, possibly explaining the differences that appear depending on directionality (Chmiel, 2021). Additionally, the absence of anticipation will lead to higher cognitive load in the presence of a mismatch between syntactic structures (Seeber, 2011; Seeber & Kerzel, 2012). While interpreters thus likely rely on top-down processing of the incoming auditory material to some extent (see, e.g., Vandepitte, 2001; van Besien, 1999), certain elements of discourse may tend to elicit more spontaneous reactions, like cognates (see de Groot, 2011), or cannot be anticipated and rely on bottom-up processing; This appears to be the case for instance with numbers (Mead, 2015b), which furthermore are not redundant and therefore give the listener only one chance for processing (see Korpal & Stachowiak- Szymczak, 2020; Seeber, 2015a).

If bilinguals need to flexibly shift between control modes, this is even more the case in interpreters, who check their own product against the original, especially when content has been anticipated.[25] This is necessary in order to verify predictions, but also at times when the speech is less predictable, such as the beginning of new sentences. For interpreters, the risk of missing the beginning of a sentence because they are still engaged in rendering the end of the previous one is well known: In most cases, the beginning of the new sentence does not so much interfere with the retrieval of the previous content as it is, actually, less attended to. This is highly consistent with Chernov's (1994) predictions, as he proposes that anticipating the original speech allows interpreters to focus on their production and to plan it efficiently. It is highly likely that top-down processes engaged in producing the end of the previous sentence on the basis of memorised content make the system less receptive to new content. Therefore, for successful interpreting, overreliance on proactive control is not a reliable strategy. In a DMC framework (Braver, 2012), reactive control facilitates newly emerging associations to inform task goals. It is likely, therefore, that interpreters also rely on reactive control to acquire context elements that are then going to inform their representation of the speech and the subsequent sentence- and supra-sentence-level predictions. Chernov (2004) highlights how context integration facilitates production by testing interpreters using highly contextualised, meaningful sentences in comparison with syntactically coherent, but meaningless ones and finding that the latter could not be successfully interpreted. Keller (2018), in a compelling break-down of interpreters' focus of attention while on task, underlines that interpreters, while attending to the incoming and outcoming speech streams,

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[25] In addition, written speeches require "checking against delivery", meaning that interpreters need to check the visual input against the actual speech as the manuscript was sent to interpreters prior to the speaker's intervention and may have been further modified.

also maintain an evolving mental representation of the speech (e.g., Kintsch, 1988; see also Seeber, 2015a), which is continuously updated with new elements (including contextual) and can be used to anticipate future content, as well as informing their output (Kohn & Kalina, 1996). The role of preparation, on which interpreters rely to familiarise themselves as much as possible with the subject matter of their assignment, also needs to be highlighted, as it increases the availability and relative importance of active knowledge in processing the incoming speech (see, e.g., Johnson & Kieras, 1983) and may therefore foster top-down processing and proactive control rather than reactive control mechanisms. Interpreters can only rely on a partial mental representation of the speech, as they need to start their own production earlier than a natural context would allow (Seeber, 2015a). It can be assumed that interpreters less proficient and/or less confident in how well they understand a given L2 will rely more on such top-down mechanisms to help them recognise the incoming linguistic forms, whereas in interpreters more proficient in their L2, the demands of the task will also foster more flexibility in the interplay between processing modes, stronger bottom-up reliance on the incoming speech and more parsimonious, reactive, control mechanisms.

Indeed, the influence of context – and perhaps of control signal modulation – for speech comprehension may be observable. As regards the association between language comprehension and WM, recent insights into speech retrieval from memory are modifying the way verbal WM and its interactions with other memory systems is conceptualised. Interference-based rather than capacity-based theories of memory offer promising avenues to operationalise the assessment of memory cost under various conditions of contextualisation: Campanelli, Van Dyke, and Marton (2018) propose a framework that reconciles retrieval-based and expectation-based accounts of discourse comprehension by showing that expectation modulates the retrieval of content. An empirical paradigm, allowing to manipulate the degree of predictability of items in complex sentences, suggested that predictability modulates the retrieval of expected, that is, preactivated words, against competitors. Such a paradigm could be adapted to oral comprehension and used to investigate differences as well as variations in control demands between monolinguals and bilinguals, between languages as a function of the degree of proficiency, and between interpreting contexts.

3.2.2.2 *Production*

As we have seen, when it comes to isolating the control processes at play during SI, it is hardly possible to entirely separate the constraints placed on comprehension from those placed on production, as they are informed to a large extent by the necessity to attend to both. In addition, it is necessary to take the bilingual context and the issue of relative language proficiency into consideration. It is plausible that language comprehension and production do not rely on entirely separate systems, but that they depend on shared mechanisms (Pickering & Garrod, 2013); This view is consistent with common coding theories and internal modelling of interpersonal action, which we will explore more in depth in relation with motor control (Section 4.2). Thus, prediction during interpreting can also be part of the production process itself and might be possible in a between-language setting (Amos & Pickering, 2019).

Wide-ranging findings support the idea that speech production involves domain-general control processes (see Fedorenko, 2014, for a review). In a context of competition between two active language systems required to perform a task, as in the case in interpreting, production is even more constrained. In a recent study, Van Paridon, Roelofs and Meyer (2019) compared errors in interpreting and shadowing at various speeds (speech rates), to find a significantly higher number of errors in the interpreting condition regardless of the speech rate as well as a greater sensitivity to the speech rate in that condition. The authors suggest a bottleneck at the level of lemmas (i.e., semantic-syntactical representations of words), accounting for the impossibility to select one for both production and comprehension simultaneously. However, rather that suggesting a bottleneck in central attention, this last idea is also consistent with a shared-representation account (e.g., Feng et al., 2014). It would appear logical that semantic representations are shared between languages in a parsimonious environment. The same behavioural phenomenon would be observed, in that the system would enforce seriality in the processing of the same lemma for comprehension and for production. The results observed by Van Paridon et al. are not inconsistent with the fact that paraphrasing is intrinsically difficult regardless of whether the target language is different from the source language or not, and actually tends to be more difficult when that is not the case (Christoffels & de Groot, 2004).

Regarding control mechanisms underpinning speech production, it is suggested that domain-general top-down processes influence the language system proactively (Strijkers, Holcomb, & Costa, 2011; Strijkers, Yum, Grainger, & Holcomb, 2011). In ERP studies investigating lexical access (measured using word frequency in naming tasks and non-verbal object categorization), the authors found that the conscious intention to name an object appears to allow for faster lexical access by pre-activating the lexical system through top-down, domain-general signal modulation before the activation of concept-to-word relationships. Thus, intentional mechanisms, related to the task goal, enhance activity in task-relevant representations, consistent with proactive control mechanisms.

While speech production, when constrained in content, is likely to call for proactive rather than reactive control mechanisms, in interpreters, the simultaneity with comprehension processes is likely to lead to the automatic treatment beyond articulatory processes (see Eichorn & Marton, 2015) of strong language representations (see Hartsuiker & Moors, 2016), which may be the case with interpreting where production occurs in an active, that is, highly proficient language. In that case, interpreters may rely on the less demanding, case-by-case activation of reactive control. It would be triggered when their self-monitoring detects incongruencies between the produced sounds and expected speech output.

A prevalent hypothesis regarding bilingual language control is that both language systems are activated simultaneously in bilinguals regardless of the context (see section 3.1.); Many studies support the idea that it is the case at least in a dual language context (for a review see Friesen, Whitford, Titone, & Jared, 2020). Additionally, in interpreters, speech comprehension and production overlap, creating interference and possibly conflict with common mechanisms of language inhibition in bilinguals. The possible implications that this specific experience may have on how interpreters exert control outside of interpreting is explored in the sub-section below.

3.2.3 Strategies and control mechanisms in interpreters

In recent years, the literature has stressed how diverse the bilingual experience can be, tapping and possibly fostering diverse control mechanisms. Green and Abutalebi's (2013) Adaptive Control Hypothesis (see section 3.1.2) highlights three overarching scenarios for language use, in a single-language, dual-language, or dense code-switching context. The case of SI, where the source and target language are maintained active in parallel and for two distinct purposes, comprehension versus production, is not taken into account. In addition, the competition between input and output control through the same auditory channel (see, e.g., Reinfeldt, Östli, & Håkansson, 2010) is constrained by structural conflict.

A few studies have focused on interpreters' capacity to attend to parallel stimuli. Hiltunen, Pääkkönen, Vik, and Krause (2014) tested four groups: Conference interpreters, "consecutive interpreters", that is, community interpreters mostly working in environments with less stringent simultaneity requirements, language teachers, and non-linguistic experts, that is in that case, persons who did no use a L2 in their professional life and at a professional level.[26] Though the specific bilingual experience of the groups was not delimited in absolute terms, the study found clear differences in the SI group in a shadowing task involving dichotic listening (the "cocktail party test": Conway, Cowan, & Bunting, 2001), where SI interpreters and non-linguistic experts detected their name significantly more often than other groups (and more in line with expectations in that task paradigm) when it was mentioned in the irrelevant channel, but interpreters still made no error in shadowing the relevant channel following that detection. These results can be interpreted as pointing to better divided attention in SI interpreters, as well as a heightened capacity to resist interference even when it is not proactively suppressed. However, in an ERP study of irrelevant stimuli during interpreting, Koshkin, Shtyrov, Myachykov, & Ossadtchi (2018) found that interpreters seem to attend less to distractor stimuli under high WM load. This effect, suggesting more selective attention and proactive suppression of interference, was observed regardless of the directionality (within a language pair). Interpreters' coordination abilities while dual-tasking were studied by Strobach, Becker, Schubert, and Kuhn (2015) and Becker, Schubert, Strobach, Gallinat, and Kuhn (2016). In the first study (Strobach et al., 2015), a dual choice time-reaction task was comprised of auditory stimuli (tones of three different frequencies) on the one hand, and visual stimuli (triangles of 3 different sizes) on the other, presented at varying SOAs, with interpreters responding with either hand depending on the task. Interpreters were found to perform faster than controls in single- and dual-task conditions, especially at the shortest and longest SOAs, showing a speed of processing advantage associated with a dual-tasking advantage attributed to more efficient processing at a central stimulus-response mapping stage (Musslick & Cohen, 2019, propose that the phenomenon is underpinned by reduced persistence of the previous task representations in conflicting networks, in this case, motor-response networks). In the second study (Becker et al., 2016), these findings were related to neural volume and processing differences in areas thought to be associated to the monitoring and integration of subgoals in an overarching task (the left Frontal Pole Cluster).

During interpreting, updating task-related content is necessary: It is essential for interpreters to keep abreast of the new units of meaning provided by the speaker and bind them as quickly as possible to previously heard and processed content, sometimes informing their understanding of what has already been said and prompting clarification. Empirical findings seem to suggest that interpreters as a group may benefit from their activity when it comes to training general updating abilities. Henrard and van Daele (2017) used a letter memory task to

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[26] This last choice is probably due to the difficulty of finding actual monolinguals, without any knowledge of a second language, in Finland.

test updating/monitoring; Interpreters performed better than translators and controls, though the authors caution that the effect in that specific case is difficult to disentangle from a possible memory advantage in processing letter sequences. Morales, Padilla, Gómez-Ariza, and Bajo (2015) found an interpreter advantage in updating skills in single- and dual-task conditions. They used a single and dual *n*-back task paradigm (Jaeggi et al., 2007) using visuo-spatial cues and simultaneous auditory cues requiring manual responses. The task was administered twice, as a (practice) 0-back, 1-back, 2-back and 3-back in the single and dual condition. Interpreters performed better than multilingual controls in both blocks and all conditions of the single task; In the dual task, interpreters performed similarly to controls in the first block and better than the controls in the second block in the 1-back and 2-back conditions. The results suggest better updating abilities in interpreters, and a better adaptability of these updating abilities to a multitasking situation. However, Van der Linden, Van de Putte, Woumans, Duyck, and Szmalec (2018) did not find any difference between interpreters, bilinguals and monolinguals in a letter 2-back with interference from proactive and reactive lures (see also Wadhera et al., 2018).

A number of studies have sought to investigate cognitive control in interpreters using EF tasks. The idea that interpreting does not foster inhibition seems to be supported by behavioural findings. Köpke and Nespoulous (2006) found no advantage for experienced or novice interpreters over multilinguals or monolinguals in a Stroop task; Yudes et al., (2011) found that interpreters did not perform better than monolinguals and bilinguals in the Simon task; Morales, Padilla et al., (2015) found no advantage for interpreters against bilingual controls in the ANT task; Woumans, Ceuleers, et al. (2015) found no advantage for interpreters over balanced bilinguals in a Simon task or ANT, and no difference between interpreters, bilinguals (L2 teachers) and monolinguals in an advanced Flanker (Flanker and Go/No-Go) task; Babcock and Vallesi (2017) found no advantage for interpreters over matched multilingual controls in a Stroop task or ANT; Van der Linden et al. (2018) found no advantage for interpreters over monolinguals in the Flanker and Simon tasks. Keller, Seeber & Hervais-Adelman (2020) compared student translators and interpreters in a bilingual Stroop task prior to SI training and re-tested the groups after 1 year, during which the interpreting students had received SI training[27], and found no group differences in both runs. The absence of a specific effect on inhibition as a result of interpreting training makes sense, since two languages are actively used at the same time and do not compete in the same modality (see

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[27] One year of SI training is a widespread practice in many Masters' programmes at EMCI Universities for instance (see www.emcinterpreting.org).

also Ferreira et al., 2020). Henrard and van Daele (2017) set out to test for different types of inhibition, in particular resistance to proactive interference. They used a battery of EF tasks analysed in Friedman and Miyake (2000, 2004) and including a prepotent response inhibition task (Antisaccade), as well as a task tapping resistance to proactive interference (Brown Peterson task; See Appendix A). They compared three groups comprised of 60 interpreters, translators and monolinguals each, aged 25 to 65. Interpreters performed faster but also better than the other groups in the Antisaccade task; Regarding RT differences, it should be pointed out that interpreters were significantly faster in simple reaction-time tasks and that this may have also translated into a processing speed advantage in the Antisaccade task. However, interpreters also significantly outperformed both other groups in terms of accuracy, while there was no difference between translators and monolinguals. The authors suggest that the increase in performance may be linked to the necessity for interpreters to sort out the most relevant information in the source speech under time pressure and separate it from elements that can be omitted if needed. This may provide interpreters with an added edge in inhibiting a prepotent response. Resistance to proactive interference was better in bilinguals than in controls, but better still in the interpreter group than in bilinguals, indicating an accrued effect of the interpreting experience. It should be stressed, however, that the experimental task was different from the Friedman and Miyake (2004) variant in that participants in Henrard and Van Daele's study had to remember three visually presented consonants, perform an unrelated interfering task such as digit inversion and recall the letters after various time intervals. Proactive interference is therefore tested in this specific paradigm only to the degree to which letters are reintroduced in ulterior lists, but mental associations can be created between the three consonants to facilitate recall (especially in a profession often faced with acronyms) and the interpreters' advantage could be linked to better management of articulatory suppression. The authors themselves suggest a possible advantage for interpreters in keeping letter sequences in memory. Additionally, the effect of age was significant in the various tasks; Differences between groups were non-significant for 25–34-year-olds, hinting at the possibility that advantages in tasks tapping executive control appear later in life. Hiltunen et al. (2014), looking at error types during a free recall exercise (based on Unsworth & Engle, 2007), found that SI interpreters' better recall performance was also associated with a distinct error pattern. While intepreters working only in consecutive made less errors related to intrusions from irrelevant words presented on the recall list, SI interpreters had less intrusions from previous lists and more repetitions. Repetitions may be reminiscent of "stalling" strategies (see Setton, 1998) used by interpreters as they wait for new content they can use for production. The pattern regarding previous-list intrusions once again points to a tendency in interpreters to better resist proactive interference, which can be linked to the ability to both successfully update and then maintain task representations.

Babcock and Vallesi (2015) sought to investigate inhibition of proactive interference specifically by looking at lag-2 repetition costs in various types of bilinguals. Babcock and Vallesi compared students untrained in SI, students slightly exposed to SI but only a couple of months into their training, trained students not yet practicing, and trained and practicing graduates. They used a specifically designed task-switching paradigm and a language-switching paradigm requiring participants to use their L1, L2 or L3. No difference was found in terms of lag-2 repetition costs for the task-switching paradigm, or the L3; However, one group (students having just completed their SI training) differed from the others in the language-switching paradigm involving the L1 (with higher lag-2 repetition costs) and L2 (with reduced costs). This group also differed from the others in its (higher) self-reported L2 proficiency. The results are difficult to explain with regard to the specific bilingual experiences compared here, but make sense with respect to variations in language proficiency (see also e.g., Blumenfeld & Marian, 2013; for a review and analysis see Bonfieni, Branigan, Pickering, & Sorace, 2019). They could also be linked to the fact that lag-2 repetition costs do not so much reflect reactive inhibition as they can be attributed to an excess of proactive control or a lack of reactive control when seeking to maintain the "new" goal representations against the backdrop of interfering previous ones. In that case, lower lag-2 repetition costs are indicative of more flexibility in updating task representations, something which could be further investigated by distinguishing between post-error and pre-error RTs. This would suggest that control strategies as applied to language-related tasks are modulated by language proficiency.

Although interpreters seem to show no signs of a specific edge in the forms of inhibition that tap reactive control and results are not unequivocal regarding the (proactive) maintenance of task representations for inhibition purposes, other differences were highlighted between interpreters and other groups, which may shed light on control mechanisms predominantly used in that group. In switching tasks, diverging results were reported. In Henhart and van Daele's (2017) comprehensive study, both bilingual groups performed similarly or better than monolinguals in the plus-minus task, but there were very strong variations within the interpreter group, suggesting a wide array of performances and possibly reliance on different strategies. Keller, Hervais-Adelman and Seeber (2020) found a general slowing in a verbal task-set switching task (trilingual naming task) after a year of SI training. This phenomenon, also observed in bilinguals by Prior (2012) in a task requiring shifts between responding to shape or color, might be indicative of a global proactive strategy. Babcock and Vallesi (2017) investigated the control processes involved in task switching in more depth, by differentiating between local (i.e., switching) costs and global (i.e., mixing) costs. They did not find any differences between professional interpreters and multilingual controls in switching cost (the difference between RTs in repeated trials and in trials after switching) but found smaller mixing cost (the difference between RTs in repeated trials in mixed blocks and trials in single-task blocks) in interpreters. The authors suggest that this reflects better global, that is, sustained control, and no difference in local, that is, transient control in interpreters. Sustained control involves the proactive maintenance of task sets, while transient control relies on reactive adjustments with each trial. Thus, SI training seems to correlate with improvements in measures reflecting proactive control. However, Yudes et al. (2011) tested interpreters, bilinguals and monolinguals using the Wisconsin card sorting task (WCST) to measure flexible set-shifting, in other words, the capacity to adjust to rules provided by external cues (indications of errors).[28] While the same groups showed no difference in the Simon task, as we saw earlier, they did so in the WCST, with interpreters outperforming the other groups. This suggests that interference suppression is not specifically trained in interpreters over other bilinguals, but that they are adept at flexibly adapting to external cues. This would be consistent with reliance on monitoring and error correction, which are processes related to reactive control. This is supported by an ulterior study by Yudes et al. (2013). The authors investigated error detection while reading aloud and found that interpreters performed better, detecting more errors and more semantic errors. These differences were still significant when the group's better performance in a WM (reading span) task was controlled for. Interpreters also showed better global comprehension. Thus, interpreters, while probably relying to some extent on proactive mechanisms, which allow efficient sentence prediction, apply reactive mechanisms to detect errors more flexibly than other groups.

Seeking to cast light on the processes underlying performance beyond behavioural differences between groups, Dong and Zhong (2017) used an ERP paradigm to investigate performance in the Flanker task in novice and advance interpreting students: Though little or no behavioural difference was found between the groups, more experienced interpreter participants show larger (stimulus-related) N1 amplitudes, suggesting that participants with

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[28] It should be noted that the WCST is not a pure measure of switching ability as the task includes inhibition and WM requirements, and that it does not distinguish between errors of various origins (Marton et al., 2017).

interpreting experience show enhanced early attentional processing and monitoring. Additionally, larger N2 amplitudes were also recorded in interpreters, suggestive of higher monitoring in that group. Reduced later P3 amplitudes in the same group in incongruent conditions suggested less stimulus-response activation, a finding that presumably reflects that more control is exerted (see Asanowicz et al., 2020). This pattern of stimulus-related observations does not allow us to draw conclusions on proactive control mechanisms but it is indicative of enhanced reactive control with more interpreting experience.

To sum up the empirical findings described above, many of the traditionally used paradigms, notably when it comes to testing inhibition, do not reveal any difference between interpreters and other bilinguals. A slowing effect of age is reported in numerous studies, however, including in interpreters. This tends to support the idea that changes in executive control induced by interpreting might be highly specific to processes involved in the activity itself (García, 2014; Santilli et al., 2019). The presence or absence of inhibition does not imply the presence or absence of one specific control mode: Rather, the partial overlap between inhibition and the common EC factor (Friedman & Miyake, 2012), which in turn reflects goal maintenance in the PFC, bears testimony to the fact that goal activation and maintenance underpin the various functions through which cognitive control is observed. However, it appears that interpreters rely to some extent on proactive control mechanisms, but also differ from bilinguals in their reactive control mechanisms, even though these findings may be qualified by the fact that some of the longitudinal-design studies test interpreters very shortly after training. Insights with regard to the possible effect of the exposure to interpreting training is provided by Rosiers, Woumans, Duyck, and Eyckmans (2019), who found no differences in tasks reviewed above between students at the start of an interpreting Master's, a translation Master's, and a multilingual communication Master's. The authors used the Simon task, ANT, Colour-shape shifting task and a 2-back task using shapes that could be easily named and verbally rehearsed. No advantage for the interpreter group was found either in simple (forward) and complex (backward) digit span tasks. While the study only looks at students of a particular institution and at a unique point in time, it challenges suggestions of specific executive function predispositions to study interpreting and instead suggests that training and experience modulate the group differences observed elsewhere. However, to further investigate this claim, one should look at whether the students did in fact become interpreters, and comparisons could be made with interpreting programs requiring aptitude testing for admission. Hervais-Adelman et al. (2014) note that interpreting calls on both transient and more lasting modes of control. The DMC framework (Braver, 2012; Braver et al., 2007) is a compelling candidate to accommodate that idea while also showing compatibility with the role proposed for the ACC network for instance by Botvinick (2007) and Feng et al. (2014). The self-monitoring component of SI (Hervais-Adelman & Babcock, 2019), for instance, is probably associated with exertion of reactive control.

Among the increasing number of neuroscientific articles and reviews that have been published of late on the topic of interactions between linguistic and cognitive control in bilingual populations (see section 3.1.1), some deal specifically with interpreters (e.g., Hervais-Adelman & Babcock, 2019; Ferreira et al., 2020; García, Muñoz, and Kogan, 2019; Van de Putte et al., 2018). We will attempt to provide an overview of salient issues. Reviews insist on recurrent methodological issues, like task impurity and validity concerns, or the difficulty to account for differences across the interpreter population (Ferreira et al., 2020; García et al., 2019), as well as limitations inherent to fMRI and other imaging paradigms[29], and unresolved questions regarding the interpretation of increases or decreases in cortical volume (Hervais-Adelman & Babcock, 2019).[30] From an extensive review, García et al. (2019) conclude that interpreting training appears to foster rapid response, but highlight the domain-specificity of interpreters' demand management abilities, arguing that verbal and executive mechanisms might not entirely overlap. The authors stress, however, that the intensity of the demands related to various bilingual contexts modulate domain-general improvements beyond AoA or proficiency. They also suggest that interpreters seem to be able to flexibly manage their attention between divided and focused mode on the basis of current demands, though further research on that aspect is needed. Additionally, supporting the idea that interpreting requires different components based on directionality, neuroimaging studies highlight differences between SI into the A or the B language in neural activation overall and in specific parts of the brain (Elmer, 2016; Rinne et al., 2000; for a review see Hervais-Adelman & Babcock, 2019). Hervais-Adelman and Babcock identify a network of regions where studies have consistently noticed activation during SI. One is the left interior frontal cortex, which has long been identified as a region of interest for language comprehension, analysis, retrieval and production, and which seems to show greater activation during SI than other tasks involving language processing. The right cerebellum is also included, which in addition to grammar

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[29] Other limiting factors can be identified, such as the necessity to employ region-of-interest approaches which, though justified, by definition do not yield a complete and continuous picture of activation patterns.

[30] This last question is not without similarity with, and may be related to, the issue of interpreting neural efficiency and increases or decreases in activation in given brain regions or pathways.

processing functions has been suggested to participate in action control together with the basal ganglia (Hervais-Adelman et al., 2014, 2015). Articulatory preparation appears to be served by the left premotor cortex and anterior insula. Studies carried out on interpreters with several years of experience suggest that areas highlighted during SI in novices (such as the right caudate nucleus and cingulate) and less activated after training are not involved anymore, presumably because the language control processes they are thought to subserve are not required any longer, reflecting greater automaticity. Hervais-Adelman and Babcock derive from the existing findings a neurocognitive model of SI, which builds on the bilingual control models by Calabria et al. (2018) and Stocco et al., (2014) mentioned earlier (Section 3.1.3), which encompass circuits underpinning domain-general cognitive functions. While a thorough discussion of the various proposals far exceeds the scope of this study, it is interesting to point out a few elements that feature prominently in the literature on cognitive control. The caudate and putamen are part of the basal ganglia, which according to the PBWM model (e.g., Chatham et al., 2011) are central to a gating mechanism that allows to selectively lift inhibition and select and update active representations in the PFC. In complex tasks, this is crucial for the hierarchic processing of subgoals while maintaining higher-order goals (see also Chiew & Braver, 2017). In addition, Hervais-Adelman and Babcock's model includes two distinct control networks, for transient, moment-to-moment control on the one hand, and the sustained management of task-related demands on the other, though ACC function in that model is centrally associated with both putamen and caudate functions, which each subserve the respective networks.

To conclude, transient activation is more efficient in automated tasks requiring little processing, and presumably in the face of dual-task demands whenever possible, making reactive control a good candidate to serve successful interpreting in experienced professionals. A number of processes, especially motor-related aspects, seem to become automatised with increased interpreting expertise (Hervais-Adelman et al., 2015), leaving fewer shared representations activated. However, interpreters seem to also rely on sustained, proactive control, mediated by goal maintenance, which keeps task representations activated and leads to the on-purpose engagement of effortful processing – and possibly of shared representations. The strengthening of a hierarchical structure for the interpreting task, with flexibly managed subgoals and a flexible engagement of shared representations might thus foster task integration.

Breaking down a complex task involving simultaneous processes is especially difficult as the context – concurrent processing – can hardly be dissociated from the content (actual processes involved) – not least, because an intricate hierarchy of processes is likely involved (Cohen, 2017). This is why the present study on concurrent multitasking processes involves two separate groups of expert multitaskers and attempts to break down their respective complex tasks. The comparison seeks to highlight domain-specific processes on the one hand, and potential domain-general commonalities arising from concurrent processing on the other hand.

4 Control processes and multitasking in conductors

In the same way as interpreters are multilinguals who are additionally used to working with languages in the context of a specific activity that shapes their specific experience, conductors are musicians who have also specialised in the activity of conducting ensembles. The overwhelming majority of conductors were highly proficient instrumentists first (Merlin, 2012; see also Salonen, 2013). Conductors' musical experience as a group is therefore far from homogeneous. However, part of that experience, such as a curriculum including music theory and ear training, and the practice of ensemble music, is common to all professional musicians, barring rare exceptions.

Research in musicianship has blossomed later than research in bilingualism. However, scientific interest in musicians' cognition and brain functions has sharply increased since the turn of the century (e.g., Patel, 2003; Peretz & Zatorre, 2003). The debate on whether the bilingual experience may influence domain-general control mechanisms is ongoing (e.g., Keller et al., 2020; Titone et al., 2017; see section 3.1.1). The possible effect of musicians' experience on control processes specifically remains less explored than bilinguals' linguistic experience on their control processes. In addition, much is yet to be discovered regarding control mechanisms during musical performance itself. In bilinguals, the reactive control mechanisms associated with conflict monitoring and resolution are widely perceived as essential for language processing (see section 3.1.3). In contrast, the mechanisms underlying music processing are different; Given the prominent role played by "anticipation", or prediction (for a detailed review see Huron, 2006), music processing likely relies on proactive control to a major extent.

This study draws from a set of cognitive control theories (based inter alia on Botvinick et al., 2001), which were presented earlier (see section 2.3). We will use a concrete example in order to give a short and schematic account of what these theories suggest in a musician's case:

A pianist is preparing to play a piece that she does not know by heart, the score opened before her. Her prior knowledge of that piece and the experience from the previous performances influence her idea of the performance she strives to give. This includes, for instance, an evaluation of her declarative and procedural memory of the piece and of the level of difficulty she anticipates. This evaluation also depends on her state of mind as she sets out to play. Such task representations inform the level of control that her brain is proactively ready to exert

(DMC: Braver, 2012; Braver et al., 2007) to influence the relative strength of the different neural pathways needed to perform the task. Control is considered to be an emergent property of the cognitive processes at hand (e.g., Botvinick & Cohen, 2014; Cohen, 2017; Feng et al., 2014), and therefore is not thought to materialise by itself. However, let us imagine that there were a "control specification" switchboard with a choice of pathways relevant to the task and levels increasing from 1 to 5, and that the control signal were set on 2 in specific pathways.

The pianist starts playing, focused on ever incoming bars of music. As she performs the piece, however, the emergence of conflict – signalled in her brain just before or after errors – indicates the need to adjust the current control signal (Botvinick et al., 2001, 2004; Botvinick & Cohen, 2014; Yeung et al., 2004). Where applied, control will force seriality on shared representations that are engaged on two different accounts and may lead to slowing (multitasking vs. multiplexing: Feng et al., 2014; Musslick et al., 2016). Taking these aspects into account, control will be adjusted based on a cost-benefit analysis of applying more or less control to the task being performed (EVC: Shenhav et al., 2013). On our imaginary switchboard, this may require moving the level of control up to 3. This reactive adjustment (DMC, Braver, 2012; Braver et al., 2007) will have an influence on the continuation of the task, and subsequent conflict signals may require further fine-tuning and adaptation of the control signal, while also taking the effect of previous adjustments into account (Yeung et al., 2004). In the case of our pianist, reactively adjusting the intensity of the control signal while on task might lead to disruptions in a performance that is complex and continuous and relies on the smooth execution of anticipated complex motor sequences. Hence, we suggest that she may tend to rely more on proactive that on reactive control, so that the signal can be adjusted ahead of incoming music segments. This section endeavours to explore this assumption.

4.1 Representation maintenance and response planning in musicians

Humans have engaged in music (making and listening) from very early on (see e.g., Higham et al., 2012). Music processing relies on many components and engages the brain – including its more primitive structures – in an almost global manner (Fitch, 2006; Levitin, 2012; Peretz & Zatorre, 2005). Therefore, it involves regions and functions that underpin a vast number of other tasks. There are thus many possible directions for the search for specific influences of music processing on cognition; but that also makes it difficult to identify specific associations between music-related and other processes and to pinpoint their directionality (see Corrigall, Schellenberg, & Misura, 2013). For instance, when we listen several times to the same two musical pieces played in a row (e.g., tracks on a music album), we can usually hear the start of the second one in our mind after the end of the first; An fMRI study of this phenomenon finds that the brain activity associated with learning sound sequences is similar to motor sequence learning, pointing to common predictive mechanisms (Leaver, Van Lare, Zielinski, Halpern, & Rauschecker, 2009).

The present study examines active practitioners of music, who are additionally able to form mental representations of the musical structure of a piece, like the progression of harmonics, and to retrieve such representations when reading music (Lechevallier, Rumbach, & Platel, 2010). Music training and music making involve the processing of information at the auditory, motor and cognitive level (Morazadeh et al., 2015; Schlaug, Norton, Overy, & Winner, 2005). There has been interest in potential near-transfer (e.g., to language or auditory processing) or far-transfer (e.g., to executive functions) effects of music training and experience (Amer, Kalender, Hasher, Trehub, & Wong, 2013; Besson, Chobert, & Marie, 2011) on domain-specific or domain-general abilities (Schlaug et al., 2005).[31] It should be kept in mind, however, that – just as in the case of the multiplicity of bilingual experiences mentioned above – individuals' specific musical experience can vary greatly and is, therefore, a major factor accounting for individual differences between musicians (see e.g., Furuya, 2017; Merrett, Peretz, & Wilson, 2013 for reviews). In this thesis, the focus lies on control functions, especially as related to the completion of complex tasks. We will, however, need to touch upon a number of other cognitive abilities first in an attempt to provide a more complete picture of how musical experience intersects with the way the brain is engaged in a task.

4.1.1 Musicianship and cognition

Cognitively speaking, many skills are required to perform music, like reading and translating a symbolic system (notes on a score), retrieving musical pieces from memory, or improvising on the basis of established patterns. In addition, these skills are used to perform fine and rhythmically precise motor sequences, relying on multisensory feedback and monitoring (Moradzadeh, Blumenthal & Wiseheart, 2015). Most accomplished musicians past a certain degree of proficiency have gone through formal training. They have learnt music theory, which is a corpus of rules for the organisation of music, comparable to grammar and syntax

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[31] It should be noted that for all the frenzy around a "Mozart effect", that is, a lasting effect of passive music exposure on cognitive functions, there is little evidence for it (for a review see Okada & Slevc, 2020), although there are substantive findings on the effects of listening to music on the regulation of emotions (e.g., Schellenberg, 2006).

for language, and they have learnt sight-reading. Sight-reading calls for activating the knowledge of these rules to correctly interpret the pitch and duration of the notes depending on the meter and key to anticipate and perform the musical piece (Schlaug et al., 2005); at the same time, other parameters must be taken into account, such as indications regarding technique and expression and the context of the given composition.

Musical training – involving, more often than not, the practice of an instrument – usually starts during childhood.[32] The overwhelming majority of professional musicians have started playing at an early age. In the same way as bilingualism, musicianship has been the object of focus primarily for its possible incidence on development (e.g., Hannon & Trainor, 2007; Miendlarzewska & Trost, 2013). Therefore, a vast body of literature deals with the links between musical training and the development of specific individual traits as well as the acquisition of other competences. There is abundant literature on the structural and functional differences between musicians' and non-musicians' brains, and the changes attributed to musical training are evidenced by longitudinal studies as well as cross-sectional comparisons (see reviews in Herholz & Zatorre, 2012; Merrett, Peretz, & Wilson, 2013). Functionally, musicians have better connectivity between and within brain hemispheres (e.g., Leipold, Klein, & Jäncke, 2021) and greater white matter integrity later in life (e.g., Andrews et al., 2021). Structural differences include differences in primary motor area representations thought to allow more efficient motor control in musicians (see Münte, Altenmueller, & Jaencke, 2002), but also in frontal cortex functions (Tillmann et al., 2006) and in areas associated with executive functions (Sluming et al., 2002).

The practice of music is also associated with cognitive benefits. For instance, early music training (one year or less of lessons in children 8 years old or younger) has been linked to general IQ and improvements in certain intelligence components (Shellenberg, 2004, 2006; cf. Schellenberg & Moreno, 2010) among other cognitive abilities (see Okada & Slevc, 2020 for a review), as well as increased processing speed (Bugos & Mostafa, 2011). Musical training is associated with facilitated language processing in children (Moreno et al., 2008) and adults (Wong, Skoe, Russo, Dees, & Kraus, 2007), as well as better verbal memory (e.g., Jakobson, Lewcky, Kilgour, & Stoesz, 2008). In particular, rhythm is thought to play a role in the transfers from music to language processing (Shahin, 2011). Rhythmical abilities have been isolated as factors in the acquisition of reading skills (Gordon, Fehd, & McCandliss,

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[32] In most countries, formal curricula and training in music theory at music conservatories usually start on average at 6-7; Programs and classes of musical initiation and instrument playing are offered for younger children (see e.g., DESTATIS, 2017).

2015; Strait, Hornicker. & Kraus, 2011). Musicians also have an increased ability to selectively attend to and distinguish speech in noise (Parbery-Clark, Skoe, & Kraus, 2009; Strait & Kraus, 2011; Strait, Parbery-Clark, Hittner, & Kraus, 2012; Yoo & Bidelman, 2019) and appear to owe this at least in part to their better rhythmical competence (see review in Slater & Kraus, 2015). This selective listening ability also draws on other factors that appear to be fostered by musical experience, such as selective auditory attention (Strait & Kraus, 2011), and auditory perception and WM (Pallesen et al., 2010; Parbery-Clark et al., 2011, 2012; Wan & Schlaug, 2010). Regarding WM and other memory skills, a meta study by Talamini et al. (2017) concludes that musicians' short-term, working and long-term memory seem to be stronger than non-musicians’ regardless of the modality. The authors argue that the results do not seem to show a self-selection bias, with people with better memories choosing to become professional musicians. Instead, they point to the multisensory nature of music training as contributing to better memory integration: As someone learns to play an instrument, both the sounds and the motor response are associated with the music notation. This process of sensory-motor integration is thought to enhance active and controlled learning skills (akin to applying chunking strategies for memorising), which may be helpful when remembering stimuli in other kinds of tasks (Talamini et al., 2017).

Research on cognitive aspects associated with music experience can be analysed from two main perspectives: What music training provides, but also what it requires. For instance, the age of musical training onset – like the age of L2 acquisition – represents a variable and possible confound that cannot be overlooked when studying the relationship between musical abilities and other competences. Physiologically, certain auditory processes on which music – and language – rely, show greater flexibility until a certain age: Absolute pitch in musicians, for instance, seems to depend greatly on whether their training started before or after the age of 6 (Levitin & Zatorre, 2003). Nevertheless, absolute pitch does not seem to affect the functional and structural brain changes that occur with musical experience (Leipold et al., 2021). Many theories and studies focus on a possible “critical age” for musical training (for a review see Trainor, 2005); However, Trainor suggests that complex forms of pitch processing beyond pitch recognition remain amenable to training over the lifespan.

Musicians and music lovers attach great importance to a concept referred to as “musicality” (also referred to as musical quality, ability or aptitude), which Schellenberg and Weiss (2013) describe as “natural music abilities or the innate potential to succeed as a musician” (p. 499). Musicians also describe musicality in a more restricted sense as a certain sensitivity to what music expresses and a sense of to how to play it or sing in order to fully do it justice, bringing the notion of musicality closer to that of expressiveness (e.g., Palmer, 1989; Çorlu, Muller, Desmet, & Leman, 2014). Expressiveness can be described as any quality of the music beyond the correctness of pitch and rhythm, like timbre, timing, energy, articulations, and dynamics (see Bresin, 1998; Gabrielsson & Lindström, 2010; Repp, 1997). Juslin, Friberg, and Bresin (2002) define expressiveness as multi-dimensional and related to the structure of the music, the emotions that are conjured up, the movements that are suggested, and motor precision on the part of the player – a level of motor precision that requires skillful playing (Palmer, 1989). Many musicians, and a long tradition of trainers, are adamant that the necessary qualities are acquired early in life: According to Gordon's (1990) Music Learning Theory for instance, musical aptitude is no longer affected by the music environment after age 9.

However, age might be more of a correlate of than a prerequisite to the acquisition of musical ability: It goes without saying that the level of musical aptitude required to become a professional musician can hardly be attained without considerable practice. In addition, sufficient proficiency has to be achieved in time to meet usually stringent age limits imposed on higher musical studies. This practically makes an early start a necessary requirement for success. Moreover, a significant proportion of professional musicians come from musical families, and the frequency and precocity of their contact with music can hardly be disentangled as factors. Still, Watanabe, Savion-Lemieux and Penhune (2007) found that musicians who began training before age 7 outperform later-trained musicians on various motor synchronisation tasks, even once total years of study were accounted for. A study by Steele, Baily, Zatorre and Penhune (2013) controlled for the number of years of musical experience when comparing early and later starters (before or after 7 years of age). The two groups, consequently, differed in age but had the same number of years of experience. They were compared in a temporal motor sequencing task (tapping along with a learnt rhythmical pattern). Though the accuracy of the sequence after learning was the same in both groups, the authors did find better synchronisation with the stimulus in early starters. The study did not compare musical performance across the groups, but suggests that early musical training does lead to accrued brain plasticity (possibly due to general plasticity diminution with age, see e.g., Westerhausen et al., 2011) by providing enhanced auditory and motor connectivity, fostering the acquisition of musical skills and long-lasting influence on behaviour. A critical difference in plasticity was described in Schlaug, Jäncke, Huang, Staiger and Steinmetz

(1995) and subsequent studies (e.g., Steele, Bailey, Zatorre, & Penhune, 2013; Zatorre, Chen, & Penhune, 2007): Musicians usually have a larger corpus callosum than non-musicians, but musicians trained before the age of 7 show more growth in that region. In contrast, Hutchinson, Lee, Gaab and Schlaug (2003) found no such link between starting age and observed volume difference between musicians and non-musicians in the cerebellum, another crucial area for music processing.

The brain changes that are associated with music training in the literature are hard to tell apart from those that might have been caused by other factors, such as type of practice and instrument, individual attentional differences, environmental factors, and interactions between them (Merrett, Peretz, & Wilson, 2013; Miendlarzewska & Trost, 2013). In addition, genetic and innate factors also come into play: Certain observed transfer effects from music training to language processing (learning of pseudowords, Wong et al., 2008) appear to require structural traits in the brain (specifically the left auditory cortex), which seem to predict the ability to distinguish sounds in a foreign language (Golestani, Molko, Dehaene, LeBihan, & Pallier, 2007; Golestani, Paus, & Zatorre, 2002).

To sum up, it appears from an abundant body of literature that musical experience is associated with observable changes in the brain structure and on brain functions as well as with a possible behavioural enhancement in a number of domains, although these effects are modulated by several other factors with substantial interplay among them. The effects are noticed already after little training and in amateur musicians, but are increased with longer experience and with degree of expertise. The following section will explore whether such changes also extend to higher-order cognitive processes.

4.1.2 Proactive and reactive control mechanisms in musicians

Musicians need to process multiple musical elements – notes, melody, rhythm, and intonation – simultaneously (Moradzadeh et al., 2015). In addition, music-making and training engage higher-order cognitive functions, WM (essential to maintaining information regarding incoming and past elements of the music), selective attention and inhibition (e.g., of alternate melodic lines in an ensemble), monitoring and updating (e.g., during score-reading) as well as switching (e.g., between groups of notes and their various attributes within a musical piece or between auditory streams when not playing alone; Miyake and Shah, 1999; Moradzadeh et al., 2015; Okada & Slevc, 2020). Studies using non-musical tasks suggest the possibility of domain-general transfer: For instance, musicians perform better than non-musicians in switching tasks (Moradzadeh et al., 2015), including at an older age (Hanna-Plady & MacKay, 2011).[33] Lifelong musical experience seems to slow down cognitive ageing (for a meta-analysis see Román-Caballero, Arnedo, Triviño, & Lupiáñez, 2018). Observed effects include reduced loss of auditory processing functions (White-Schwoch, Woodruff Carr, Anderson, Strait, & Kraus, 2013) as well as slowed cognitive decline (Kraus & White-Schwoch, 2014). Furthermore, shorter-term musical training is associated with cognitive improvements in patients with dementia (Van de Winckel, Feys, De Weerdt, & Dom, 2004).[34] Such benefits on the preservation of cognitive functions are possibly related to emotional effects like mood regulation and the recollection of memories (Diaz Abrahan, Shifres, & Justel, 2019; see Särkämö, 2018, for a review). Regarding variations across findings on the cognitive benefits of musical experience, Okada and Slevc (2020) postulate that, as in bilinguals (see section 3.1.1), the effects of musicianship on executive functions is likely to be seen more strongly in populations with reduced EF abilities compared to young adults, such as children, elderly adults, or neuropsychological patients.

Music – like language – unfolds over time: The listener creates associations between incoming stimuli and stimuli already processed, and derives a notion of its structural organisation, recognising themes, patterns, tonality changes, etc. Peretz and Zatorre (2005) stress that stimulus maintenance plays a central role in music processing, as it allows the cognitive system to relate various elements in a musical sequence to one another. The sequential processing of music, requiring an online maintenance of stimulus and of representations, raises the question of whether this also entails goal-related proactive control processes. Music recognition is probably enabled by accessing and selecting potential predictions in a perceptual memory system (Dalla Bella, Peretz, & Aronoff, 2003; Peretz and Zatorre, 2005). Huron (2006) stresses that the way we enjoy music from a young age is linked in an essential way to the generation of musical expectations. This process is thought to be largely automatic, at least by the time we reach adulthood. Still, it requires proactive mechanisms to maintain incoming information online in WM and to allow the necessary associations with various sources of knowledge about music (Peretz & Zatorre, 2005). Berti, Münzer, Schröger, and Pechmann (2006) observe that musicians perform better at maintaining a tonal representation despite tonal interference: Concretely, they can hold a pitch

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[33] As task-switching paradigms, Moradzadeh et al. use a Quantity/Identity task (Cepeda, Cepeda, & Kramer, 2000), in which participants alternatively indicate the number of digits visually presented or their value; Hanna-Plady and McKay use the Trail-making task, described in Appendix A.

[34] Motor and timing effects of musical experience are also associated with improvement in aphasia or stroke patients (Lim et al., 2013; Zhang et al., 2016).

in memory for a longer time in the presence of interfering stimuli. This ability also correlates with better WM capacity. Professional musical performance, too, is forward-looking. Players and conductors need to embrace the direction of a given musical phrase in order to produce the required technical elements and expression smoothly. In order to execute the right movements in the appropriate order and at the correct rhythm, musicians need to anticipate the necessary motions (Engel, Flanders, & Soechting, 1997; Baader, Kazennikov & Wiesendanger, 2005). To that effect, they need to form a mental representation of the motor sequence, comprising the motoric as well as the cognitive and strategic components of the eventual performance of that sequence (Driskell, Copper, & Moran, 1994). In model simulations (Honkela, 1997), the model underpinning successful musical performance is one which allows some openness to the input while containing an internal schematic drive, (i.e., anticipation), in order to intentionally realise musical situations rather than just recognising them as given. Honkela describes anticipatory behaviour as a change of state in the present as a function of some predicted future state, requiring, therefore, an expectation and its confirmation or disconfirmation. While keeping goals active is essential to guide the execution of a piece, musicians need to maintain an action-perception loop, that is, the product is used as feedback for the ongoing performance (Çorlu et al., 2014). It seems, therefore, that music-making (playing or singing) calls on both proactive and reactive control mechanisms.

Trainor et al. (2009) suggest that the advantage often observed in musicians in attentional and memory processes may be underpinned by the integration of top-down and bottom-up processes required to learn to play: Music students keep in mind the sounds to imitate, compare them to their own production, and adjust their movements to match the intended sounds as closely as possible. At both the perceptual and attentional levels, these top-down and bottom-up processes are probably sensitive to certain phases in brain maturation (Kral & Eggermont, 2007; Penhune, 2011). This may account for some of the observed interindividual differences in the effects of musical experience depending on the age of training (Herholz & Zatorre, 2012).

Notable types of tasks in which trained adult musicians appear to perform better than non-musicians involve inhibition (Okada & Slevc, 2020), though the effect is not systematic: In D'Souza, Moradzadeh and Wiseheart's (2018) study, musicians had better scores in WM measures, but neither musicians nor bilinguals significantly outperformed controls in the Stroop and Flanker tasks. In other studies, however, musicians perform better than non-musicians in a visual Simon Arrows task as well as an auditory Stroop task (processing the pitch, not the meaning, of the words “high” and “low”: Bialystok & DePape, 2009), a stop-signal task (Strait, Kraus, Parbery-Clark, & Ashley, 2010), and a Go/No-Go task (Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014). Musicians outperform controls (but not bilinguals) in a Simon task (Schroeder, Marian, Shook, & Bartolotti, 2016). Older musicians show better performance than non-musicians in a battery comprising these tasks and composite measures, except for the Go/No-Go task (Amer et al., 2013). A higher level of musical expertise (professional vs. amateur) is also associated with better performance in the Stroop task (Travis, Harung, & Lagrosen, 2011). Regarding non-professionals, amateur musicians are still faster than non-musicians in regular Stroop and Simon tasks (Jentzsch, Mkrtchian, & Kansal, 2014). Short-term music training (four weeks) suffice to give children an edge in the Go/No-Go task (Moreno et al., 2011).

One question that these results raise is the level and precise point in time at which potential interference is inhibited in musicians. For instance, in the stop signal task, participants exert proactive control to monitor for a stop signal and suppress their response prior to the stop signal presentation, and reactive control after the stop signal to inhibit the response or process errors (Clark, King, & Turner, 2020). In addition, the control mechanism underpinning inhibition can depend on the type of interference that needs to be overcome[35]. Different mechanisms may underpin the inhibition of a prepotent response, of external “distractor” interference from irrelevant stimuli, or of internal, proactive interference from former goal-relevant stimuli in WM (Badre & Wagner, 2005; Friedman & Miyake, 2004; Irlbacher et al., 2014; see Colzato et al., 2008; Marton et al., 2017). A study by Hennessy, Sachs, Ilari, & Habibi (2019) found higher activity in control-related brain regions during inhibition tasks in children after 3 years of extracurricular musical training than in untrained children; However, behavioural measures showed no difference in a Stroop or Flanker task, while some differences were observed in a delay-of-gratification task. These results point to enhanced goal maintenance but not necessarily better resistance to interference from distractors or from stimuli triggering a prepotent response. This, in turn, suggests increased reliance on proactive control in the musically trained children, although it was not exerted sufficiently in this case to successfully perform the tasks (in addition, the children may have applied proactive control to various extents across tasks based on the valuation of the reward). In their Go/No-Go task ERP study, Moreno et al. (2014) compared bilinguals and musicians and found that in spite of

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[35] For a general introduction to the distinction between various types of inhibition see section 2.1.2; For a discussion regarding the findings in bilinguals and interpreters, see sections 3.1.2 and 3.3.2.

similarly successful performances between the groups, their electrophysiological responses differed. Whereas the bilinguals showed indications of reactive control, there was no indication of that in musicians, for whom an early cue-related positivity seemed to reflect the processing of relevant stimuli, pointing to the construction of a representation of the current task context at an early stage and reducing the need for later cognitive control processes. An explanation proposed by Schroeder et al. (2016) for the accrued capacity of musicians to suppress interference rests on the OPERA hypothesis of the effects of musical training (Patel, 2011). OPERA stands for Overlap, Precision, Emotion, Repetition and Attention: The hypothesis suggests that musical training fosters focused attention, as musicians selectively attend to sound sequences in detail. In musicians, therefore, interference from irrelevant stimuli would be inhibited more by selectively directing attention to the relevant stimuli instead (Schroeder et al., 2016), pointing to accrued reliance on proactive control.

Nevertheless, reactive control, based on conflict monitoring and resolution, also underlies several components of music-making. For instance, musicians sometimes need to adjust their performance to other players' (Palmer, 2013). The involvement of control processes during ensemble performance will be explored more in detail below (Section 4.2). Polyrhythmy, that is, the performance or processing of two different meters, is also considered to rely on this type of control: Brain areas triggered by polyrhythmic tapping include a network associated with these mechanisms, including the ACC (Vuust, Wallentin, Mouridsen, Østergaard, & Roepstorff, 2011). An investigation of error monitoring in highly-trained pianists found evidence of conflict monitoring, including at a very early stage in processing: An analysis of note onset and offset timing and key press velocity (volume) showed lower velocity for erroneous keystrokes, and slowing before and after errors (pre- and post-error slowing; Maidhof, 2013).[36] When the pianists played with both hands, the velocity reduction affected only the hand making the error, but the slowing affected both hands, pointing to more domain-general processing. Similar observations were made in pianists performing well-known pieces without auditory feedback (Ruiz, Jabusch, & Altenmüller, 2009). Studies consistently show similarities in EEG data (for a review see Maidhof, 2013): Pre-error negativities were observed prior to the completion of the erroneous keystroke, as well as a positivity shortly after the error occurred. This positivity is interpreted as the recognition of an

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[36] Four types of possible errors were identified: 1) substitutions – that is, the performance of a note with a wrong pitch, 2) omissions – that is, a note that is not performed at all, 3) intrusions (or additions) – that is, performance of a note that is not in the score, and 4) fingering errors – that is, playing the note with a different finger than planned and thus contradicting the motor planning of a rehearsed sequence. The pianists were presented with well-learned repertoire.

error (Ridderinkhof et al., 2009), which presumably triggers an adaptation of behaviour or of the control signal, reflected in post-error slowing (e.g., Botvinick et al., 2001). In Moreno et al.'s (2011) ERP study of children given music lessons over a short period of time, a functional brain change was observed, pointing to early recognition of stimulus response pairings in the Go/No-Go task compared to later conflict-related processing in bilinguals. This suggests that though functional change in later information processing may require more experience, music training influences relatively early stages of information processing (see also Nager, Kolhmetz, Altenmüller, Rodriguez-Fornells, & Münte, 2003).

However, though electrical responses in the brain indicate that the level of musical practice is correlated with more efficient error and conflict detection,[37] it can be associated at the same time with shorter or absent post-error slowing, pointing to reduced post-error interference and post-conflict processing adjustments (Jentzsch et al., 2014; see also Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010). This finding is counterintuitive in view of the literature on post-error slowing, but may suggest that there is less need for an adaptation of the control signal in proficient musicians. This could be the case if the constraints of musical performance – like the necessity to reduce the impact of an error – encouraged in experts a running modulation of the control signal in advance of anticipated difficulties. This way, errors detected may not necessarily trigger an adjustment of the signal, as that would be likely to disturb the anticipated motor sequence to come. The risk of causing asynchrony with other players may also be a factor in reducing behavioural responses to errors (Jentzsch et al., 2014). In addition, anticipatory behaviour in musicians also changes as a function of practice and skill level: A study on pianists (Drake & Palmer, 2000) investigated the range of planning, that is, the distance between an error and its assumed source. The source of the error is interference from notes on the score prior to the one played or after it: A longer range of planning, therefore, points to longer segments of the score being held in WM. A longer range of planning was associated with a decrease in temporal (i.e., rhythmical) disruptions, meaning that it helped maintaining the right rhythm. The range of planning increased with the participants' skill level. At the same time, the proportion of anticipatory errors, that is, interference from notes that should come later and are played too soon, rather than perseverance errors (i.e., replaying earlier notes), increased with skill level and with practice. Interference from items not yet played rather than from items already played suggests that content is held in the musicians' WM *ahead* of motor

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[37] In this case, increased error-related negativity ERN and N2, both associated with ACC function.

processing rather than held *back* and points to increased reliance on anticipation and on proactive control with higher skill level.

Regarding musicians' multitasking abilities specifically, it remains as yet unclear how music training may influence dual-tasking or multitasking performance, and the question has not received a lot of attention so far. Expert musicians performed no better than controls in a dual music recognition and visual pattern recall test (Cocchini, Filardi, Crhonkova, & Halpern, 2017). However, in an investigation of bilinguals, musicians, and controls, Moradzadeh et al. (2015) found that musicians show better performance in a dual simultaneous visual-motor task (Krantz, 2007).[38] Then again, in the same study, the group differences in another dual task, a dual 1-back and 2-back task (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008) using auditory and visual stimuli, were non-significant. Insights into possible control mechanisms in musicians were provided by a task-switching paradigm where musicians showed greater local switch costs, in part related to faster RTs overall, but reduced global switch costs than the other groups. Local switch costs are associated with inhibitory control and shifting between task sets (e.g., Prior & MacWhinney, 2010), whereas global switch costs are thought to be related to goal maintenance and the ability to maintain competing task sets in WM (Braver, Reynolds, & Donaldson, 2003). These findings could therefore be attributed to musicians' superior WM capacity (see D'Souza, Moradzadeh, & Wiseheart, 2018), but may also suggest, and the two aspects are perhaps related (see Braver, 2012; Kane & Engle, 2003; Hutchison, 2011), a proclivity towards proactive control in musicians in the context of competing tasks.

Usually and in various domains, successful expert motor performance relies on implicit modes of processing that are established and reinforced by experience and do not require representation in WM; Focusing on one or the other component of that performance and making it explicit will impair the result (for a review see Eichorn & Marton, 2015). In the same way, it is possible to perform a musical piece while relying almost exclusively on automatised processes, commonly referred to by musicians as "muscle memory" (e.g., Grahn, 2015). In that case, however, any disruption of the performance will usually lead to a breakdown, making purely automatised playing a poor strategy. Optimal music performance differs from other motor activities in that it also likely involves higher-order functions to ensure that several hierarchically organised actions are precisely timed, and pitch interval production is controlled (Zatorre et al., 2007). In a study by Çorlu et al. (2014), performance

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[38] The Kranz paradigm consists of a rapid serial visual presentation task combined with a motor tracking task.

of a musical piece, even if it had been well rehearsed, suffered when combined with a cognitive task, but this did not affect the fluidity or exactness of the execution so much as it did expressiveness (Çorlu et al., 2014). This suggests that motor sequences but not expressiveness become automatised. Expressiveness, as we saw earlier, encompasses the specific energy voluntarily given by the player to the music and requires extreme timing precision: Expressiveness is thought to arise from playing very slightly before or after the expected time, engaging the listener's attention (see Levitin, Grahn, & London, 2018). Leman (2007) hypothesises that rehearsing a piece enables the automatisation of motor patterns. Thus, once a certain degree of automatisation has been reached, musicians can turn the focus on expressiveness, which requires moment-to-moment comparison of their musical product with their intention. This implies that the amount of practice modulates the cognitive load and plays a role in how expressive a musician can be (Çorlu et al., 2014).

Musicians' ability to perform concurrent tasks is also influenced by the type of movement they are required to execute (Maes, Wanderley, & Palmer, 2015): Cellists given parallel tasks, namely a synchronisation task requiring the regular playing of tones and a WM task (digit switch-counting), performed better if the synchronisation task could be performed without interruption between bow strokes (legato rather than staccato articulations). Maes, Wanderley and Palmer suggest that in high cognitive load situations, musicians may therefore benefit from the temporal control information provided by continuous body movements. This may be one of the reasons why so many performers adopt a light swing while playing. Interruptions (or breathing pauses for expressiveness, see Çorlu et al., 2014) seem to call for more explicit focus in order to remain in control of the timing.[39] The relationship between internal timing and higher cognitive functions is worthy of further investigation (see e.g., Nobre & Van Ede, 2018; Thomas & Weaver, 1975; Zalta, Petkoski, & Morillon, 2020). Furthermore, processing slow tempi seems to require more cognitive control than processing faster ones (e.g., Miyake, Onishi, & Pöppel, 2004): In a dual-task paradigm, Bååth, Tjøstheim and Lingonblad (2016) used a visuo-spatial 2-back task (modelled after Jaeggi et al., 2007) in order to engage cognitive control. Participants did not respond to the trials but kept a covert count of the target trials. The parallel task was a synchronised tapping task at shorter or longer intervals. Even though a multitasking cost in both tasks was observed with a fast tempo (intervals of 600 ms), performance was significantly more impaired when the tempo was slower (intervals of 3000

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[39] This may help account for the observable phenomenon of amateur singers or players keeping accurate tempo (and synchronisation with others in a group) while singing or playing, with less reliable pause lengths for instance between musical phrases.

ms). In that context, no fully automatised processing of short period intervals was observed (cf. Repp, 2005), but a clear difference appeared: There were additional control constraints involved in keeping a slower rhythm, and incidences on the ability to multitask.

In sum, it appears that control functions in non-musical domains seem to be fostered in musicians (notwithstanding the possible links between music and multiple cognitive domains, including verbal processing). As with bilinguals, the results are not homogeneous across all ages and musicians. It also appears that musical performance relies on proactive and reactive control to various extents, depending on the sub-components involved in the musical task at hand. However, with higher levels of musical expertise, musicians seem to increasingly rely on proactive control, which enables them to maintain active representations of the next elements of a musical sequence as it unfolds. When a musician is required to adjust to and coordinate with another player's performance, the picture is likely to be more nuanced. In addition, the representations to maintain for successful performance likely include elements of the upcoming motor sequence as well. Therefore, the section below will explore ensemble music, a major part of most musicians' and certainly of conductors' musical experience. Ensemble music requires active synchronisation, which taps into cognitive but also motor control skills. This requires a short account of the interplay between cognitive and motor control in musicians, and an exploration of salient insights on interpersonal synchronisation and coordination.

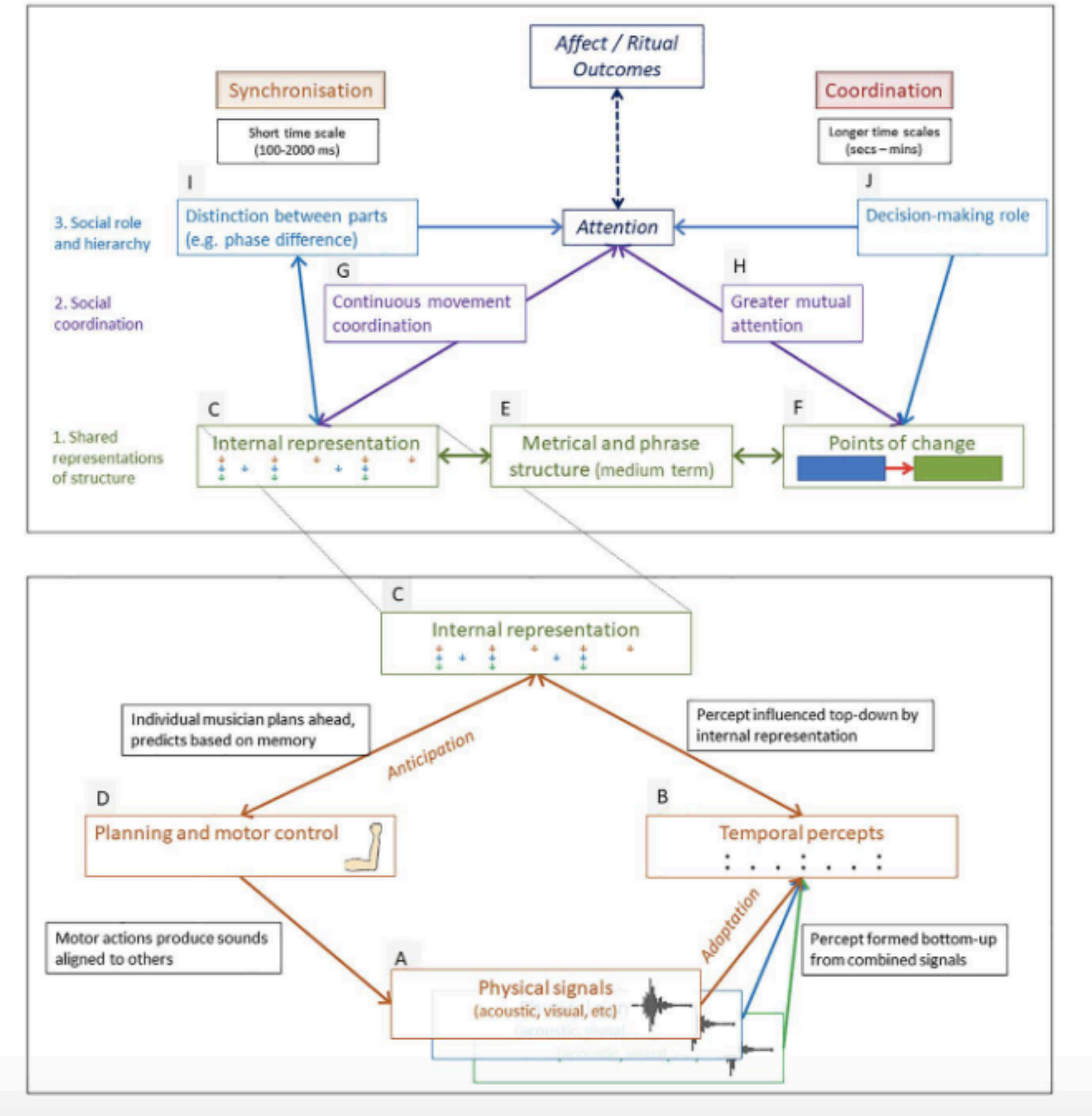
4.2 Cognitive-motor processes during ensemble performance

Through years of practice performing in ensembles, musicians become proficient in sensorimotor communication, that is, they can produce and read gestures and postures which allow them to synchronise and coordinate with others, and they can understand and predict others' intentions (D'Ausilio et al., 2012). Ensemble performance is a complex setting, where many factors come into play (Keller, 2014). Besides aspects related for instance to social interaction, internal factors that are extraneous to the performance itself impact attention and cognitive and motor control, such as anxiety, arousal, motivation and the mastery of instrumental technique (Keller, 2001). Keller (2014) proposes a summary of the external and internal strategies, mechanisms and constraints for the musician in that context, which include controlled cognitive-motor processes that involve both adaptive and anticipatory mechanisms. The overview of these mechanisms was expanded and specified in Clayton et al., 2020 (see

Figure 2 below). They rely on motor control and synchronisation processes, which will be detailed in this section.

Figure 2

Clayton et al. (2020): Model of Interpersonal Musical Entrainment, accounting for synchronization at short timescales and coordination at longer timescales.



Note. The lower pane illustrates the synchronization part of the model (boxes A-D), while the upper pane depicts elements related to shared representations of musical structure (C-F), social coordination (G & H), and social role and hierarchy (I & J). (Reprinted from Clayton et al., 2020, p.177).

Another characteristic of ensemble performance is that it involves shared goals (D'Ausilio et al., 2012). How these shared goals are coordinated with individual goals, that is, how joint action interplays with individual action, is relevant to a study of multitasking abilities in musicians like the present one. As these goals are compatible and a hierarchy between them can be established, ensemble music is likely to foster integration as a multitasking strategy (see section 2.4.3.4). Indeed, regarding potential dual-tasking abilities fostered by music performance, Bigand, McAdams and Forêt (2000) deem that true divided attention between various streams is not supported: Evidence seems to point towards the integration of multiple streams into a complex stream, a process which is favoured by repetition. However, ensemble performance does involve cognitive processes that may play a role in how musicians exert control in a complex task situation. Therefore, this section aims to provide a short account of control mechanisms in the context of sensorimotor synchronisation and joint action.

4.2.1 Interactions between cognitive and motor control

Music making is based on complex motor sequences that require the involvement of several motor control functions, notably timing, sequencing, and the spatial organisation of movement (Zatorre, Chen, & Penhune, 2007). Goal-oriented movement involves planning, online control and coordination (Gallivan, Chapman, Wolpert, & Flanagan, 2018). Like cognitive control, motor control is thought to operate on a minimal intervention principle: Cost minimisation entails a trade-off between energy and accuracy, which is modulated by optimal feedback control (Todorov, 2004; McNamee & Wolpert, 2019). It has been proposed that motor control is subserved by two complementary types of internal models (Wolpert et al., 1995, 2003; Wolpert & Kawato, 1998; Wolpert & Ghahramani, 2000): Inverse models, which use the movement goal as the basis of the motor commands, and forward models that generate an internal copy of a new command (e.g., a moving limb) and predict the outcome on that basis. Inverse models can serve as internal controllers as they provide the motor command to convert intention into action; Forward models compare the prediction with the sensory outcome, providing feedback in order to adjust future commands. These internal models are thought to serve cerebellar function (Clark et al., 2020). The duality of goal-based and stimulus-based input for control provides a parallel to the types of processing underpinning proactive and reactive mechanisms that are found in theoretical models of cognitive control. In musicians, Bernardi et al. (2013) suggest that practice, both mental and physical, uses forward internal models, generating copies of the motor command in the brain in order to refine its ability to predict its probable outcome.[40] The acquisition by musicians of precise internal models of their own practiced gestures is supported by a study of conductors

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[40] In line with the common coding theory (Prinz, 1997), this applies whether the movement is actually executed or just imagined (Frith et al., 2000).

(Wöllner, 2012), who were able to distinguish schematic simulations of their own conducting movements from other participants', with and without sound, but not simulations of their own gait. This suggests that higher-order representations of highly trained, skilled movements are formed and thus allow for their planning.

The object of motor control differs from that of cognitive control; There are differences as well in the brain networks involved, and control in these domains appears to rely on different processes that, in the case of motor control, are relatively low-level and can be automatised. However, in many respects the distinction remains fuzzy (see Clark et al., 2020; Gentsch, Weber, Synofzik, Vosgerau, & Schütz-Bosbach, 2016). The coordination of motor, perceptual and cognitive processes is thought to rely on shared resources (see e.g., Hervais-Adelman et al., 2015). Motor and cognitive control can be engaged simultaneously and complementarily within one domain: For instance, cognitive control is applied in various tasks regardless of modality and can affect movement speed. Gallivan et al. (2018) also describe instances of "cognitive leaking" into movement control (p.7), especially where more than one target is present: Movements, and the estimation of the associated cost, seem to be influenced not just by motor representations of the targets, but also by higher-level representations. For instance, movements are corrected only as far as the ultimate goal of the movement requires it. It seems fitting, considering a theory that views control as an emerging property (Feng et al., 2014), that conflict between the intended goal and the current process – in the absence of dedicated representations and pathways honed with training – would trigger control signals regardless of the domain at hand. In fact, it is not known whether control is domain-specific or whether it is made up of a certain kind of attributes and mechanisms that are applied in a broad range of domains (Cohen, 2017).

Some attempts have been made to integrate cognitive and motor control in the same model. They suggest a hierarchy of both low-level and high-level forward models of outcome prediction at the motor and cognitive level, which evolve with learning and serve to predict outcomes and to detect discrepancies with the actual outcome (Krigolson & Holroyd, 2007; Krigolson, Holroyd, Van Gyn, & Heath, 2008). Another such model is Alexander and Brown's (2010) Prediction of Response-Outcome Theory of mPFC functions (PRO). The model attributes to the mPFC, specifically the dACC and pre-SMA (areas of interest in control theories and also considered *inter alia* in Green & Abutalebi's Adaptive Control model of bilingualism, see Section 3.1.2) the function of evaluating the desirability of anticipated outcomes as well as predicting the likelihood of an adverse outcome (Brown &

Braver, 2005). This involves a cost/benefit evaluation (e.g., Botvinick, 2007; Brown & Braver, 2007; Kool et al., 2017) and entails individual differences based on sensitivities (Brown & Braver, 2008). It is of note that the ACC is instrumental in reactive cognitive control and the pre-SMA is involved in both proactive and reactive control (Irlbacher et al., 2014). The PRO model mirrors the forward/inverse models of motor control: The authors liken its prediction component to a cognitive forward model, which establishes associations between movement commands and their predicted consequences on higher goals rather than low-level actions (Alexander & Brown, 2010). The PRO model was extended by Alexander and Brown (2015) to become the hierarchical error representation (HER) model, a more comprehensive model of ACC and dPFC functions integrating bottom-up and top-down processing modes to maintain or amend predictions.

It appears in any case that expertise in complex motor tasks also involves cognitive control skills, and the distinction between proactive and reactive cognitive control processes engaged is not necessarily straightforward. Yu et al. (2019) attempted to compare closed-skilled motor expertise (i.e., in self-paced and consistent activities, in that case track and field sports) and open-skilled motor expertise (i.e., in dynamically changing activities, like team sports, and in that case, badminton) in a task-switching paradigm. The results suggested better proactive and reactive control in both athlete groups than in controls, and more proactive control in open-skilled experts (as evidenced by variations in EEG responses and reduced switch costs in predictable vs. non-predictable conditions). The authors point to the ability of these athletes, who operate in a changing environment where the opponents' actions need to be anticipated, to proactively update rules. In musicians, reliance on proactive or reactive control in cognitive tasks may thus depend on their specific experience and role in the dynamic environment that is ensemble playing.

4.2.2 Sensorimotor control, synchronisation, and coordination

When musicians play together, they need to pay attention and adapt to other musicians' rhythm and musical expression (Wöllner & Keller, 2017). Soloists are allowed to prioritise their own performance above the group effect, because the ensemble will, to a certain extent, subordinate its performance to the solo. If ensemble musicians who are not soloists base their performance solely on their individual perception of rhythm or on their individual musical intention, they are likely to end up out of sync with the others and to stand out in an undesirable way.[41] Sensorimotor synchronisation (SMS) is the rhythmic coordination of movements with predictable external stimuli (Aschersleben & Prinz, 1995; Repp, 2005). SMS involves both intentional and unintentional components. Unintentional synchronisation tends to happen, for instance, when stimuli are repeated at regular intervals, especially between 100 and 2000 ms (as is the case for example with a beat, or even someone else's steps (Repp, 2005; for reviews see Clayton et al., 2020; Larsson, Richter, & Ravignani, 2019; Levitin, 2008; Van der Steen & Keller, 2013). This phenomenon is called entrainment. However, in the case of ensemble performance, musicians need to intentionally rely on SMS to coordinate as flexibly and precisely as possible with others. This calls for both temporal adaptation, based on reactive error correction, and anticipation, based on predictive processes (Van der Steen & Keller, 2013; Keller, 2013). Indeed, purely reactive mechanisms, using sensory data to plan and execute motor reactions, would involve feedback delays that are too long to allow for a smooth execution of the movement (Wolpert, Doya, & Kawato, 2003). Therefore, sensorimotor coordination – the active type of SMS – and communication cannot rely solely on such mechanisms (D'Ausilio et al., 2012). In addition, when it comes to interpersonal coordination, relying on an internal model of one's own movements is probably not efficient enough, whether the model is based on actual or expected sensory data (i.e., inverse or forward models). Musicians probably need to acquire an internal model of other musicians to simulate their movements, slightly anticipating them (D'Ausilio et al., 2012; Keller, Novembre, & Hove, 2014). Personality factors fostering or preventing the ability to predict other musicians' action can also influence the ability to synchronise and coordinate with them (Wöllner & Keller, 2017). Van der Steen & Keller (2013) endeavour to account for both these adaptive and anticipatory aspects of SMS in a computational model, ADAM, encompassing prior findings in the literature regarding their components (see also Harry & Keller, 2019). In this model, adaptation relies on error correction of phase (synchrony with the stimulus) and period (perceived interval between stimuli). Period correction relies on attending to tempo and involves cognitive control (Repp, 2005; Repp & Keller, 2008; Semjen, Vorberg, & Schulze, 1998), and cognitive control may also underpin increases in both types of correction (Van der Steen & Keller, 2013). Anticipation relies on predictive processes, involving automatic expectancies generated from the bottom up as well as top-down processes, which are based on mental imagery (see Palmer, 2013).

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[41] As the saying goes, the right note, at the wrong time, is a wrong note.

It is important to underline that ADAM provides a snapshot of synchronisation as it is involved in ensemble playing. Therefore, these components do not preclude the exertion of additional cognitive control when it comes to anticipating and monitoring one’s own and the others’ musical performance and adapting dynamically. The need to simultaneously segregate and integrate information from multiple sources (see Bigand et al., 2000) entails cognitive demands and is described as a form of multitasking (Keller et al., 2014). Keller (2001) and Keller et al. (2014) provide an account of the attentional processes it requires: During ensemble performance, musicians need to flexibly divide their attention between their own and the others’ actions, as they also keep track of the whole ensemble output. Keller (2001) formulates the hypothesis that musicians use prioritised integrative attending, meaning that they attend to both their own part and the overall sound; In addition, they vary the amount of attention (priority) devoted to the one or the other on the basis of various factors, including the difficulty or musical characteristics of the piece. Keller underlines that processing one’s own part involves retrieving performance goals and performance plans, that is, declarative memory of the piece and intentions and expectations attached to its performance, as well as procedural memory and motor representations (Palmer, 2013). These also allow the prediction of other musicians’ performance (Keller, 2008; Wöllner & Keller, 2017). Keller (2001) also stresses that monitoring of one’s own production based on sensory feedback is also necessary. The fact that performance is guided by these internal goals suggests that the control mechanism attached is engaged from the top down, while monitoring underpins bottom-up control. This dual engagement of control serves the combination of prepared and online processes involved in ensemble performance, and the balance between the components that they serve varies as the demands of the music change or depending on the number of prior rehearsals (see Wöllner & Keller, 2017).

This more global picture of interpersonal processes is considered a form of joint action (Clayton et al., 2020; Sebanz, Bekkering, & Knoblich, 2006). Joint action, across various domains, involves a combination of higher-lever cognitive and lower-level sensorimotor processes. That combination is susceptible to strategic modulation in the form of behavioural modifications (Clayton et al., 2020). Participants in joint action can make their movements more predictable (e.g., by making them more regular or giving them more amplitude) as well as engage in forms of communication, which can be visual, to indicate their intentions (Vesper et al., 2017). For instance, musicians synchronise more accurately with a conductor than with a visual metronome (Ono, Nakamura, & Maess, 2015), probably because movement and other visual cues between the beats help the musicians anticipate. Clarity of movement, probably as internalised through repeated exposure to the others' actions, is also of the essence: In the absence of other visual indications such as posture, gaze, and facial expression, it appears to be easier to synchronise with prototypical conductor movements (i.e., an averaged point-light rendition of real-life conductor movements), which are devoid of idiosyncrasies (Wöllner et al., 2012).

The role taken by musicians in an ensemble influences sensorimotor communication (for a review on leader-follower relations in ensemble performance, see Wöllner & Keller, 2017). Palmer (2013) stresses that duettists adapt to each other's timing regardless of whether they have been assigned the leading or following role (Goebl & Palmer, 2009), suggesting that this is probably also the case in ensemble musicians. However, across studies, the leaders' onset also consistently show a slight advance on the followers', whether in pianists (Goebl & Palmer, 2009), vocal ensembles (Palmer, Spidle, Koopmans, & Schubert, 2013), or in duos comprised of pianists and violinists (Bishop & Goebl, 2017). In addition, in a joint-action setting, leaders endorse the task of communicating their intentions, which can for instance involve exaggerating their movements (see Vesper et al., 2017). Therefore, leaders probably increase their focus on their own intentions, and followers need to rely more on the external cues that the leaders provide.

This suggests that not all musicians rely equally on the same control processes to reach the common goal in ensemble performance. It is also likely that the length of the segments and the type of cue – internal vs. external – against which to measure performance vary considerably among individuals, and within them, depending on their degree of familiarity with the piece. The case of conductors, whose role is characterised by leading, is explored more in detail below.

4.3 Task components, cognitive constraints, and control mechanisms in conducting

Conductors were chosen as the second type of multitasking performers investigated in the present dissertation: Like interpreters, conductors have to manage multiple real-time constraints that appear to be incompatible, as they draw on the same cognitive and motor resources. Conductors make gestures to produce a complex, continuous sequence of sounds – via the orchestra – that they hear, paying attention to specific parts of the orchestra as well as to the global output of the ensemble, and evaluate for potential course correction. All the while they continue to produce cues for the next part of the complex sound sequence, that they have not yet heard. They need to channel all of the visual cues that they provide (facial, postural, gestural) to make them as intuitively understandable possible, as clear as possible, as univocal as possible, and as specific as possible to lead the orchestra in producing the anticipated rendition of a complex piece. They also have to tailor their cues to various instruments in the orchestra. In addition, conductors may need to rely on complex visual cues from a score displayed in front of them, while establishing eye contact as much as necessary with various players.

Although the specific domain of conducting has been the object of emerging interest in cognitive research (e.g., Nager et al., 2003; Hodges, Hairston, & Burdette, 2005; Wöllner, Deconinck, Parkinson, Hove, & Keller, 2012; Wöllner & Halpern, 2016), it remains little studied outside of music-related research. Therefore, reflecting the approach that marked this study, this section endeavours to provide a sufficiently detailed picture of the conductors' activity and suggestions regarding the processes involved. First, a description of the conductor's role is offered; second, accounts of the conductors' experience in real time and their conscious focus are provided, using remarks collected from the conductors who participated in the study, as well as secondary data and references on the practical aspects of conducting, such as conducting manuals. In a third step, the literature review will focus on the cognitive processes involved in successful conducting and explore the attentional and control-related requirements of that activity.

4.3.1 The role of the conductor

A conductor is both external to the orchestra and, in the best case, an essential part of it. Conducting can be summarised as follows: "Conductors coordinate musical ensemble performance by means of gestures as well as facial and bodily expressions" (Wöllner, 2014, p. 246). In addition, the practical activity of conducting in real time also entails multi-faceted work prior to the performance and involves a number of cognitive tasks. A wide spectrum of skills is required for successful conducting: Next to the technical skills reflected in the ability to produce appropriate gestures and the obvious musical skills including vast musical knowledge, the ability to analyse scores and aural skills – i.e., a finely-trained ear for music perception and analysis – as well as interpersonal and leadership skills are crucial (Watson, 2020). Furthermore, the role of the conductor is not set in stone and it fluctuates alongside the broad variety of the repertoire. Indicating playing speed (tempo) is at the heart of the conductor's work; but that work has grown to encompass volume (dynamics) and expression (musical phrasing), and to become more artistic and interpretative (Watson, 2019). Throughout history, musical ensembles have not consistently had conductors (for a detailed history and analysis of the practice of conducting see e.g., Bowen, 2003; Schuller, 1998; for reviews see e.g., Watson, 2020; Wöllner, 2014). However, the need to set, coordinate and indicate the beat for the performance of a given piece always existed when a large number of musicians played together.[42] This was not always done by a conductor, and today still, the first violin of an orchestra is called "concertmaster" and can play an intermediate role between the orchestra and the conductor; The timpanist is also among the musicians whose guidance can be useful for the orchestra (see e.g., Merlin, 2012). In addition, the audience does not always perceive the leadership of the conductor (see e.g., Gillinson, 2009). The use of a conductor, therefore, is sometimes questioned.

Typically, smaller ensembles are self-coordinated. It is suggested that the synchronisation advantage of playing with a conductor starts at nine or ten musicians (Rasch, 1988). Even though there are sometimes successful attempts at dispensing with conducting even in larger ensembles, someone in the ensemble is usually tasked with "conducting" the ensemble by way of visual cues. However, the way musicians coordinate during the performance of a given piece is usually informed by shared intentions communicated during rehearsals (e.g., Keller, 2014; see Section 4.2.1): The same piece, though performed as written, can sound extremely different from one ensemble and execution to the next. It is, of course, possible to give new notes to an ensemble and coordinate the sight-read piece from a purely rhythmical point of view. The result will be harmonically correct, yet a unified and expressive notion of what the music is about will not be really or fully conveyed. In conductorless ensembles, the task of reflecting on the composer's intent, the desirable ensemble effects, the wish to conform to historical canons or break with them, and generally imprinting a deliberate collective colour on the music, has to be carried out collectively.[43] Where a conductor is present, their role prior to the actual public performance encompasses this reflection, and how to communicate it to the orchestra. That includes providing indications during rehearsal as to

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[42] Bowen (2003) cites ancient Greek tablets reporting of a "giver of Rhythm" conducting 800 persons with a golden stick in 709 B.C. (p. 94). In baroque and classical times, one of the players (who was usually also the composer) would be tasked with providing guidance to fellow musicians – often from the harpsichord, whose "basso continuo" musical line already provided a red thread for the musical composition. The pacemaker role could also be taken on by the first violin, whose melody line often stood out. Mozart usually led his works playing the harpsichord or pianoforte, Haydn sometimes also conducted while playing the violin (Schuller, 1998). Alternatively, a music master with a sceptre-like staff could also provide the rhythm by lifting it or tapping on the floor (an example is Jean-Baptiste Lully, who lived and perished by the baton in the 17th century).

[43] Camerata Alma Viva (Geneva) is one example of conductorless ensemble that places the focus on collective processes; see also conductorless concerts inter alia by the Berlin Philharmonic Orchestra.

how the desired effects can be realised. And during the performance, a main aspect of the conductor's role is to offer memory triggers for the players to bring these intentions and effects to the fore, as well as possibly suggest new ones to build on the previous work.

Therefore, what a conductor provides to the orchestra during musical performance can be compared to notes on a text that will be interpreted simultaneously. Such notes are not the verbatim speech, they are more or less specific indications regarding the speech, which serve as cues to help rendition. During musical performance, instead of a speech, musicians have the score of a piece, which they have either memorised entirely or can look at while playing. The conductor's attitudes and gestures are cues for the rendition of the piece, which can also be memory triggers regarding the aspects that were highlighted during rehearsal. The objective of rehearsal is, in fact, developing shared cues (Ginsborg, Chaffin, & Nicholson, 2006) and shared performance goals (Keller, Novembre, & Loehr, 2016). Having a conductor provide these cues and reminders in real time and in situ, rather than simply relying on individual notes makes of the ensemble one "interpreter" of the piece. The conductor is a major help in channeling individual performance into a collective one. We explored the relationship between the task goal and its hierarchical structure in Chapter 2. In the case of ensemble performance, goal-oriented processes in each individual are subordinated to a goal that is centrally maintained by the conductor.

This has several practical implications. One is that a conductor makes a decisive difference in the execution of a piece. The interpretation of the piece will rest on their individual intention, informed by their individual knowledge, sensibility, and their evaluation of what they can expect from the musicians (e.g., the type of sound or tempo that the orchestra is able to maintain successfully), as well as the efficiency of their cues. All can vary greatly from one conductor to the next. In the same way, the same conductor may conduct differently across performances depending on their or the orchestra's experience and a multiplicity of other internal or external factors. Another implication is that ensemble performance is greater than the sum of its parts. Some segments (for instance very fast and dense tremolos, arpeggios or vocalises) require displays of virtuosity that are almost impossible to achieve alone, but that each musician will be able to perform – with practice – within the ensemble. A good conductor knows how far they can make the musicians push their individual limits.

In line with these observations, D'Ausilio et al. (2012) used infrared cameras to capture the movements of the conductor's baton and of the violinists' bow and analysed the patterns using Granger causality tests. They found that the conductor's movements predicted those of the violinists and that the degree of prediction varied between conductors, notably with experience. They also subjected music experts to a blind listening test of the same piece, and found that the rendition where a conductor had exerted greater influence and other musicians in the orchestra less influence on individual performance was appreciated more. While musicians should listen to one another to produce good music, it appears that an overarching and shared sense of direction is key to the aesthetic completeness of a performance.

4.3.2 The conducting experience

The conductors' concrete activity has been described mostly in conducting technique manuals, some of which remain influential, like Rudolf (1950), Schuller (1998) or Meier (2009), or in analyses, biographies, interviews and testimonies on conducting and specific conductors (e.g., Bowen, 2003; Service, 2012). However, these sources do not systematically explore, and reveal comparatively little about, cognitive aspects that are relevant to the study at hand. Therefore, to support or complement the literature, the conductors involved in the present study[44] were asked about their specific experience regarding their individual state of mind while conducting and important aspects for a conductor to focus on in their opinion.

One of the pauses during the experiment was used to let conductors share their thoughts on these two questions; their reflections were then summed up by the researcher, compiled, and sorted into thematic categories based on the elements that emerged from the participant's comments. As the conductors differed in their experience in detailing explicitly what they do as they conduct, the information provided encompasses off-the-cuff intuitions as well as the product of in-depth reflection. The picture that emerged from the various remarks bears testimony to certain shared bases for the role and activity of the conductor as well as to the highly individual character of conducting. Distinct phases and aspects of the conductors' work were thus highlighted. They are presented below with references to the related literature, and to the extent possible, in the "chronological" order of their appearance in the life cycle of a piece in the conductor's work.

4.3.2.1 Preparation

The conductors included in the experiment listed the necessary analysis work prior to any rehearsal, including the in-depth study of a given musical piece and diverse types of annotations to make on the score to help them remember important aspects during conducting.

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[44] The data of all 22 conductors initially included in the study (19 M, 3 F) were included in the analysis for this section. For a detailed description of the group, please refer to section 5.1.3.

These include structures, themes, motives or instruments to bring out, effects to stress or attenuate. However, conductors are usually mindful of making sure that their annotations do not stand in the way of their ability to be fully present and immersed in their musical intent and in the dynamic they create on the day of the performance. Therefore, their personal annotating style also reflects how much they leave open for "live" inspiration (see also Service, 2012). Furthermore, conductors make additional choices when the idea they formed of the music meets its interpreters. The product of rehearsals may lead the conductors to diverge from the written score in ways they will judge non-obtrusive but relevant to the expression of the piece, like for instance doubling a part.

4.3.2.2 Different goals for rehearsal and performance

The study participants generally stress a difference in purpose between conducting during rehearsals[45] and during performance. This difference needs to be highlighted as conductors can engage in a radically different exercise at the various stages of the preparation of a piece. Hence, even for individual conductors, conducting is never a strictly defined activity, which consistently engages the same components. During rehearsal, the conductor seeks to transmit the idea of the piece that they have in mind, and at the same time they focus on analysing the piece and the orchestra's output: When musicians play, conductors must notice and keep in mind the aspects on which to work next. During the concert, the priority lies in the transmission of the piece to the audience. The conductor of course never stops listening in order to dynamically adjust as needed, but the analysis of the product for later reference is less important at that stage. Conducting a concert is usually particularly tiring. A number of conductors insist that during the concert, they endeavour to "take the orchestra somewhere, further", and that performance during a concert is qualitatively different not only in its outcome, but in the processes at play. The performance is about bringing the "interpretation" to a new level "live", i.e., online, without any possibility to rewind and correct. In rehearsals, the players familiarise themselves with the structure and expression of their and other musicians' parts and improve interpersonal coordination (see also Ragert, Schroeder, & Keller, 2013). Therefore, the players know the music. But the intent of each live performance is communicated to them by the conductor. Depending on the circumstances, this communication serves as a reminder for the musicians to perform according to indications given during rehearsal, or spurs them on to implement a new interpretation of the piece. This point, highlighted by participating conductors, is also illustrated in Service (2012)'s report on

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[45] For conductor interviews regarding rehearsals specifically, see Biasutti (2012).

musicians' testimonies regarding the ideal degree of preparedness: Under-rehearsing makes musicians uneasy and less aware of the music they are supposed to express, but over-rehearsing would not leave enough mental space to experience it fully. Musicians need to feel that the technique is in place and that they have acquired and "digested" a notion of where the music is going, but they also need to have room to perform spontaneously under the conductor's guidance for the performance to bring out something new.

4.3.2.3 Added constraints for performance

Conductors mention other factors influencing their state of mind during conducting. A change of location can be a prosaic, but crucial element of difference between rehearsal and performance. In that case, conductors may have to adjust to the specific acoustics of the concert hall, which they might need to get familiar with in only a few days or hours. Their degree of familiarity with the concert environment will also inform their degree of vigilance or reliance on procedural memory when it comes to adjusting the orchestra dynamics.

4.3.2.4 Rhythmic complexity

Additionally, differences emerge between various rehearsal or concert situations depending on the repertoire at hand. Very contemporary repertoires sometimes include intricate rhythmic patterns and combinations and/or very complex interactions between instruments. They provide fewer bases for the musicians to rely on academic or familiar syntactic patterns in the music. Conductors specialising in that repertoire tend to conduct in a very similar way between rehearsal and concert: They avoid change and only add cues if needed during the performance. There are two reasons for this strategy: First, the conductor provides necessary familiarity landmarks for the musicians during the execution of the piece. Second, conductors are also in charge of decomposing the rhythm in extremely precise and readable patterns to allow for an exact and synchronised execution. According to some study participants, not every conductor has absolute tempo (i.e., the ability to recognise and provide tempo correctly in all circumstances), but some do, and some mentally use extracts of songs or musical pieces as references in order to retrieve a given tempo if needed. In all cases, however, a lot of work has gone into internalising rhythmic patterns and transitions. Experienced conductors do not usually work on their gestures when they are not in front of an orchestra, but they make mental notes of specific motor sequences, like for instance what will happen immediately after turning a page, in order to be ready when the time comes.

4.3.2.5 Adapting processes to the musical genre

Generally speaking, certain pieces will require more adaptation "on the spot" on the day of the performance than others, for instance if a soloist is involved. Under those circumstances, the orchestra takes on the role of the accompanist and has to follow the conductor's cues to respond to the soloist's interpretation. In that situation, the conductor proactively gives indications to the soloist while also leaving them breathing space to interpret the music, and reactively adapts any cues to the orchestra to the soloist's performance. Conductors may also adapt their conducting style and method from one performance to the next for a number of reasons, not least depending on the music played. For instance, musical phrasing in baroque music – performance of which has tended to be more historically informed in the past two decades – places great emphasis on recurrent rhythmic-dynamic patterns. These may need to be stressed more than in Romantic music for instance, where the melody line may be the main object of focus and other elements are perceived as subservient. Within a piece, the conductor may differentiate between "vertical" and "horizontal" segments, with different types of cues and intentions communicated to the musicians. A Bach oratorio, for instance, will contain very different elements, including chorals, which are really a progressive succession of vertical chords, and fugues which are an exercise in interweaving horizontal melodic themes. Therefore, the true fabric and complexity of the music will best be brought to light by different expressive devices, depending on its predominantly harmonic (vertical, chord-based) or contrapuntal nature (relying on independent, yet compatible melodic lines).

4.3.2.6 Adapting processes to instrument sections

The participants furthermore stressed that the makeup of the orchestra will also determine what happens during conducting. Cues for strings are not the same as cues for winds, for instance. Breathing occurs differently, requires more or less time, as does the onset of the sound (for a review see Clayton et al., 2020). Therefore, the speed and head start of the cue will be different. In the same way, a crescendo or diminuendo may be indicated differently in the brass section because a strong crescendo might sound too loud or a strongly signalled diminuendo may interrupt the influx of air and the sound altogether. The conductor must bear in mind what reflex reactions the gestures they produce will likely yield from the various musicians (see also Meier, 2009, on orchestra and choir conductors).

4.3.2.7 Personal traits and preferences

Additionally, with appropriate regard to the chosen repertoire and potentially based on other considerations – personal strategies (cognitive habits and comfort zone, efficiency) or tastes (interpretation of a piece, consideration of a composer's biographical or historical background) – individual conductors may differ in their choices. Some feel more comfortable conducting by heart – some even without a score at all – while others rely on precious visual cues[46] to ensure that the performance is informed by the multi-faceted exercise of reflection that has taken place beforehand. In both cases, extensive analysis and memorising efforts are part of the conductor’s work leading up to the performance, and even leading up to the rehearsals. The choice of conducting with or without a score will determine the device(s) and processes the conductor relies on, and whether the performance is measured – continuously – against memory alone or against memory supported by visual cues. In the literature, Meier (2009) stresses the implications of that strategical choice: Conducting from memory offers an advantage in freeing the eyes for more visual contact with the musicians and for the communication of emotions. However, this may entail the risk that conductors worry about – or experience – memory lapses, which could stand in the way of the performance.

4.3.2.8 Conscious focus during the performance

When asked about what is going on in their minds during conducting, study participants insist on the issues of awareness, action and reaction. Some conductors indicate that they are sometimes simultaneously aware of their internal (memorised and anticipated) music and the external music, and sometimes switch from one to the other. In the same way as interpreters work with a time lag separating the input they hear from the output they produce, there is a time lag between the conductor’s gesture and the sound from the orchestra, a sort of gesture-to-sound span. Therefore, some conductors are aware of thinking ahead, whether their gestures occur much ahead of time or not, as they are following the red thread of the intended music. Conducting is made easier by gazing at the orchestra as a whole. The beat and gestures are guided by the internal, intended music, and everything that is heard is compared to that baseline for balance, tempo, intonation, dynamics and phrasing. When further intervention by the conductor is needed to adjust something that is diverging from what was intended, reactivity is of the essence. Not least, as it will also determine how quickly the conductor will

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[46] Annotations and symbols on the score, which are not unlike notes on a speech for simultaneous interpreting with text. Such annotations can include notes to self, like “slow down here” (e.g., not required in the original piece but necessary in order to avoid an otherwise potentially chaotic effect), “listen to [specific instrument]”, circling of a note to be brought out in a chord, colour cues for various recurring structures or themes, etc.

be able to turn back to the mental red thread they follow. However, that red thread is not constraining: No two performances are conducted in the same way. There is room for spontaneous intent, and some conductors reported feeling a sense of performative thought on occasions where their intent seemed to immediately materialise in the realisation by the orchestra. One conductor mentioned an instance of having to conduct a performance while (temporarily) auditively impaired. This made their work difficult, as their reaction to the output had to be based mainly on visual cues from the orchestra. However, the conductor was able to focus more on their own intent and the final result was quite satisfactory. The participant explicitly refers to Celibidache's concept of "music phenomenology" (Celibidache, 2008, 2012), where the conductor acts as a unifying conscience, whose purpose it is to understand and transmit the intrinsic properties of the musical piece for the present audience to experience. This entails declarative knowledge of the physics of music, of the various playing techniques and of the notes. But it also requires an intense, moment-to-moment mindfulness of each note's relationship to every other note in the musical piece. For conductors following this vision, this comes with total consciousness coupled with total openness to the music, and the ability to sometimes withdraw entirely (i.e., cease conducting for a moment) to let the sound sequence develop as organically as possible.

The double focus of conductors on internal and external music is also highlighted in the literature: Boulez described it as keeping a form of distance from the piece, or as it were, painting a picture and looking at it (Di Pietro, 2001). Rudolf (1950) phrases this necessity as follows:

> Despite intense involvement in the music, some part of you must act as a control mechanism and prevent you from losing yourself in the music to the extent that your ears no longer bring an objective perception of what the musicians are doing. In this way, you will be able to think ahead and be alert for any emergency, and the players feel that they can rely on you in any situation. (p. 307)

4.3.2.9 Conducting as a complex task

All in all, conducting consists of making movements while bearing in mind a considerable amount of information – all the more so when conducting from memory. Many transitions and complex combinations are well-rehearsed and already consolidated before the performance. However, there is a long oral tradition among musicians – as well as some urban legends – reporting certain conductors' notorious ability to combine complex tasks, illustrating how conducting has long been perceived as a form of concurrent multitasking.

This perception is probably linked to the conductor's essential, visible role in managing rhythmic patterns – including competing ones – as they occur simultaneously. It is therefore interesting to note that conductors who also conduct opera find that "simply" directing an orchestra feels almost automatic in comparison. The added task of directing the singers and paying attention to what is happening (musically) on stage, to then adapt the orchestra's output accordingly, turns the actions involved in orchestra conducting into one unified task in their mind to combine with the monitoring of the stage. The possibility of a greater degree of automation suggests that specific pathways have been established in the conductors' minds for these processes and their coordination. However, participating conductors experienced both in opera and concert settings stress that their conducting determines much more of what the orchestra produces during a concert. This underlines that good conducting (and good music) goes beyond ensuring synchronicity and correctness of intonation. Conducting is also more than a series of gestures: The participants in the study did not mention focusing particularly on the technical aspect of gestures, which suggests that this is already very much automatised in experimented conductors. In the literature on conducting technique, Schuller (1998) remarks that what matters most is what the conductor does *between* the beats. Conducting is not supposed to simply consist of time-beating: Where the art resides and how the music is shaped depends first and foremost on how the conductor moves from one beat to the next. Or as Arturo Toscanini, a famously demanding conductor, said: "Any *asino* can conduct... but to make music, eh? Is *difficile*!"[47]

The following review further explores the cognitive processes involved in successful conducting as described above and looks into the attentional and control-related requirements of that activity. The focus will lie first on the psychomotor aspect of conducting, and then on parallel temporalities, that is the delay between action and feedback, with emphasis on the cognitive implications in the case of performance from memory and sight-reading. We will sum up the required temporal as well as auditory and spatial focus shifts, to finally zoom in on characteristics of the type of multitasking likely involved in carrying out the complex task of orchestra conducting.

4.3.3 Control processes during conducting

During performance conductors need to entirely become a conduit for expression: They are perceived as an entity embodying the music, and not only the orchestra but also the

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[47] *Asino*: Idiot (lit. donkey, ass); *Difficile*: Difficult. Source for the quotation: Antek (1963), p.16.

audience's perception and evaluation of the music depend on the conductor's expressive gestures and devices (Kumar & Morrison, 2016; Morrison, Price, Smedley, and Meals, 2014). Therefore, all aspects of their external attitude need to channel the intended expressiveness, and conductors are supposed to avoid extraneous visual signals in the same way as interpreters need to make sure that everything that goes over the microphone is part of the message. As Rudolf (1950, p. 307) instructs: "Every gesture you make should be meaningful to the players". This includes facial expressions, which are a key vehicle to communicate the conductor's intention to the orchestra (Wöllner, 2008). Even general body movement needs to be kept in check. The conductor, therefore, needs sustained postural and gestural self-control (Wöllner et al., 2012).

For novice conductors, one of the difficulties in the first stages of skill acquisition is to inhibit their natural reflex of reacting to the beat and to suppress involuntary bouncing (see Philips, 1989). They also have to change their postural habits and internalise new ones (such as broad shoulders, lifted elbows, etc.). The acquisition of conducting technique (see, e.g., Meier, 2009) involves learning the widest range of gestures, motions, and signs. The gesture repertoire acquired and internalised by conductors is very personal (conductors are typically able to recognise their own gestures and distinguish them from other conductors'; Wöllner, 2012, 2014b) and may vary across teaching traditions. The gestural vocabulary also encompasses emblems, that is, consistent items that musicians recognise across ensembles (Sousa, 1988). This probably factors into the ability of ensembles to follow a new conductor's lead. Conducting technique relies on extremely fine motor control skills: These involve not only continuous time-keeping and modulation, but also the timing of precise motor events (for instance, indicating entries on the various beats of a musical bar), velocity and fluidity control (larger or smaller gestures, softer or sharper angles, more or less rebound on the beats – all depending on the dynamics and expressive indications of the music). Moreover, motor coordination is also needed to integrate manifold elements, like the various considerations above, but also different instruments entering at various points in a bar or phrase, complex rhythms, and importantly, the fact that both hands serve different functions and that their movements are mostly dissociated. This brachial independence allows devoting one arm to marking the beat and the other to enhancing phrasal qualities, entries, cues or stopping signs, or the occasional concurrent rhythm for a given instrument, and turning pages. In expert conductors, the integration of all these elements is already acquired as we have seen earlier, and their focus during performance is on the desired result rather than the process (see also

Hasty, 2004). Not only are their gestures clearer, allowing better synchronisation, but they show very little variability (Wöllner et al., 2012).

As we have seen, the motor control of these patterns and movement sequences is probably automatised to a large extent in experienced conductors. However, many aspects of this purely "gestural" part of conducting probably still require some degree of cognitive control. These aspects include, but are not limited to, irregular or concurrent rhythmic patterns, or changes that require an adjustment of the beat-marking motion, such as meter changes (e.g., from 4/4 to 3/4) and changes in articulation (e.g., from *legato* to *marcato*). Tempo changes can additionally rely on computing a ratio (e.g., a possible common subdivision of the beat) on which to base the transition between the current and the new tempo, and – depending on the immediacy or the progressivity of the change – either stopping and restarting, or modifying the beat marking accordingly.[48] What is more, all of these new developments in the piece must be communicated efficiently to the relevant parts of the orchestra at the right moment prior to their occurrence. These instances can be thought through and practiced before performance, and during performance, the mental representations formed are likely to guide the execution of these actions as well as the exertion of control.

However, the conductors' task goes beyond expressing their musical intentions by means of gestures. Simultaneously, conductors also need to mentally (and visually, when a score is present) keep track of the musical piece and to monitor the players' output (Wöllner & Halpern, 2016). Therefore, conductors need to maintain a mental – aural – representation of the piece as they wish to hear it (Chaffin, 2011; Green, 1969), which becomes dynamically available as they conduct. Moreover, when reading from a score, even if it has been rehearsed, the conductors need to chunk (i.e., compile) the information from a few instrumental parts up to two or three dozen, depicted in as many staves on the page, and plan ahead on that basis (see Drake & Palmer, 2000; Lehmann, Sloboda, & Woody, 2007). It is likely that the motor planning is integrated within this dynamic performance goal and that the representation which guides conductors' behaviour is multimodal (Keller, 2001; Palmer, 2013). In any case, this suggests that conductors rely on proactive control to maintain a strong representation of their performance plan.

In addition, the conductors' actions occur between parallel continuous timeframes. The first is the mental or visual-mental timeframe, in which the representation of the piece is made

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[48] For practical details regarding technical gestures involved, see conducting manuals, e.g., Farberman, 1999; Meier, 2009; Rudolf, 1950; or specific pedagogical articles, e.g., Griglio, 2019.

available. It informs the second timeframe, the gestural timeframe, which can be very close but not necessarily identical, especially in the case of sight-reading. The third timeframe is that of the output. Conductors usually anticipate the beat in their gestures (Wöllner et al., 2012) due to different instrumental onsets and as a function of attack timing (Rasch, 1988). The gesture happens up to 1 second before music onset, placing a continuous asynchrony on the mental and perceptual auditory thread of the conductor. Therefore, auditory feedback on the accuracy of the realisation of the conductor's internal representation (Chaffin, 2011; Nager et al., 2003) and the detection of errors in musicians' playing do not occur immediately. While error detection is part of the conductors' task, this delay probably has consequences on the extent to which conductors can afford to rely on that mechanism while also maintaining a smooth performance.[49] Often, during rehearsal, the conductor makes a mental note of the problematic bar and instrument section to correct at the end of a given segment, once the orchestra has stopped playing. During performance, conductors may need to react quickly with the proper gesture(s) to avoid a loss of synchronisation or an imbalance in dynamics compared to the desired product. In addition, orchestra conductors do not improvise the same way that solo musicians sometimes do, but there is an element of improvisation in the fact that they can, on the spur of the moment, decide to bring out elements of expression that have not been rehearsed and that seem to emerge organically from the current performance. Therefore, context monitoring processes are also involved. This awareness of the performance product and the flexibility to amend the performance plan likely relies on processes that also underpin improvisation, which is thought to require some degree of cognitive control alongside automatic processes and is served by brain regions involved in both proactive and reactive control (Beaty, 2015).

In sum, the dynamically changing context places fluid demands on the conductor (Chaffin, 2011). The controlled processes involved in conducting are likely to rely to a significant extent on proactive control: This allows conductors to lead and therefore to think ahead, and to remain consistent and fluid in their indications, so that the musicians themselves can confidently anticipate the musical orientation that is being communicated to them. However, the flexibility that is also required probably demands a combination of proactive and reactive control. Since the various processes described above require control, the major question raised is what incidence their simultaneity has on the exertion of control. In any case, optimal

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[49] Attempts at creating robot conductors fall short inter alia in that they lack the ability to evaluate the tempo and volume of the musicians' output and react to it, and are more generally unable to modify their performance plan (see Salgian, Agina, & Nakra, 2014).

performance may benefit from a state of flow (Csikszentmihályi, 1990; for evidence in conductors see Jaque, Karamanukyan, & Thomson, 2015), which likely involves a balance between automatised and controlled processing. The extent to which cognitive control is involved in such states and the level of proactive and reactive control mechanisms is still unclear, but there are pointers suggesting the activation of top-down cognitive modulation mechanisms (Gold & Ciorciari, 2020) that are characteristic of proactive control.

4.3.4 Divided attention and multitasking in conducting

This study looks into the mechanisms underpinning successful continuous multitasking performance. It is therefore of interest to explore the complex, continuous processes involved in conducting in order to shed light on the extent to which controlled processes can occur in parallel. However, conductors have been little studied from that vantage point (see Wöllner & Halpern, 2016).

While conducting, in addition to leading the orchestra, the conductor needs to keep in mind the structure, hierarchy and articulation of musical themes and subthemes developed – sometimes in parallel – in a particular piece; the respective rhythm and phrasing of several instrument sections; and specific cues or prompts to provide to one or the other section in addition to the indications directed towards the whole orchestra. Nager et al. (2003) stress the necessity to simultaneously combine two simultaneous and complex forms of attention shifting: The need to consecutively or continuously focus on one specific instrumental soloist or section and to monitor the totality of the auditory scene, and the recurrent need to compare the auditory output produced to an inner model of expected musical pattern and effect. The fact that novice conductors find it difficult or fail to attend to the ensemble's rendition of the score they are directing (Hasty, 2004; Chaffin, 2011) shows that, at least prior to sufficient practice, doing so relies on concurrent attentional processes. Chaffin describes conducting as a multitasking context in which the primary dual task of making movements based upon preconceived representations of the music is combined with divided attention requirements between the conductor's own production and that of the ensemble. Wöllner and Halpern (2016) insist on the distinction between two abilities that this requires: Divided attention on the one hand, and the ability to switch focus – revealing of attentional flexibility – on the other.

Conductors need to attend to many different types of stimuli, though it is unclear whether they switch entirely between them or increase their focus on the one or the other within a more integrated consciousness of the performance. Even within one sensory mode, conductors may be required to move their central focus. Their visuo-spatial focus moves from an individual focus on the score, or one specific musician, or one instrument section, to a general focus on the whole of the orchestra. Their auditory focus needs to move both in space (zooming in on a specific instrument part or listening to the whole production) and between internal or external sound representations (Chaffin, 2011; Nager et al., 2003; Wöllner & Halpern, 2016). In addition, different temporal aspects – anticipation or reaction –are involved in focusing on these various elements.

Regarding the auditory focus, it appears that conductors can identify the origins of sounds with more accuracy than pianists or non-musicians and thus better distinguish between spatially dissociated stimuli (Nager et al., 2003). This ability helps them to detect errors in the various instrument sections with a high degree of accuracy (Lehmann et al., 2007). In addition, ERP measures showed that musicians pre-attentively monitor a wide auditory space even while focusing on a specific point within that space, and that in conductors, a deviant stimulus detected triggers signals revealing of readiness to shift attention (Nager et al., 2003). The authors highlight that the enhanced pre-attentive monitoring signals may be attributed either to the effects of the musical experience on earlier error detection, or to the fact that musicians allocate some attention outside of their intended auditory focus. In conductors, in any case, these signals are interpreted as relevant for further action.

Thus, conductors appear to better, and proactively, monitor auditory context, as well as to efficiently adapt. Regarding the issue of the continuity of focus, Wöllner & Halpern (2016) specifically tested conductors' divided attention capacities. They compared conductors and pianists and students in both disciplines in a selective attention task and a divided attention task using two melodic streams, distinguished through differences in timbre and onset. The streams included slight deviations in rhythm or pitch, and participants had to tap as soon as they detected such a deviation. The participants focused only on one stream in the selective attention condition, and on both streams simultaneously in the divided attention condition. No significant difference was found between conductors and pianists in the baseline task (only one stream played) and the selective attention condition, but in the divided-attention timing task conductors performed significantly better – with experienced conductors better still than students. Thus, in addition to showing cognitive flexibility – a prerequisite to successfully switch between selective and divided attention – conductors seem to be able to process two continuous auditory streams simultaneously.

The present review on musicians, ensemble playing, and conductors specifically highlights how musical experience involves and appears to foster not only psychomotor, but also cognitive control processes, including in a variety of non-musical tasks. However, it should be noted that this does not always translate into differences in behavioural measures for those tasks (e.g., Jentzsch et al., 2014; see section 4.1.2). Musical experience in general is likely to be associated with increased reliance on proactive control. This also applies to conducting specifically: Behavioural adjustment while on-task, that is, during performance, should be modulated proactively rather than reactively, especially in conductors. However, it remains essential for musicians to monitor extraneous stimuli, especially in an ensemble setting, and to remain flexible so they can continue to adapt to their environment. Optimal performance would require both proactive maintenance of the performance plan and reactive monitoring and adapting processes to occur in parallel rather than in succession.

Musicians' and conductors' multitasking abilities have been little explored so far, and it remains to be seen whether musicians' superior ability to selectively extract stimuli in complex environments and to divide their attention transfers to carrying out continuous tasks concurrently (Chaffin, 2011). In the case of conducting, the experience of professional conductors suggests that, at least with training, one such form of continuous multitasking can be achieved. However, this indicates that the necessity of processing each component task separately creates difficulties, which are eventually overcome by automatising and/or integrating some of the processes.

5 Aims of the present study

5.1 Questions arising from the literature: Variables influencing multitasking

It appears from a closer look at two complex task expert groups that many questions remain unanswered regarding the possibility of multitasking skill transfer, starting with the nature of multitasking skills. The role of cognitive control during continuous multitasking and its interplay with multitasking performance also remain to clarify. To conclude the theoretical overview on controlled processes during complex tasks, we will endeavour to briefly lay out what current insights suggest we can expect from expert multitaskers faced with a new multitasking situation. We will also examine possible covariates of multitasking performance.

As complex tasks, simultaneous interpreting and conducting are comprised of automatic and controlled processes (Bajo & Padilla, 2015; Chaffin, 2011). In SI, processes like the perception of the source language appear to take place automatically; Others require a form of deliberation. For instance, the interpreter needs to make a decision to start speaking, based on an evaluation of whether enough information is available from the source speech. This requires weighing two potential risks against each other: On the one hand, starting too soon, without any visibility (i.e., insight on further incoming elements), increases the danger of having to predict and making incorrect predictions; On the other hand, lagging too far behind entails the risk of overwhelming one's WM capacity and losing content. In conducting, acoustic perception also happens automatically, but it has to be compared to the intended product, a comparison which entails constantly bringing one's attention on the next segment of that intended product.

Both activities are time-constrained and happen "online", that is, in real time, with few to no possibilities of correcting an error. In addition, in both cases, the performance needs to be perceived as seamless by an audience. Regarding SI, the work of the interpreter should be as invisible as possible during a speech to not interfere with a sense of direct perception of the original speaker's intent.[50] Regarding conducting, the work of the conductor is supposed to be visible, as this contributes to a multisensory perception of the expressivity of the music (Morrison et al., 2014; Wöllner, 2008), but on the condition that the gestures are consistent with the music and the performance is of high quality (see Kumar & Morrison, 2016, for a

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[50] This notwithstanding the importance of not being perceived as a machine by the listeners and various stakeholders.

review). As such, although the task components in conducting and SI pertain to diverse domains, it is likely that conducting, like SI, places "exceptional demands" (Hervais-Adelman et al., 2014, p. 4227) on both continuous (task set maintenance) and moment-to-moment control (Hervais-Adelman & Babcock, 2019). As we saw earlier, two intertwined systems seem to be involved to serve both modes of control (Braver, 2012; Hervais-Adelman & Babcock, 2019; Unsworth, 2012).

Anticipation, expectation, prediction, planning and thinking forward are functions that are relevant in both language and music cognition. To process linguistic and musical structures, bilinguals and musicians appear to rely on networks that overlap to a major extent, including regions associated with cognitive control (Slevc & Okada, 2015). Furthermore, they share apparent advantages over non-bilinguals and non-musicians in non-linguistic and non-musical inhibition tasks (Bialystok & Depape, 2009; Schroeder et al., 2016) even though domain-specific advantages also appear in processing auditory stimuli (pitch or words) related to their respective specialised experience (Bialystok & Depape, 2009; see also Wöllner & Halpern, 2016). Findings from brain imaging studies on musicians on the one hand and simultaneous interpreters on the other hand seem to point to functional changes above and beyond certain domain-specific processing regions (e.g., Sluming et al., 2002). As stressed in Miendlarewska and Trost (2013), in musicians these changes are noticed in regions which control primary musical functions or are used for the multimodal integration of musical skills, and therefore, may serve potential skill transfer between musical and other skills. Luo et al. (2012) found increased functional connectivity in motor and multi-sensory areas in musicians in the resting state, suggesting that coordination between motor and multi-sensory networks may be better trained in that population. Such findings can be compared to functional changes highlighted by Hervais-Adelman et al. (2015) in trained vs. novice interpreters, possibly related to improved complex task management. These instances of improved coordination may however highly depend on the degree of automation and integration of processes specific to the various activities.

Distinct constraints are placed on interpreters and conductors when it comes to how task representations are maintained and updated, as highlighted in Chapters 3 and 4 of the present review: While conductors primarily maintain their own performance plan active to lead the orchestra, thus relying on endogenous representations and their own initiative, interpreters need to constantly inform and update their production plan, relying on external cues. Therefore, while both activities require a fine balance between proactive and reactive control mechanisms, it appears that conductors need to adopt a primarily "leading" mindset, whereas interpreters need to adopt a primarily "following" mindset, in order to perform optimally. This is likely to have consequences on the flexibility of task representations (see, e.g., Yudes et al., 2011, 2013; Stavrakaki et al., 2012). However, the two modes of cognitive control appear to be associated with the reward and valuation system (e.g., Shenhav et al., 2013; Tombu & Jolicoeur, 2012), and as such may be linked to individual motivation to rely on already acquired, internal representation or conversely to acquire new information (Beeler, Cools, Ostlund, & Petzinger, 2014; Chiew and Braver, 2017).

These control mechanisms may also have different implications for the general ability to multitask. Unlike media-multitasking, which is characterised by an openness to distractors and apparent detrimental effects on cognitive control (see Loh & Kanai, 2014; Ophir et al., 2009; Uncapher, Thieu, & Wagner, 2016; cf. Alzhabi & Becker, 2013[51]), continuous multitasking in the context of complex tasks is expected to rely on cognitive control in order to sustain an adequate level of performance in the component tasks. With training, multiple tasks can be facilitated by the automatisation of some of the processes, or by the improved coordination or self-organisation (acquired scheduling) of certain processes (Strobach, Frensch, Soutschek, & Schubert, 2012; Schubert, Liepelt, Kübler, & Strobach, 2017), reducing the need for strategic control (Just & Buschweitz, 2017). Greater automaticity may also be associated with the development and strengthening of dedicated representations and pathways for tasks that otherwise rely on more general representations (Musslick et al., 2016). Consistent with this assumption, Hirst et al. (1980) find concurrent multitasking abilities attributed to the acquisition of skill in participants trained in reading texts while typing from dictation. Automaticity is ruled out by these authors as the participants were able to process and understand the content of both sources of information; however, we have seen that there appears to be a continuum between automaticity and control, which may depend on the degree to which conflict is still generated in shared representations for the execution of a task (Musslick & Cohen, 2019). Relying on reactive control is thought to foster automatisation, contrary to relying on proactive control, which fosters the use of explicit strategies (Braver, 2012).

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[51] Alzhabi and Becker (2013) found that participants who media-multitasked more frequently did not perform worse in a dual number-letter task, and performed better in the single, task-switching condition, than controls. However, this type of task does not place load on WM and requires high flexibility in updating and integrating rules in reaction to stimuli.

However, proactive control may contribute to setting task boundaries for complex tasks that contribute to encompassing the component tasks within a global hierarchy, thereby promoting integration (Freedberg et al., 2014). The acquisition of skill and the organisation of the processes serving a complex task – including the greater or lesser automaticity of the processes at the various hierarchical levels – seem to crucially depend on the goal structure that is established (Tenison, Fincham, & Anderson, 2016). From the above insights on cognitive control and its associated mechanisms, it appears plausible that task consolidation in experts happens at least partially through strengthened goal representation. This raises the question whether specific multitasking expertise entails stronger goal maintenance in new multitasking contexts, which may in turn reduce flexibility to learn new tasks, or whether on the contrary, experts show greater flexibility between proactive and reactive control thanks to associations that have been strengthened.

In addition to specific multitasking experience, other individual variables may also influence reliance on one or the other control mode, like WM capacity (Kane and Engle, 2003; Unsworth, 2012), and some may affect multitasking performance. For instance, the question of gender-related differences in multitasking is often raised; however, current research does not support differences in multitasking abilities beyond the possible effects of individual experience – itself often determined by gender – on specific domains, like the processing of spatial information (Strayer, Medeiros-Ward, Watson, 2013; see also Hirnstein, Larøi, & Laloyaux, 2019, for a review). Age – and WM variations with ageing – may modulate individual's control strategy, with older adults favouring reactive control more than younger ones (Paxton et al., 2008). IQ has been comparatively little explored in connection with dual-tasking or multitasking abilities, other than to warn against the negative effects of habitual media multitasking on intelligence measures (e.g., Minear, Brasher, McCurdy, Lewis, & Younggren, 2013). However, it appears that domain-general control, often associated with WM and attentional capacity, is also related to fluid intelligence (Cochrane, Simmering, & Green, 2019). Engle and Kane (2004) also assume an association between working memory capacity – encompassing not only WM span but also rehearsal strategies and executive attention necessary for goal maintenance – and fluid intelligence; this is supported by Burgess and Braver (2010), who highlight the link between fluid intelligence and the tendency to resort to proactive control. Regarding the *n*-back task in particular, single- and dual-*n*-back task scores were correlated to Wechsler intelligence scale scores (Saxena, Majnemer, Li, Beauchamp, & Gagnon, 2019), though in that study dual-tasking costs per se were not. In

Jaeggi et al. (2010), training in single and dual *n*-back was correlated with improvements in fluid intelligence as measured by matrix reasoning. This transfer was also found to depend on other factors of individual variability, such as beliefs regarding the possibility to shape one's cognitive abilities (Jaeggi, Buschkuehl, Shah, & Jonides, 2014), suggesting a complex interaction of individual factors in cognitive performance. Dual-tasks are expected to be more sensitive than single-tasks to measures of global cognition, including to measures of various components of intelligence (e.g., Ben-Shakhar & Sheffer, 2001; Stankov, 1988). In addition, the first administration of a dual-task may be more correlated to global cognitive measures than subsequent administrations (e.g., Ackerman, 1987; Ben-Shakhar & Sheffer, 2001). This may reflect growing automatisation in subsequent administrations and the decrease in reliance on cognitive strategies and attentional processes; Therefore, it may be worthwhile to study multitasking performance across time.

5.2 The present study

This study investigates performance and control processes in concurrent dual-tasking in simultaneous interpreters, orchestra conductors and a control group of participants whose professions do not require time-constrained continuous multitasking, such as written translation, research, or teaching.

5.2.1 Background

As we have seen in Chapter 2, a series of models based on the cognitive control framework (Botvinick et al., 2001; Yeung et al., 2004; Botvinick & Cohen, 2014), the dual mechanisms of control framework (Braver, 2012; Braver et al., 2007), as well as the expected value of control hypothesis (Shenhav et al., 2013) converge in proposing a complex control system where control is applied in the most parsimonious way possible to allow the completion of task-relevant goals. This implies that the system is able to maintain an active representation of these goals and to factor in the possible hierarchical organisation of sub-goals to proactively modulate the signal in task-relevant neural pathways ("Proactive Control"). The system also encompasses an adaptive adjustment component to serve these goals, in which conflict monitoring serves to trigger a reactive control mechanism as a function of evolving demands on the system during the completion of the task ("Reactive control"). Feng et al. (2014) further propose that forcing sequentiality, or dissociation, on processes that call upon the same representations, is actually a feature and not a limitation of control. In a dual-task setting, this view would imply that control serves to dissociate the processes involved in pursuing both task goals. The easiest way to do so would be to simply direct the signal away from the least relevant task at a given moment, which seems to be the case whenever the tasks allow it (see "perfect time-sharing" experiments, e.g., Schumacher et al., 2001; see also Strobach, Liepelt, Pashler, Frensch, & Schubert, 2013; Schubert et al., 2017). However, the present study seeks to investigate whether two tasks calling for continuous controlled processes (in this case, the sustained exertion of two specific executive functions: updating and monitoring) can be performed successfully at the same time. As underlined at the end of Chapter 2, optimal performance would require that the neural signal for both tasks be adjusted dynamically ("traffic regulation") rather than in an all-or-nothing ("switchman") manner when it is absolutely necessary to maintain representations active in WM, as is the case here. We can shed light on the control allocation and adjustment process by using a specific combination of tasks involving targeted constraints, as well as recording control-related measures during their completion.

5.2.2 Concurrent multitasking

Concurrent multitasking in a dual task paradigm is characterised by the fact that controlled processes related to both tasks need to happen in parallel and not serially. Testing whether continuous multitasking indeed takes place rather than task switching requires exercises which rely on the constant dual use of specific executive functions such as monitoring and updating.

5.2.2.1 Parallel exertion of executive functions: Updating and monitoring

In order to ensure the continuous and parallel exertion of EFs, tasks are needed that require the use of these functions in a way that does not allow removing content held in WM. This can be achieved by combining single tasks into dual tasks based on clearly defined EFs. Adding a parallel task has frequently been used as a means to trigger automation where possible and to distinguish between control-involving tasks and automated ones (Schneider & Shiffrin, 1977; Schneider & Chein, 2003). In the present case, our experimental tasks are novel for the participants, and each designed to activate not only the representation of items in WM but also their manipulation, in this case, updating. They were designed to place only moderate load on WM capacity to avoid introducing any confusion between WM capacity and the EFs involved.

The two-back task (see section 6.2) fits these requirements. Due to the element of target recognition through familiarity which it involves, the progressive *n*-back task (Kirchner,

1958) has been challenged as to its ability to measure WM capacity (Kane, Conway, Miura, & Colflesh, 2007); however, this is not the purpose here. Indeed, only one of the degrees of recalling difficulty, the two-back task, is used, which places constant, relatively light requirements on WM capacity, and stimuli are not repeated within blocks except for targets. In addition, while this set size does require constant WM updating and monitoring for optimal performance, the task involves fewer complex processes than many other tasks used to measure executive functions.

The second task, mental beep-counting, also requires active storage and manipulation of items in WM: In order to avoid long-automated counting processes overtaking active count-keeping in WM, our beep-counting exercise includes two intertwined series of (high and low) tones, played in random order, to be counted separately. Any possible continuous counting process is interrupted by the constant necessity to keep track of, and update, both current counts. Furthermore, any reset of the WM content precludes success in the task, as accuracy depends on having been able throughout to closely follow both evolving counts.

The combination of the above tasks creates a condition where the same executive processes, monitoring and updating, are triggered for separate goals with minimal leeway for temporal re-organisation. This places extreme constraints on the control system, limiting opportunities for serial processing and allowing us to test its capacity to respond to the parallel tasks demands. Failure to do so inevitably results in a breakdown of performance in one or both tasks. For each dual-task exercise, multitasking cost is calculated as the difference between single-task (baseline) and dual-task condition.

5.2.2.2 Processing speed

It has been suggested (e.g., Dux et al., 2006, 2009; Garner et al., 2014) that higher processing speed is associated with better multitasking performance. According to these authors, this would be the case if speed facilitated the serial processing, constrained by control, of conflicting representations, and therefore single-task training suffices to facilitate multitasking performance. A positive association between speed and performance would also be noticed once pathways had been strengthened (Cohen et al., 1990) or once separate, specific representations for each task were created, in turn providing the possibility for their automated processing (Musslick et al., 2016). Consequently, it is of interest to see 1) whether faster performers in the present experiment consistently also perform better in both tasks of the dual task in its first occurrence and 2) whether the association changes after single-task training.

5.2.3 Reactive and proactive control

The balance between both control mechanisms (proactive and reactive) seems to be essential for optimal task completion. However, mental habits and personality traits are believed to influence individual tendencies to lean towards the one or the other. The complementary, yet partly contradictory nature of performance adjustment in reaction to incoming stimuli or as a function of a given goal (see section 2.4) becomes salient in a situation of continuous multitasking, where the necessary maintenance of competing goals and the need to adjust performance to optimize response on separate accounts each suffice to place a major strain on the system.

When studying multitasking capacity, it is therefore necessary to account for both of these underlying mechanisms. Experts in various complex tasks with a component of cognitive control can be expected to show individual as well as group differences in the control habits they have developed, which in turn may influence their multitasking performance.

Reactive control (Braver, 2012; Braver et al., 2007) relies on conflict monitoring, which detects conflict at the response level and signals a need for control adjustment in the relevant pathways. Post-error slowing (PES) (Rabbitt, 1977) has emerged in the literature as a measure of conflict monitoring (see section 2.4.2.4). The longer response time in correct trials immediately following an error in comparison to the trial immediately preceding it, is regarded as a reliable indicator of the activation of the monitoring system (Botvinick et al., 2001). It is commonly considered an increase in response caution, which allows the subject to adjust her level of control before the next response in order to maintain her level of accuracy. PES, i.e., the difference in response time between items following an error and items following accurate responses, is measured taking into account post-error RT and pre-error RT only, in order to avoid possible biases, like possible training effects during the task (see Dutilh, van Ravenzwaaij, et al., 2012).

Proactive control, on the other hand, is based on reinforced goal representations, which modulate the intensity of signal in task-associated pathways from the top town. Success in meeting task goals on a continuous basis in control-demanding tasks is therefore revealing of the control processes at work. Goal-maintenance measures, explored in section 2.4.3.5, are sometimes difficult to disentangle from accuracy measures: Achieving accuracy in a setting which calls for constant control due to the nature of the task itself and to competition between parallel goals, does provide a fairly solid indication of successful goal maintenance. Goal maintenance and neglect are therefore usually measured using accuracy scores in tasks calling for proactive control. In an experimental dual-task setting, however, priority instructions provide a way to require proactive control over attention allocation (Kramer, Larish, & Strayer, 1995; Gopher, 1996; Anguera et al., 2013; Bier, de Boysson, & Belleville, 2014; Bier et al., 2017). Goal maintenance is then measured using accuracy in the task that participants were specifically instructed to give priority to. In the present study, such instructions are provided regarding the beep count, where the final accuracy directly depends on having maintained the mental count active throughout the task.

5.2.4 Group advantage

5.2.4.1 Ability to multitask

Individuals differ in the way they exert cognitive control, and in their multitasking abilities. Professionals like interpreters and conductors routinely carry out specific complex tasks. While it is possible that some multitasking abilities may be present in candidates who go on to successfully carry out those activities (see Strayer and Wilson, 2010), such abilities are amenable to training. The possibility of complex-task training extending to domain-general abilities remains unclear. If such is the case, interpreters and conductors should have an edge in a new dual task over individuals in professions that do not routinely rely on concurrent multitasking. Therefore, interpreters and conductors should perform better in the dual task and show less multitasking cost compared to the single component tasks than controls.

5.2.4.2 Specific control processes

As discussed in Chapter 3, bilinguals in general are thought to show adaptive language control and can be expected to exert noticeable conflict monitoring if this linguistic control pattern is transferred domain-generally; Interpreters, because of the type of task they are trained to perform, are also expected to show a heightened tendency to use reactive control, measurable in the form of PES. Musicians, and to a larger extent still, conductors (see Chapter 4), rely heavily on anticipation and representation maintenance for music processing and performance, and might be used to modulating control a priori. If bilingual or musical experience shapes proclivities in the exertion of control outside of the linguistic or musical realm, bilinguals and musicians may be expected to rely more, respectively, on either control mechanism when faced with a new complex task.

5.3 Research questions and hypotheses

In addition to addressing the following research questions, the theoretical reflection allows us to formulate the hypotheses below, which are tested in the experimental routine.

5.3.1 Concurrent multitasking

RQ1:

Are there behavioural indications of parallel information monitoring and updating in the context of new continuous complex tasks?

Hypotheses:

1a. Performance in the dual tasks will be above chance across the experimental groups. The present paradigm is novel. If participants are able to carry out two concurrent tasks, even if both of them require cognitive control, it is expected that they will perform satisfactorily, though not at ceiling, in the tasks (e.g., Jaeggi et al., 2007; Watson & Strayer, 2010; Heathcote et al., 2015). However, failure to do so will result in performance below chance (Heathcote et al., 2015; Just & Buschweitz, 2017).

1b. Multitasking cost: Across the sample, there will be a decrease in performance, manifest in reduced accuracy and increased RT – when measured, in the 2-back and beep count task between the single and dual condition. The cost should be higher with higher control demand (e.g., for dual-tasks paradigms Navon & Gopher, 1979; Pashler, 1994; Meyer & Kieras, 1997a; Dux et al., 2006, 2009; for a continuous visuomotor tracking task with a perceptual discrimination task and motor response Bender, Filmer, Naughtin, & Dux, 2017; for dual comprehension Buschweitz et al., 2012; for dual *n*-back tasks Heathcote et al., 2015; Jaeggi et al., 2007). Therefore, the decrease in performance should not be observed in a dual beep count and choice key press task where the response modalities (covert, verbal on one side, motor on the other) are compatible and the key press task relies on the same stimuli and may help process them for counting.

1c. Watson and Strayer's "supertaskers" hypothesis: Some participants in the sample will perform well in both tasks involved in a continuous dual task. Watson and Strayer

(2010, 2012; Strayer & Watson, 2014) repeatedly found that a subset of the tested participants, around 2.4 to 4%, were able to multitask with remarkably little or no cost without prior training in the continuous multitasking paradigm at hand (e.g., driving while performing an OSPAN). This is ascribed to a combination of WM attributes and efficiency in cognitive control networks (Medeiros-Ward et al., 2015). If this ability is found consistently in the population, a small subset of the present sample should perform within one standard deviation of their baseline performance in both tasks (accuracy and RT in the two-back, accuracy in the beep count task) when performing them concurrently.

1d. Processing speed: Higher processing speed will be associated with better performance in the dual conditions, including after single-task training. Processing speed has been linked to better performance in dual-task paradigms; this may be related to greater automation (Shiffrin & Schneider, 1977), manifest in pathway strengthening (Cohen et al., 1990), and reduced reliance on shared representations (Musslick et al., 2016); Alternatively, it has been proposed that single-task training allows faster processing in a central processing bottleneck (Dux et al., 2006, 2009).

5.3.2 Multitasking in complex tasks as a domain-general advantage

RQ2:

Do professional interpreters and conductors perform more accurately or faster than controls in new continuous complex tasks?

Hypotheses:

2a. Interpreters and conductors are expected to perform faster and more accurately in the dual condition than the control group, and in both tasks of the task set, especially in the first occurrence of that task set. Findings regarding musicians' multitasking performance beyond dual-task paradigms are not clear-cut (Moradzadeh et al., 2015), but conductors seem to have an advantage in processing concurrent audio streams over pianists (Wöllner & Halpern, 2016). Interpreters were found to be faster and more accurate than multilingual controls in a dual-task paradigm (Strobach et al., 2015) and showed faster training effects in a dual *n*-back (Morales et al., 2015). However, these paradigms were all forgiving in case of a WM content resetting. If continuous multitasking skill transfer is observed, interpreters and conductors are expected to show a multitasking advantage, that is, better performance as groups in a new, untrained paradigm, over controls.

2b. Complex task expertise and multitasking cost: The decrease in performance between the single and dual condition will be lower in conductors and interpreters than in controls. If interpreting and conducting train the practitioners in coordinating two continuous tasks and flexibly adjusting control processes beyond their professional activity, interpreters and conductors are expected to show less multitasking cost (decrease in accuracy and increase in RT compared to the single tasks) than controls.

2c. Complex task expertise and processing speed: Interpreters as expert bilinguals will show higher processing speed than other groups in all tasks. Moreover, processing speed will also be correlated with the bilingualism variable across the sample (e.g., Bialystok et al., 2008; Costa et al., 2008; Hilchey & Klein, 2011; Marton et al., 2017).

5.3.3 Complex task expertise and control processes during multitasking

RQ3:

Do interpreters and conductors seem to rely, respectively, on more conflict monitoring and goal maintenance than controls in a situation of continuous multitasking (i.e., are conflict-monitoring-related measures and goal-maintenance-related measures different in interpreters, conductors and controls)?

Hypotheses:

3a. Interpreters and conflict monitoring: Interpreters will show higher post-error slowing and post-error accuracy than conductors and controls, indicating better monitoring skills. High monitoring skills are expected in interpreters as they are assumed to rely on reactive control to keep track of the incoming speech to update their representation of the speech and adjust or correct their predictions (see section 3.3.1).

3b. Conductors and goal maintenance: Conductors will show higher beep count accuracy in the dual tasks than interpreters and controls, indicating better goal maintenance. The beep count task requires to sustain the dual count to the end and neglect therefore entails large accuracy costs. Conductors are expected to show high levels of goal maintenance as they are assumed to rely on an internal, continuously maintained performance plan to guide the musicians (see section (4.3.3).

5.3.4 Other variables affecting performance

We will seek to account for the effects of age and non-verbal IQ in order to distinguish them as the case may be from the expected group effects. The potential effects of IQ and age on multitasking performance might also differ between the groups, depending on the way they exert cognitive control, and vary with musicianship and bilingualism across the sample, consistent with findings on reduced cognitive ageing and better performance in tasks requiring control in older bilinguals and musicians. In addition, we will seek to distinguish the potential effects of musicianship and bilingualism on multitasking performance from those of professional experience in interpreting and conducting.

Part II. The experiment

6 Methods

Experts in two complex tasks, simultaneous interpreting and orchestra conducting, are compared to controls to investigate whether their performance in novel dual tasks is conditioned by their experience and factors that may come into play. An experimental setting was created, which included a dual task requiring concurrent multitasking, as well as baseline tasks. Performance was assessed using accuracy and processing speed (RT). The dual task was administered at the start of the routine and repeated at the end to measure short-term training effects. All participants' musical and linguistic background was taken into consideration. Measures of reactive control (conflict monitoring) and proactive control (goal maintenance) were taken. Age, gender, non-verbal IQ, and bilingualism were recorded as control variables.

6.1 Participants

Participants in the experiment (n = 67) were 28 to 73 years old and belonged to one of three groups: interpreters (n = 26), orchestra conductors (n = 20), and controls (n = 21). Sample descriptive statistics are provided below (Table 1 and Figure 3). Participants were recruited via advertisements or via personal contact through e-mail addresses communicated with the participant's prior consent by institutions or mutually known third parties (the recruitment procedure is detailed in Appendix G). The two experimental groups were composed of professional interpreters or conductors with at least 5 years of experience to constitute a categorical rather than a continuous Group variable, in order to test the hypotheses at hand more effectively. By the same token, controls had been active in their respective professions for a minimum of 5 years. Controls worked in translation or translation studies (6), IT (4), Speech and language pathology (2), administration (2), education (2), research (2), health (1), law (1) and art (1).

The following recruitment criteria were applied: Participants had to be between 25 and 75 years old. Good comprehension of written English or French was required, to ensure the full understanding of simple instructions regarding the various tasks, of the conditions of participation and of the consent form and questionnaire. The testing routine was fully available in EN and FR. However, provided the necessary level of EN or FR comprehension was met, the experiment was also open to certain individuals whose more proficient languages (i.e., daily exposure for over five years) were languages other than English or French. Participants knew in advance the available choice of languages and self-reported their level of bilingualism prior to the session. For the experimental groups, prolonged professional inactivity was an exclusion criterion. In controls, command of specific complex higher-level tasks – e.g., certain sports at professional level – was tolerated as long as it was also represented in target groups, for matching purposes, but previous occupation in air traffic control or other activity similarly likely to represent a multitasking experience, or current extensive practice of video games, was an ineligibility factor for recruitment. The experimental groups were recruited to be as representative as possible of the general population of expert interpreters and conductors. The questionnaire (see Appendix H) administered at the end of the testing session recorded prior activity and training in order to pinpoint possible disparities between experts with various former study or professional backgrounds. The choice of the control group took into account as many characteristics of the expert groups as possible (except for their domains of expertise), including diverse training backgrounds, in order to avoid confounds. A preliminary sample size estimation was carried out using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). For linear regression models to have 80% power to detect an effect of 0.1 with a significance level of .05 based on the main predictors (groups and conditions), 100 participants would have been required, which was the initial goal set. This sample size could not be reached due to the difficulty of recruiting the professional groups for this experiment. The final sample was expected to allow for 80% power of detecting an effect of 0.15 or a 90% power of detecting an effect of 0.2. A-posteriori analyses and the possible incidence of the various sampling-related aspects on the results are discussed in Chapter 8.

Sixty-nine participants (26 interpreters, 22 conductors and 20 controls) had initially been recruited. Two conductors had to be excluded from the entire analysis: One participant felt unwell during the testing session, although they persevered until the end, and consistently underperformed in all tasks beyond the first items. In the second instance, the participant did not follow the instructions for the 2-back task properly during the first half of the session and their overall accuracy mean across the 2-back exercises was significantly lower than the sample mean (> 3 SD).

Table 1

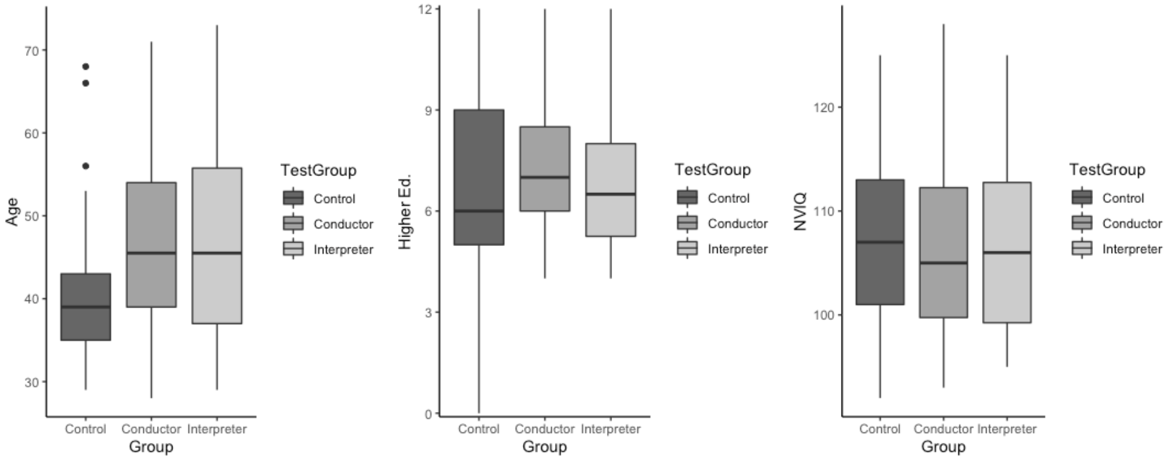
Sample descriptive statistics

Characteristics	Sample	Interpreters	Conductors	Controls	Group difference
F:M	34:33	20:6 (F 76.92%)	4:16 (F 20%)	10:11 (F 47.62%)	
Hand. R:L	58:9	21:5 (R 80.77%)	19:1 (R 95%)	18:3 (R (85.71%)	
Age	45.3 (11.8)	46.9 (11.9)	47.4 (11.9)	41.3 (10.9)	n.s.
Higher ed.	7.2 (2.6)	7.3 (2.6)	7.5 (2.2)	7.0 (3.0)	n.s.
Pro. Exp.	18.8 (11.3)	21.2 (11.8)	22.5 (11.0)	12.4 (8.4)	$\chi^2 = 1.1, p = .004$
Musicianship	54.9 (38.3)	38.8 (29.5)	95.4 (11.9)	36.4 (35.9)	$\chi^2 = 17.2, p < .001$
Bilingualism	62.0 (34.6)	84.1 (12.9)	51.6 (33.9)	44.5 (39.9)	$\chi^2 = 32.4, p < .001$
Non-verbal IQ	106.9 (9.1)	106.6 (8.8)	106.9 (9.5)	107.2 (9.6)	n.s.

Note. The reported data are means (SD), unless otherwise indicated. Pro. Exp: Years of professional experience in current activity. Higher ed: Years of higher education. Group difference was assessed by means of one-way ANOVAs or Kruskal-Wallis tests depending on the normality and homogeneity of variance of the distributions.

Figure 3

Distribution of age, higher education and non-verbal IQ by group in sample (n=67)



Participants' standardised score in the Test of Nonverbal Intelligence (TONI 4) was used as a measure of fluid intelligence (Brown, Sherbenou & Johnsen, 2010). The test assesses problem-solving and abstract reasoning and was chosen as it could be administered regardless of the participants' first language. Musicianship was assessed on a continuous scale (0-100) based on the participants' self-reported number of years of formal musical training, the specific competences acquired (sight-reading and ensemble playing ability), and the frequency and recency of musical activity. The conductors' median musicianship score was

100 (range: 50-100, probably due to very conservative answers in one case; the second lowest score is 85), while the interpreters' and controls' medians were 37.5 and 32.5 respectively, with ranges from 0 to 100. Bilingualism was rated on a continuous scale (0-100) based on the participants' self-reported fluency in more than one language, number of early-acquired ("native") languages, and number of years and recency of daily bilingual/multilingual language exposure. Conductors' and interpreters' median bilingualism score was 75. However, though the median scores were identical, it should be highlighted that unlike in interpreters, whose active exposure to bilingual contexts was logically high for all the group (range: 67.5 – 100), the conductors' bilingualism scores (range: 0-100) tended to be either very low (little exposure to bilingual contexts) or very high (conductors living abroad, working with international musicians, and extensively traveling for work). Controls had a median bilingualism score of 50 (range: 0 to 100). The highest degree completed and number of years spent in tertiary education were used as indication of the participant's socioeconomic status (SES). Four values above 12 years of higher education, corresponding to extended courses of studies like PhDs or additional MAs pursued by the participants while they were already professionally active, were windsorised.

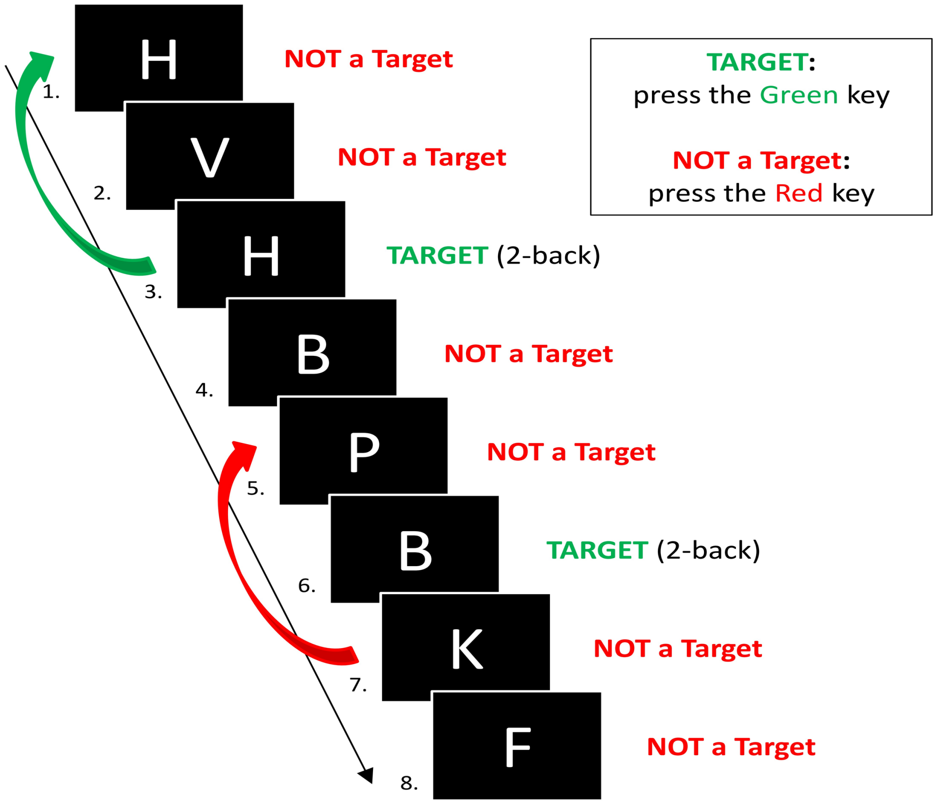
6.2 Materials

6.2.1 2-back task

The letter *n*-back task (Mackworth, 1959, based on Kirchner, 1958) is frequently used as a measure of WM updating (e.g., Wadhera et al., 2018), that is, the ability to continuously refresh content held in WM in order to process new incoming information as a function of a task goal. The cognitive processes involved in this task include encoding and actively maintaining the last *n* items, updating new items for active maintenance, and rapid binding of items to their serial order, to match responses with stimuli at the correct *n* place (Chatham et al., 2011). In the absence of interference due to non-target letter repetition, this last aspect is not constrained in the current study (see Figure 4 below). Participants are asked to press one of two keys to state whether each new displayed letter matches the letter displayed "n" letters prior, for instance 2 letters prior in the case of the 2-back task. In addition, although the task is feasible on the basis of familiarity, the last two items can generally be verbally rehearsed even in a dual-task context, providing clear insight in the most likely strategy (Jaeggi et al., 2007). The set size was chosen for the updating requirements it places on WM without challenging its storage capacity, in order to focus on the WM-processing aspect taxed in the task.

Figure 4

2-back task instructions



Note: Reproduced with permission of the Cognition and Language Lab, Graduate Center, CUNY.

Two blocks of 26 trials were presented, including 6 target trials per block. Stimuli (upper-case Roman alphabet consonants) were displayed for a duration of 600 ms, followed by a blank interval of 2400 ms, allowing for a total probe time of 3000ms during which a response was allowed. Target items were letters on the screen that had already been displayed 2 letters prior; All other items were non-target ("new"). Participants were asked to press a green button for target trials, and a red button for non-target trials. The response buttons for target and new items respectively were set, using coloured stickers, on either side (on the "x" or "m" key) of a QWERTY keyboard depending on the participant's handedness, with the target button located on the side of the dominant hand. Response time and accuracy were recorded for each trial.

6.2.2 Beep count task

For the beep count task (adapted from Hengl & Loiseau, 2007), participants were asked to keep a covert count of randomly mixed tones (hereafter "beeps") of two different pitches ("high" and "low"). The beeps presented during the routine were 600 ms-long tones with a frequency of 1368.5 and 197.7 Hz respectively, and two different timbres to further distinguish them. They were played at a volume of 50 dB and at irregular onset intervals of 2800, 3000, 3200, 3400 and 3600 ms. The total number of beeps by block ranged between 20 and 29 and the proportion of high and low beep varied. Participants entered the total number of high and low beeps when prompted at the end of each block, which in the dual condition also corresponded to the end of each 2-back block. Participants were provided instructions to keep counting the beeps as a priority.

6.2.3 Beeps and key-press task

For the beeps and key-press task, participants had to press one of two keys (A for "high", Z for "low" for right-handed participants, K or M for left-handed participants) depending on the type of beep heard, while covertly keeping count of the beeps. The two task goals – beep counting and key choice - were not expected to interfere with each other, unlike in the other dual task, and key-press RT was recorded as a separate baseline measure of processing speed for comparison with the 2-back RT data.

6.3 Procedures

6.3.1 General Procedures

The experimental design was submitted to the CUNY Institutional Review Board under the University's Human Research Protection Program. Approval was obtained in October 2015 and renewed in August 2016 and October 2017. A pilot was carried out in December 2015 and January 2016 at the CUNY Graduate Center. Participants in the experiment were recruited between March 2016 and March 2018. All participants gave informed consent in writing (see Appendix H).

The TONI was administered during one of the breaks. The 20-item biographical questionnaire (Appendix I) was administered at the end of the testing session in order to gather participants' characteristics as well as data for potential follow-up analyses on possibly relevant experience for multitasking purposes (instrument(s) played, advanced sports, simultaneous raising of two or more toddlers, piloting experience beyond driving).

6.3.2 Design and testing modules

A dual task, comprised of a visual 2-back task and an auditory beep count task, was used as an indicator of multitasking capacity. The dual task was administered a first time at the beginning of the testing routine to test all participants' spontaneous multitasking ability in the task at hand – i.e., their performance without prior training in any of the task components. A single 2-back task and a single beep-counting task were used as baseline. Another dual beep counting task with choice reaction (pressing one of two keys depending on the type of beep played) was also administered as a measure of processing speed during the beep-count task in the absence of conflict.[52]

The 2-back task was administered a total of 8 times (henceforth described as "iterations"). The first iteration was the first dual 2-back task ("DT1"). The 2-back task in single-task condition was then administered 6 times, with the first counting as the baseline for repeated measures comparison and the following 5 considered "reps". The dual 2-back task was administered a second time at the end of the testing session ("DT2") to test the participants' multitasking ability in the task at hand after single-task training. Task order was randomised for all modules other than single or dual 2-back modules.

The exercises discussed and analysed in the present study were part of an experimental routine containing a battery of 10 different tests (Figure 5), some of which were repeated, amounting to a total of 15 testing modules per session, each one lasting a maximum of 5 minutes. The routine was administered in one session, of a duration of approximately 1 hour and 45 minutes, including breaks every 20 minutes to avoid excessive fatigue. All exercises started with a series of practice trials in their first occurrence. The researcher stayed in the room to answer questions at the start of the exercises and launch the modules.

The experimental setting was designed to provide a continuous multitasking exercise different from interpreting as well as from conducting and therefore provide comparability across participants[53]. The drawback is that multitasking as assessed here is an experimental variable influenced by a specific exercise design, with the risk that the findings may not apply to all situations of multitasking (the issue of ecological validity will be discussed in Chapter 8). The physical setting, while removed from the field of either interpreting or conducting, was as neutral as possible to avoid introducing uncontrolled variables.

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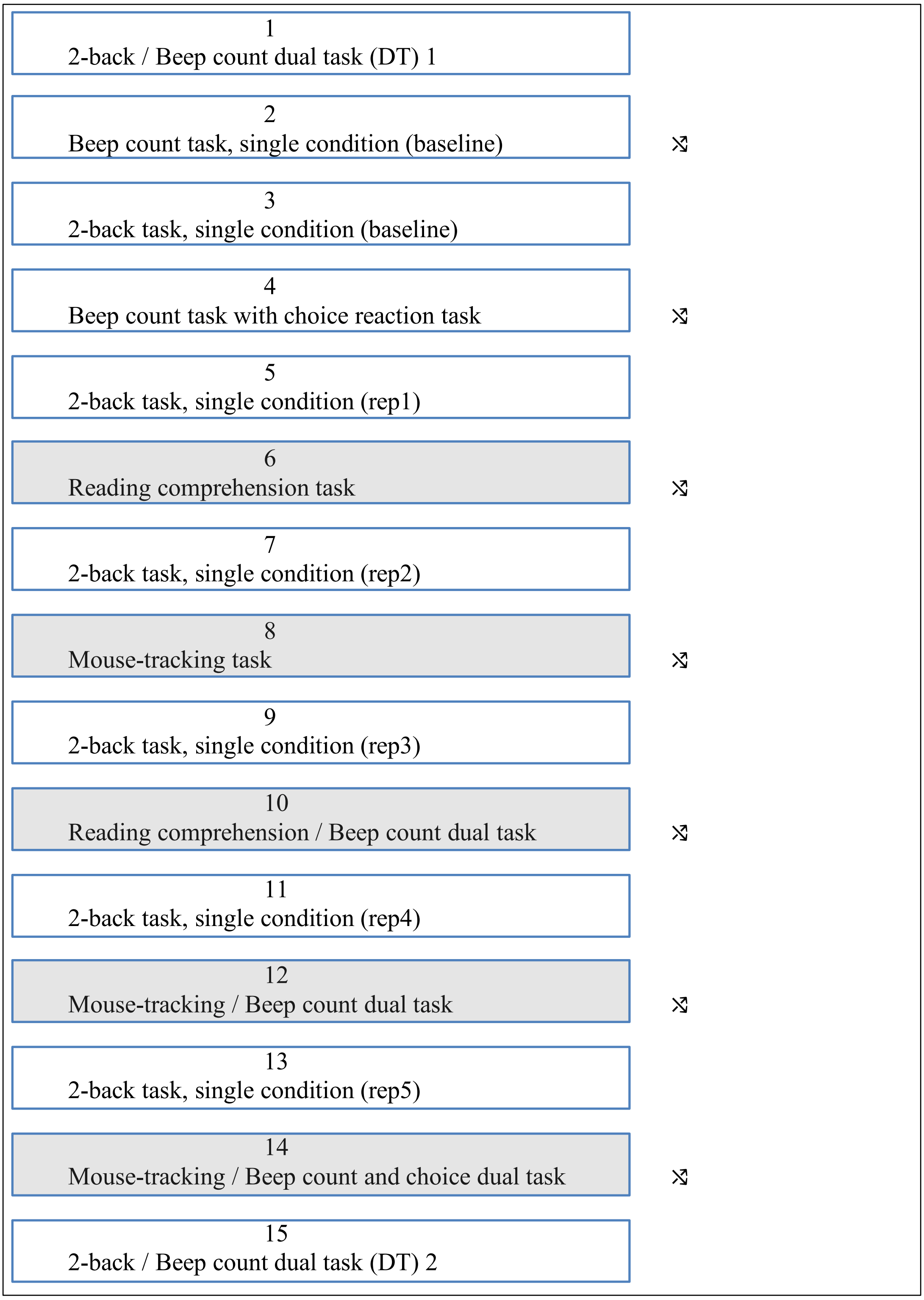
[52] The beep and key-press task was itself intended as the baseline for other tasks combinations, which are not part of the present study.

[53] Other task combinations not included here included more language-related or motor-related components to compare possible task proximity effects.

Figure 5

Experimental routine modules



1
2-back / Beep count dual task (DT) 1

2
Beep count task, single condition (baseline) 🔀

3
2-back task, single condition (baseline)

4
Beep count task with choice reaction task 🔀

5
2-back task, single condition (rep1)

6
Reading comprehension task 🔀

7
2-back task, single condition (rep2)

8
Mouse-tracking task 🔀

9
2-back task, single condition (rep3)

10
Reading comprehension / Beep count dual task 🔀

11
2-back task, single condition (rep4)

12
Mouse-tracking / Beep count dual task 🔀

13
2-back task, single condition (rep5)

14
Mouse-tracking / Beep count and choice dual task 🔀

15
2-back / Beep count dual task (DT) 2

Note. 🔀: task order randomised. Tasks in grey boxes are not included in the present study.

6.3.3 Apparatus

The apparatus used to test participants was entirely portable, anticipating the limited availability of interpreters and conductors in a given location as well as the need to accommodate the constraints linked to their real-life activities and to travel in order to test enough participants. In New York, sessions were organised in a testing room at the CUNY Graduate Center, 335 Fifth Avenue in New York, or in a focus room at the UN Headquarters in New York. In Geneva, the test was administered at FTI, University of Geneva. When testing outside of these locations (tests were also carried out in Washington, D.C., Montreal, Lausanne, Konstanz, Châlons-sur-Saône, Lyon, Ambilly, Béthune, Le Mans, Angers, Paris, and Vienna), a prerequisite was the availability of a neutral setting, a room of ca. 10 to 20m2 with a table and chair of standard height.

A dedicated computer with no internet connection (Lenovo G50-45, running on Windows 8.1, with a 64-bit AMD A8-6410 APU processor with AMD radeon R5 graphics, a processing speed of 2.00 GHz, a 6 GB RAM, and a 15.6” display with a resolution of 1366x768 pixels) was used to deliver the experimental routine as programmed using the (Windows-compatible) E-prime software (version 2.0), based on the Visual Basic programming language, and an html-based, locally running, ad-hoc program for the mouse-tracking tasks. A hearing test was administered at the beginning of the testing session, using a calibrated Micro Audiometrics DSP Pure Tone portable audiometer, to verify that candidates had no temporary or permanent impairment to hearing frequencies of 500, 750, 1000, 1500, 2000, 3000 and 4000 Hz at a level of 20 or 25dB.

7 Results

The hypotheses formulated section 5.3 deal with the capacity of three distinct groups (interpreters, conductors, and controls) to multitask in a setting where parallel WM monitoring and updating is required. The two tasks at hand, performed in single and dual conditions, were a 2-back task and a beep count task. In a first step, the dependent variables (DV) were analysed separately for each task – 2-back task and beep count task – in order to pinpoint the differences in performance in single and dual conditions. In a second step, an account is given of individual and group performance in the parallel tasks.

7.1 Data analysis

The DVs for the analysis were 2-back accuracy and response time, and beep count accuracy, which were examined using mixed-effects (hierarchical) regression analysis, allowing to nest responses (level-1) within subjects (level-2) and account for variability both within and between subjects (Osborne, 2000; Raudenbush & Bryk, 2002). The occurrence of missing data and the different types of variables in the dataset also made it a safer choice. These multilevel models were computed in R (R Core Team, 2019) using the *glmer* and *lmer* functions of the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015).

Performance on the 2-back task was scored as either correct (1) or incorrect (0) for each trial and to account for the variable's binary nature, it was analysed using a multilevel logistic regression model. To that effect, a generalised linear mixed model (GLMM) was fitted for binary accuracy data, by specifying family = "binomial" and link = "logit" in order to handle the nonlinear character of the data (Jaeger, 2008).

For RT data, analyses were carried out by means of linear mixed-effects models (LMMs), using Maximum Likelihood as the estimation method in order to allow the comparison of LMMs with different fixed-effects structures. The distribution of RT data being skewed by nature, the data was log-transformed for analysis as that allowed better readability of the residual plots. However, verification showed that there were no differences in the pattern of results between analyses using log-transformed data and RT in milliseconds. Only accurate trials were used for the analysis of RT, leading to the exclusion of 3.5% of the RT data for the single 2-back, and 21.8% for the dual 2-back where the error rate was much higher (total: 8.1% of the 2-back RT data).

Performance in the beep-count component was assessed on a continuous scale (0-1) as a function of the total error rate, that is, the difference between the participant's provided count and the correct count for each of the two tones. As the number of high and low beeps was recalled at the end of each block, there were two observations for each subject by iteration. These were collapsed into individual data points and analysed using LMMs.

For both model types, estimates (β), standard errors (SE), as well as Z statistics (GLMM), t statistics (LMM), and p values, are reported. To obtain p values, the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017) was used. To compare successively built models, Likelihood ratio tests were carried out using the function *anova()* in R in order to compute the log-likelihood ratio (*-2LL*) and chi-square (χ^2) statistics in addition to the Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC). Appendix D provides a short summary of the successively fitted models.

7.2 2-back task.

7.2.1 Data preparation

Within the final sample, a number of observations had to be discarded. In the first dual task, two interpreters had misunderstood the 2-back instructions and responded only after every third item instead of responding to each stimulus; although they did complete the task, their accuracy was logically very low, and their performance cannot be compared with the other participants'. In the same task (DT1), one control focused on beep counting only and did not provide 2-back responses. In the second dual task (DT2), one interpreter gave up on the 2-back entirely as well and focused exclusively on beep counting. Conversely, three participants (two controls and one interpreter) who did respond to the 2-back stimuli were unable to provide a final beep count during the first dual task, their performance, therefore, cannot be considered a multitasking performance. One additional interpreter provided an estimate which was too far off (> 3 SD from the sample mean). Accuracy observations were excluded by iteration for subjects whose mean accuracy lay more than 3 SD above or below the mean for each condition (single/dual), as well as remaining observations in the problematic cases flagged above. All outliers were on the low end of the distribution.

RT observations more than 3 SD above or below the mean of log-transformed response times were excluded for each condition (single/dual) separately, yielding clean minimum values above 150ms in both cases (1 remaining data point at 149ms was removed). This method of cleaning was data-driven and chosen because it allowed identifying problematically low as well as high RT outliers, and was more conservative on the high side than not log-transforming the positively skewed RT data. RTs corresponding to excluded accuracy observations were discarded. Together, these steps resulted in the removal of another 0.8% of the data. It should be noted that more conservative approaches tend to erase group differences and therefore favour the risk of false negatives (type II error) over false positives (type I error). Last, for each model, we examined level-1 and level-2 standardized residuals and re-fitted the model without observations with residual values more than 3 SD below or above the mean to double-check the result patterns. The number of observations removed is indicated in each case. Where the result pattern remains unchanged, the original model was maintained.

7.2.2 Descriptive statistics

2-back accuracy and RT by group and iteration are reported in Table 2.

Table 2

Mean 2-back accuracy and RT by group and iteration

Group	Iteration	n	Mean ACC (%)	(SD)	Mean RT (ms)	SD
Control	2b_DT1	18	74.4	13.4	1059	281
Conductor	2b_DT1	20	77.2	12.5	968	312
Interpreter	2b_DT1	22	77.1	10.9	895	268
Control	2b_baseline	21	95.2	3.9	702	226
Conductor	2b_baseline	20	96.9	2.6	766	328
Interpreter	2b_baseline	24	95.6	4.0	633	134
Control	2b_rep1	21	95.3	4.5	685	231
Conductor	2b_rep1	20	97.2	3.5	771	300
Interpreter	2b_rep1	26	96.8	4.0	648	171
Control	2b_rep2	21	96.1	4.7	686	219
Conductor	2b_rep2	20	97.1	3.1	743	269
Interpreter	2b_rep2	26	96.3	3.9	589	147
Control	2b_rep3	21	97.7	2.2	683	222
Conductor	2b_rep3	20	96.9	4.5	701	188
Interpreter	2b_rep3	26	96.3	3.9	623	169
Control	2b_rep4	21	95.5	5.0	727	274
Conductor	2b_rep4	20	96.9	3.6	736	229
Interpreter	2b_rep4	24	96.6	3.5	611	175
Control	2b_rep5	21	95	4.4	709	277
Conductor	2b_rep5	20	97.1	4.9	718	208
Interpreter	2b_rep5	26	96.8	3.3	590	155
Control	2b_DT2	21	79.7	11.2	911	210
Conductor	2b_DT2	20	79.5	8.5	938	235
Interpreter	2b_DT2	25	79.3	10.4	885	298

Note. Dual tasks are highlighted.

7.2.2.1 2-back accuracy

Across the sample, the highest individual accuracy scores ranged from 95.8% in the first dual task (DT1) to 100% in all other iterations of the 2-back. The lowest scores were 41.67% in DT1; 50.0% in DT2; 81.25% in rep2, 4 and 5; 83.3% in the baseline and rep1; and 85.4% in rep3. Median scores were 79.2% in DT1, 80.2% in DT2, 96.9% in the baseline, and 97.9% in all the single reps, indicative of a clear performance ceiling in the single 2-back task, which disappeared in the dual condition. Figures 6 and 7 below display the means and score distribution by iteration and by group.

Figure 6

2-back: Mean accuracy by group (error bars: +/- 1 SE). Range displayed: 70-100%

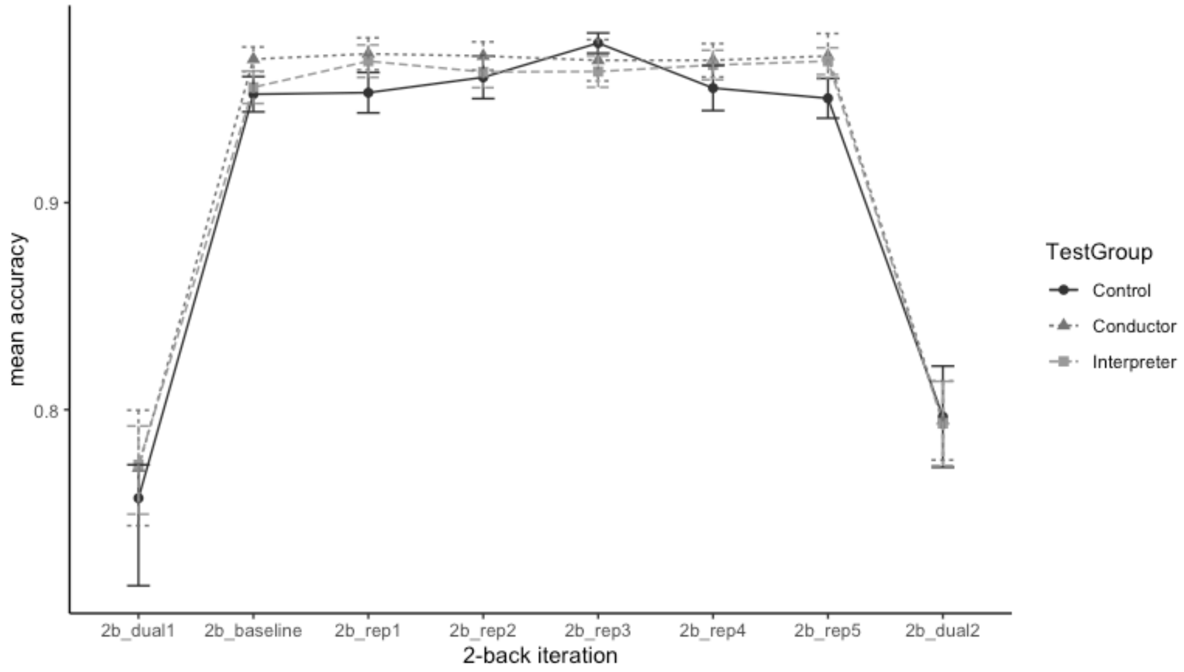


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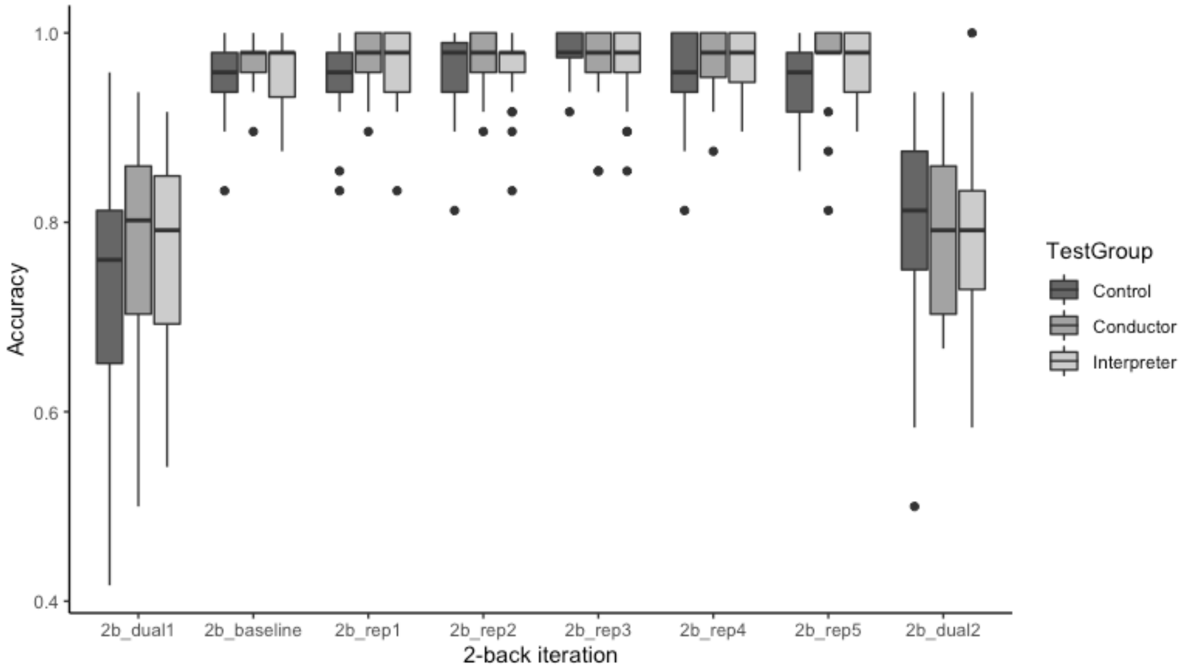
Figure 7

2-back: Accuracy distribution by group (outliers: >1.5 IQR). Range displayed: 40-100%.



On average, a small advantage in accuracy is observed in conductors and a small disadvantage in controls in all the single tasks, with the exception of rep3 (though median scores are the same in all groups in that iteration); in the first dual task, the controls have a lower average than both expert groups, but that disadvantage is lost in the second dual task, with a higher median score in controls. However, the group differences in all iterations are small and group distributions largely overlap.

7.2.2.2 2-back RT

The lower and upper thresholds in RT values were as follows: Single 2-back: 200-2128 ms, Dual 2-back: 152-2997 ms. The fastest responses to "target" items in the 2-back start around 240ms, indicative of higher response thresholds than for "new" items (152 ms and 195 ms for single and dual task respectively). Figures 8 and 9 below display the RT means and distribution by iteration and by group.

Figure 8

2-back: Mean RT by group (error bars: +/- 1 SE)

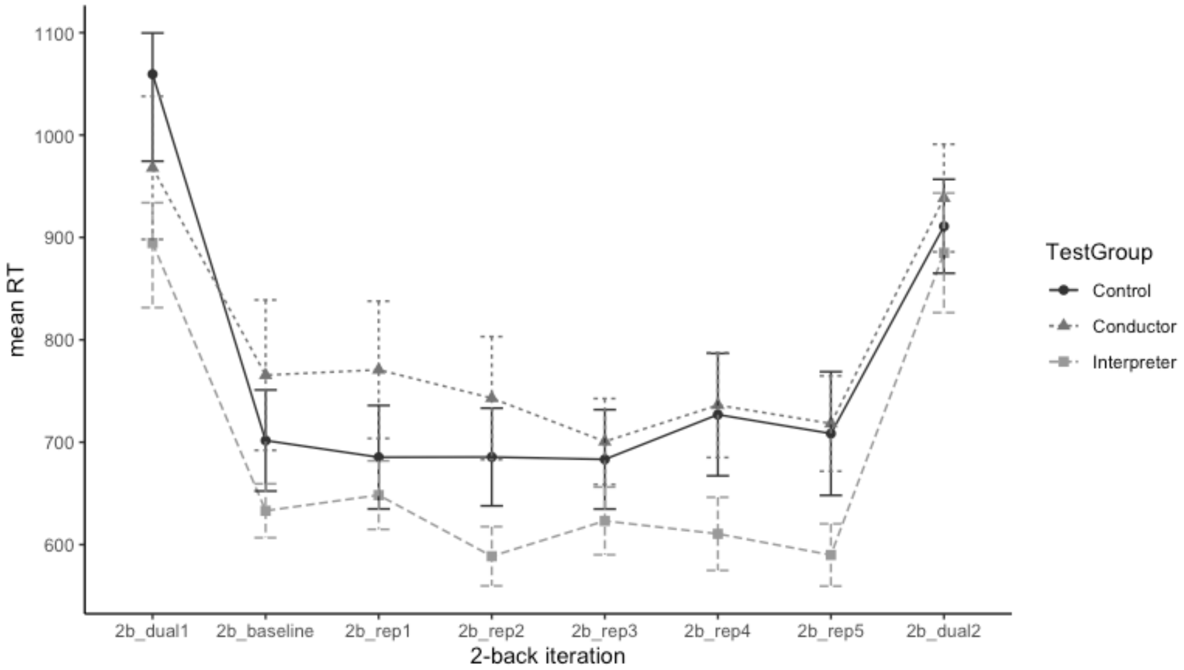
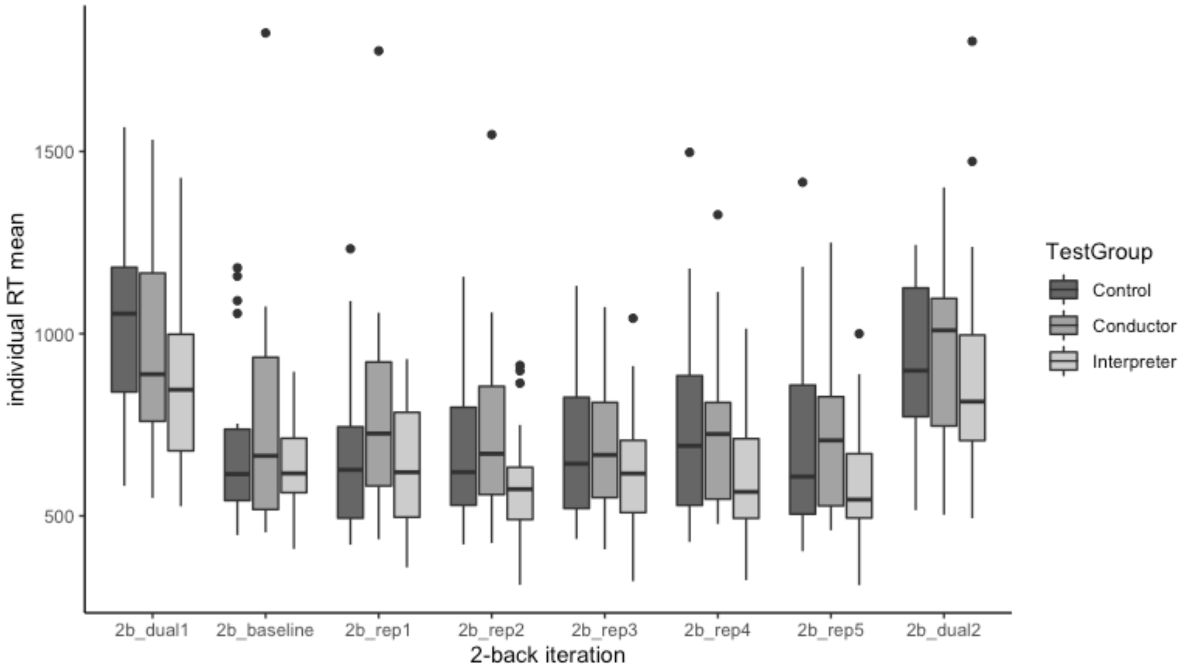


Figure 9

2-back: RT distribution by group



Interpreters as a group appear to be faster than the other groups, and expert groups show slightly lower RT and higher accuracy means than controls in the first dual task. However, inferential models will seek to explore whether these advantages are significant and hold when individual differences are taken into account (hypothesis 2), as well as whether the speed advantage in interpreters is modulated by bilingualism and/or by professional expertise (inasmuch as a group effect is identifiable beyond bilingualism). At the group level, that speed advantage does not seem to be associated with higher accuracy; models will seek to ascertain whether the association is present on an individual basis (hypothesis 1d) and differently in experts and controls (hypothesis 2c), or if, on the contrary, there is a trade-off between response time and accuracy in the dual as well as the single tasks.

7.2.3 2-back: Multitasking cost

Prior to fitting global models, pairwise tests were carried out on the whole sample ($N = 67$) to compare the three DVs across tasks in the single and dual condition: baseline and DT1, baseline and DT2, as well as rep5 (the last single task 2-back) and DT2 for 2-back accuracy and RT. Although the sample was larger than n = 30, the normality of the distribution of mean differences was ascertained through Shapiro-Wilk tests, and dependent 2-group Wilcoxon signed-rank tests were carried out in addition to paired samples t tests for verification purposes where the normal distribution criterion was not fulfilled. All tests were one-tailed to test the directional multitasking cost hypothesis, assuming an increase in 2-back RT and a decrease in 2-back and beep count accuracy between the single and the dual condition; However, two-tailed tests were also carried out in order to provide more conservative confidence intervals. The estimates for the beep count performance are indicated further below (Beep count task). Results were significant in all cases ($p < .001$). The detailed results are available in Appendix C. The means of the differences between the baseline tasks and the first dual task (DT1) were -19.5 for 2-back accuracy, and 275.0 for 2-back-RT. The mean of the differences between rep5 and DT2 (accuracy: -16.8, RT: 243.4ms) was larger than between the baseline 2-back and DT2 (accuracy: -16.3, RT: 215.5ms). The results indicate lower performance in both dual tasks than in the single condition, with higher performance in DT2 than in DT1 and in rep5 than in the baseline task. A comparison of the two dual tasks showed a significant difference for accuracy, but not for response time.

Table 3 and Figure 10 summarise multitasking cost (MT cost) in the 2-back (accuracy and RT) for the three groups between the baseline and DT1, Table 4 and Figure 11 between the baseline and DT2.

Table 3

MT cost (%), 2-back accuracy and RT between baseline and DT1

Group	N	Acc: Cost (%)	(SD)	RT: Cost (ms)	(SD)	%	(SD)
Control	18	21.8	13.1	362.8	359.5	64.2	65.4
Conductor	20	20.3	12.6	218.4	341.7	40.3	53.8
Interpreter	22	19.2	12.0	252.1	258.0	43.1	50.2

Figure 10

2-back accuracy and RT: MT cost between baseline and DT1 (error bars: +/- 1 SE).

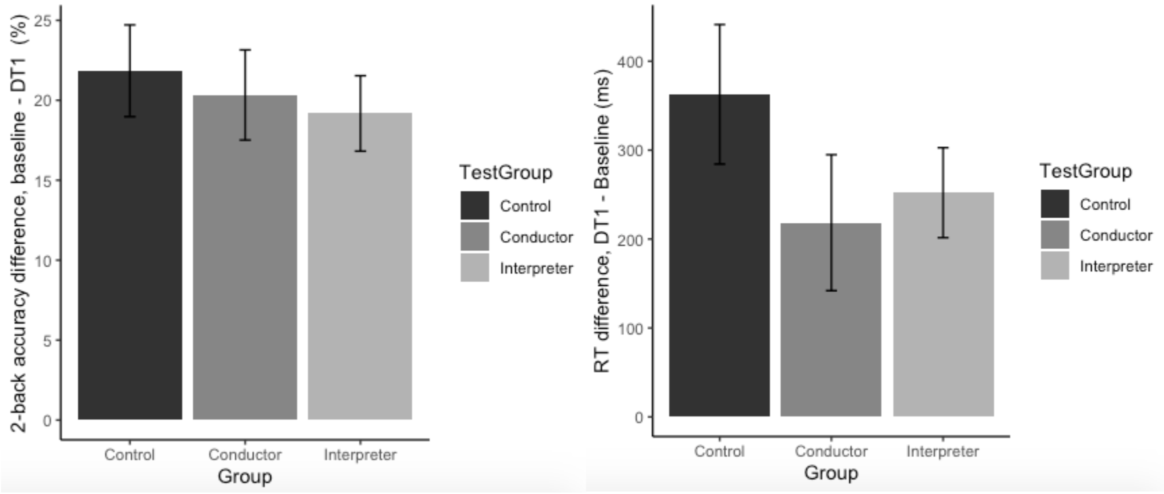


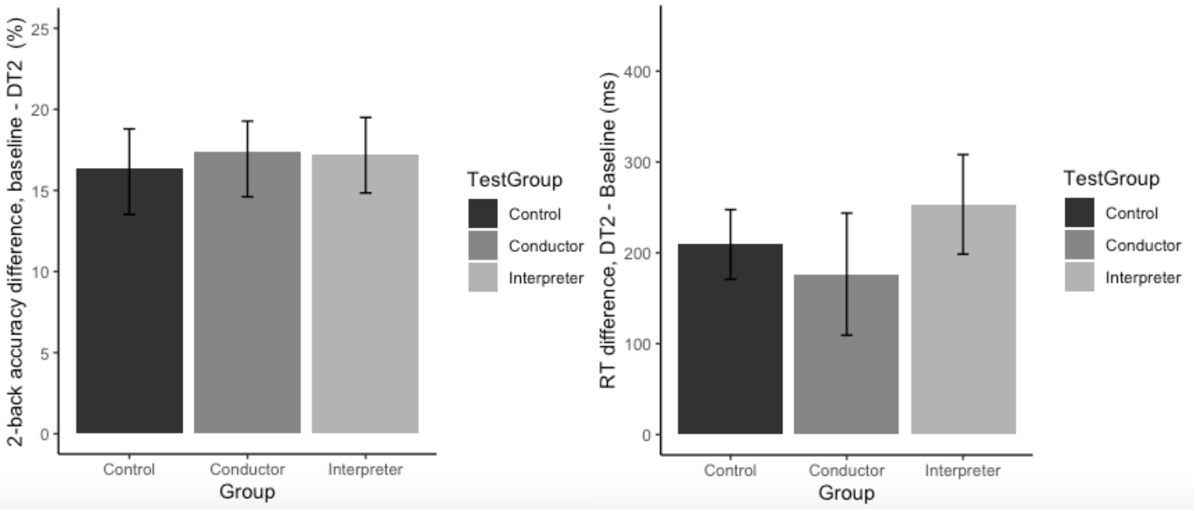
Table 4

MT cost (%), 2-back accuracy and RT between baseline and DT2

Group	N	Acc: Cost (%)	(SD)	RT: Cost (ms)	(SD)	%	(SD)
Control	21	16.4	11.0	209.2	175.9	35.3	31.6
Conductor	20	17.4	8.3	176.5	300.6	33.5	42.7
Interpreter	24	17.2	11.7	253.4	279.5	41.7	48.4

Figure 11

2-back accuracy and RT: MT cost between baseline and DT2 (error bars: +/- 1 SE).



Experts show higher accuracy and shorter RT group means in the 2-back exercise in the first, "spontaneous" (= untrained) dual task and the differences with the baseline are on average smaller. This will need to be compared with performance in the parallel task (beep count). However, in the second dual task after short-term single-task training, controls seem to have gained more accuracy and speed (see Figure 12 and Table 5); in the second iteration of the dual task, their overall performance is comparable to that of both expert groups.

Figure 12

2-back accuracy and RT: Gain between DT1 and DT2 (error bars: +/- 1 SE).

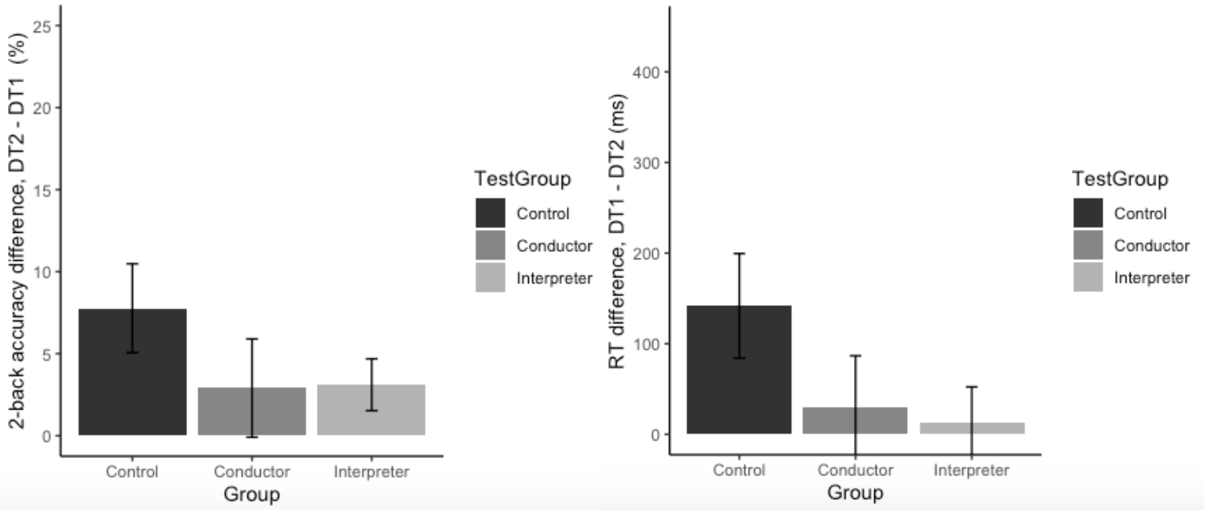


Table 5

Gain (%) in accuracy and speed between DT 1 and 2 after single-task training

Group	N	Acc: Gain %	(SD)	RT: gain (ms)	(SD)	%	(SD)
Control	18	7.8	12.4	141.8	264.2	26.7	46.1
Conductor	20	2.9	13.4	29.5	255.9	6.7	40.9
Interpreter	22	3.1	8.1	13.2	199.4	4.5	29.6

7.2.3.1 Multitasking cost: 2-back, Accuracy

To test hypotheses 1b and 2a – 1) there is a multitasking cost, and 2) expert groups exhibit less of it than controls – a GLMM was fitted to test the relationship between 2-back accuracy and the fixed effect *Iteration* (3 levels: single-task baseline, DT 1 and DT2) and *Group* (3 levels: controls, interpreters, and conductors, baseline: controls), with an interaction term set between *Group* and *Iteration*. A random intercept was entered by *Subject*. By including a random slope for iteration, we assumed that the effect of time varies across subjects in the population. However, a random slope was not supported by the data. A likelihood ratio test against the null model (Model ACC 0), a model with fixed effect *Iteration* only (Model ACC 1), and fixed effect *Group* only (Model ACC 2) showed that the fit was significantly improved in the full model (Model ACC 4). A more parsimonious model without the interaction term between *Group* and *Iteration* (Model ACC 3) showed decreased AIC and BIC values and a higher predictive power, suggesting that the full model may have been overparametrised in the absence of an effect of the interaction.

L1 and L2 residuals for the full model (ACC 4) were analysed and observations with residual values of more than 3 estimated SDs above or below the mean were filtered out and the model was refitted. Doing so removed 165 observations (1.41%). This did not modify the original pattern of results. There was no significant effect of *Group,* with the highest increase against the baseline estimate – β =3.123, on a logit scale – for Conductor (β = 0.412, SE = 0.288, Z = 1.429), and almost no accuracy advantage for Interpreter: (β = 0.052, SE = 0.253, Z = 0.204) nor for any interaction between *Group* and *Iteration*. The effect of *Iteration*, however, was significant (p < .001) for both dual tasks versus the baseline, with a steep accuracy decrease in DT1 (β = -2.053, SE = 0.172, Z = -11.951) and a slightly lower decrease in DT2: β = -1.676, SE = -0.169, Z = -9.932). The absence of a *Group* effect indicated that the two other groups did not differ significantly from controls in the various iterations, while the strong effect of *Iteration* for DT1 and DT2 was indicative of significant performance decrement from the single to the dual task.

The same analysis was also performed including all 2-back iterations (6 single, 2 dual), in order to account for the groups' performance across all 2-back reps. In that configuration, a parsimonious model (Model ACC 3i) excluding the interaction term between *Group* and *Iteration* was better supported by the data and provided a better fit, with a singular fit in the full model (Model ACC 4i), which also did not show any effect of the interaction. A random slope was not supported by the data. The baseline estimate (Control, baseline 2-back) for Model ACC 3i was $\beta = 3.142$ (on a logit scale). The effect of *Iteration* was significant for Rep3, with the highest increase in accuracy ($\beta = 0.285$, SE = 0.138, $Z = 2.065$, $p = .039$), DT1 ($\beta = -2.030$, SE = 0.102, $Z = -19.992$, $p < .001$) and DT 2 ($\beta = -1.819$, SE = 0.101, $Z = -17.943$, $p < .001$). The absence of a *Group* effect indicated that the two other groups did not differ significantly from controls in the various iterations. With both interpreters and conductors showing consistently higher estimates in the full model compared to controls except in rep3 and DT2 (with almost equal scores in DT2), the reduced model with controls as the baseline does not obfuscate any significant difference between interpreters and conductors.

A comparison between single and dual performance across all 2-back trials, not accounting for the participants' performance evolution with time, allows us to consider their overall performance in single and in dual condition throughout the session. To that effect, we fitted a GLMM with fixed effects *Group* and *Condition* (single/dual), with an interaction term set between both fixed effects, and with random intercepts by *Subject* and *Iteration*, as this was the maximal random structure supported by the data. This full model (Model ACC 4c) showed an effect for *Condition*: Dual ($\beta = -1.923$, SE = 0.104, $Z = -18.561$, $p < .001$) as well as for *Group*: Conductor ($\beta = 0.3899$, SE = 0.183, $Z = 2.128$, $p = .033$) and the interaction between Conductors and Dual condition ($\beta = -0.317$, SE = 0.130, $Z = -2.441$, $p = .015$). L1 and L2 residuals were analysed and observations with residual values more than 3 estimated SDs above or below the mean were filtered out and the model was refitted. Doing so removed 663 observations (0.97%). The pattern of results was modified, with the effect of *Group* and of the interaction between *Group* and *Condition* removed. This suggests that the group effect in conductors, indicative of higher 2-back accuracy overall, and the advantage for that group in the dual tasks, as well as the reduced multitasking cost compared to controls (with a higher estimate for the single task and a lower estimate for the dual task), were driven by outstanding individual performance rather than a group trend as a whole. A reduced model without the interaction effect was fit for comparison purposes, on all observations (Model ACC 3c). In the reduced model, only an effect of *Condition* (β = Dual: -2.063, SE = 0.077, Z = -26.695, $p < .001$) remained and the effect of *Group* disappeared. Likelihood ratio test results indicated that AIC decreased slightly but BIC increased for the full model and showed significantly more predictive power against the null and the full model for the reduced model (ACC 3c), suggesting that the full model may have been overparamaterised and that the more parsimonious model described the data better. Similar full and reduced models (with and without the interaction term between the fixed effects) were fit without the random effect *Iteration*, to allow a comparison between the fixed effects. AIC and BIC values were significantly improved in the reduced model with random intercept *Subject* only (Model ACC 3c'). This model showed a similar pattern and estimates to the reduced model with two random effects, with an effect of *Condition* (Dual) only (β = -2.058, SE = 0.051, Z = -40.469, $p < .001$). For that model, L1 and L2 residuals were analysed and observations with residual values more than 3 estimated SDs above or below the mean were filtered out and the model was refitted. Doing so removed, again, 663 observations (0.97%) and did not modify the original pattern of results.

7.2.3.2 Multitasking cost: 2-back, RT

To address hypotheses related to multitasking cost for RT, a linear mixed-effects model was fitted to test the relationship between 2-back RT (log-transformed) and the fixed effect *Iteration* (3 levels: single-task baseline, DT 1 and DT2) and *Group* (3 levels: controls, interpreters, and conductors, baseline: Control), with an interaction term set between *Group* and *Iteration*. The distribution of RTs is relatively homogenous between the 6 single task iterations and between both dual task iterations, making them comparable within single or dual task type, not necessarily so across types (as evidenced by residual patterns from previously fitted models). It appears relevant, therefore, to nest the parameters of RT variance not only within subject, but also within task type as level 2 factors. We assumed that the effect of time and the effect of condition varies across subjects in the population. In any case, task type needs to be considered for its possible effect in the model. A random slope by *Condition* was supported (Model RT 4).

There was no effect of *Group* (Conductor: β = 0.052, SE = 0.087, t = 0.603 p = .549, Interpreter: β = -0.090, SE = 0.081, t = -1.098, p = .276, for a baseline estimate of β = 6.472, SE = 0.060) or of any interaction between *Group* and *Iteration*. The effect of *Iteration*, however, was significant for both dual tasks versus the baseline (DT1: β = 0.336, SE = 0.059, t = 5.726, $p < .001$, DT2: β = 0.182, SE = 0.058, t = 3.158, p = .002). This points to a general increase in RT with no significant difference between the groups. Models were built gradually with the same random structure and fixed effect *Iteration* only (Model RT 1), *Group* only (Model RT 2), and *Group* and *Iteration* without the interaction term for comparison purposes (Model RT 3). The effects were the same across all models, with *Iteration* (DT1 and DT2) the only significant parameter. A likelihood ratio test of the full model against these simpler models and the null model (Model RT 0) showed that the fit was not significantly improved in the full model against the null model, whereas it was the case in the *Interaction* only model (Model RT 1), with the following estimates for DT1: $\beta = 0.270$, SE = 0.040, $t = 6.682$, $p < .001$, DT2: $\beta = 0.190$, SE = 0.032, $t = 5.591$, $p < .001$. Inspection of the residuals showed that though one L2 residual (1 subject, Conductor) stood out for relatively high values compared to the rest of the sample, there were no outliers more than 3 SD above or below the means, requiring no further steps. All the models, including the null model, were re-run with random intercept *Subject*, and without the random slope, that is, assuming a constant effect of condition, in order to compare the goodness of fit across random structures. Among random-intercept-only models, the full model (Model RT 4') was the best fit. There was again a significant effect of Iteration for both dual tasks (DT1: $\beta = 0.342$, SE = 0.022, $t = 15.298$, $p < .001$, DT2: $\beta = 0.176$, SE = 0.021, $t = 8.514$, $p < .001$), but also a significant effect of the interaction between *Group* and *Iteration* for both groups in DT1 (Conductors: $\beta = -0.121$, SE = 0.031, $t = -3.888$, $p < .001$, Interpreters: $\beta = -0.087$, SE = 0.030, t = -2.880, p = .004). However, the final comparison of the models across random structures indicated significantly better goodness of fit for the random slope models, suggesting that the effect of *Group* x *Iteration* may have been a type I error (see Barr, Levy, Scheepers, & Tily, 2013) and that there was considerable variation between subjects.

In a second step, in order to account for the groups' performance across all 2-back iterations including the 5 single-task reps, the analysis was performed on the complete dataset (8 iterations). Models were fit gradually, with a random intercept entered by *Subject* and a random slope by *Condition* (single/dual), the maximal random structure supported, and fixed effects *Iteration* (Model RT1i); *Group* (Model RT2i); *Group* + *Iteration* (Model RT3i); and *Group* x *Iteration* (Model RT4i), the full model. A likelihood ratio test showed that the goodness of fit improved the most with the full model against simpler ones. Significant effects emerged for *Iteration* (DT1: $\beta = 0.332$, SE = 0.055, $t = 6.022$, $p < .001$; DT2: $\beta = 0.179$, SE = 0.054, $t = 3.287$, $p = .002$) and for *Group* (Interpreter) x *Iteration* (rep2: $\beta = -0.074$, SE = 0.021, $t = -3.461$, $p < .001$; rep4: $\beta = -0.056$, SE = 0.021, $t = -2.636$, *p* = .008; rep5: *β* = -0.065, SE = 0.021, *t* = -3.099, *p* = .002). The effect of the interaction *Group*: Conductor and *Iteration*: rep3 approached but did not reach significance (*β* = -0.043, SE = 0.022, *t* = -1.923, *p* = .054). Inspection of the residuals showed the same remarkable L2 residual on the high end but no outliers more than 3 SD above or below the means, requiring no further steps. The models were then re-fitted with only a random intercept by *Subject* in order to compare the goodness of fit across model structures. In that configuration, the full model (Model RT 4i') remained the best fit. The result pattern was similar, with strengthened effects and additional ones (*p* < .001) for *Group* x DT1 (Conductors: *β* = -0.157, SE = 0.0252, *t* = -6.223, Interpreters: *β* = -0.106, SE = 0.024, *t* = -4.370). However, model comparison indicated once again that the maximal random structure improved the goodness of fit against random-intercept-only models and that these added effects were not strong enough.

A comparison between single and dual performance across all 2-back trials was provided by fitting a LMM with fixed effects *Group* and *Condition* (single/dual), with an interaction term set between both fixed effects, and with random intercepts by *Subject* and *Iteration*, as this was the maximal random structure supported by the data. This full model (Model RT 4c) showed an effect for *Condition*: Dual (*β* = 0.271, SE = 0.0251, *t* = 10.806, *p* < .001), as well as for the interaction between *Group* and *Condition* for Conductor (*β* = -0.087, SE = 0.015, *t* = -5.906, *p* < .001). A negative trend for *Group* appeared for Interpreter, not reaching significance (*β* = -0.124, SE = 0.070, *t* = -1.778, *p* = .079).

In order to test hypothesis 2c regarding higher processing speed across tasks in interpreters, the models were re-fitted with interpreters as the baseline. With baseline, DT1 and DT2 data, models were refitted iteratively with random slopes for *Iteration* and *Condition*; the random slope by *Iteration* showed a better fit and explained more variance. The full model (RT4_I) yielded a significant effect against the baseline performance of interpreters (*β* = 6.378, SE = 0.043, *t* = 147.296) for the parameter Conductor, with a slightly higher logRT (*β* = 0.135, SE = 0.066, *t* = 2.057, *p* = .043). The lesser difference with controls (*β* = 0.096) was not significant. Again, there was a significant increase (*p* < .001) against the baseline for both dual tasks (DT1: *β* = 0.256, SE = 0.020, *t* = 12.689, DT2: *β* = 0.225, SE = 0.020, *t* = 11.487). Interactions indicated that the DT1, the RT was higher in controls (*β* = 0.087, SE = 0.030, *t* = 2.880, *p* = .04), but slightly lower in conductors (n.s.), than in interpreters; and in the DT2, RT values were lower in both conductors (*β* = -0.065, SE = 0.029, *t* = -2.227, *p* = .026) and controls (n.s., *p* = .085). With the full data for all iterations and a random slope by *Condition*, the maximal random structure supported (model RT4i_I), the picture was more specific. The positive estimate difference from the baseline (interpreters: $\beta = 6.384$, SE = 0.053, $t = 120.818$) for conductors and controls were not significant (conductors approached significance with $\beta = 0.154$, SE = 0.08, t = 1.926, $p = .058$). In the single condition, interpreters performed significantly faster than their baseline in rep2 ($\beta = -0.077$, SE = 0.014, $t = -5.388$, $p < .001$), rep3 ($\beta = -0.034$, SE = 0.014, $t = -2.377$, $p = .017$), rep4 ($\beta = -0.052$, SE = 0.015, $t = -3.542$, $p < .001$), rep5 ($\beta = -0.085$, SE = 0.014, $t = -5.940$, $p < .001$). In rep2, other groups performed significantly slower (Conductor: $\beta = 0.059$, SE = 0.021, $t = 2.740$, $p = .006$; Control: $\beta = 0.074$, SE = 0.021, $t = 3.461$, $p < .001$). In rep4, controls were slower ($\beta = 0.056$, SE = 0.021, $t = 2.636$, $p = .008$). In rep5, both conductors and controls were again slower (Conductor: $\beta = 0.045$, SE = 0.021, $t = 2.095$, $p = .036$; Control: $\beta = 0.065$, SE = 0.021, $t = 3.099$, $p = .002$). In general, there was a significant slowing ($p < .001$) associated with the dual tasks (DT1: $\beta = 0.263$, SE = 0.050, $t = 5.293$; DT2: $\beta = 0.223$, SE = 0.049, t = 4.530). The interaction between *Group* and *Iteration*, however, was not significant.

These results indicated lower RTs in the single 2-back task in interpreters. However, in the dual tasks, especially DT2, differences compared to the other groups were erased, and conductors were tendentially faster, especially in DT1. *Bilingualism* and *Musicianship* are added to the model as effects at a later stage to account for a difference, or lack thereof, between the effect of group and of these variables on processing speed.

The difference in estimates for DT1 against the baseline only (model RT4) in the same model fitted with baseline *Control* and baseline *Interpreter* (controls: $\beta = 0.336$, interpreters: $\beta = 0.256$, both significant) also pointed to lower RTs in both expert groups – in the case of interpreters, in the first dual task. For DT2, the difference was reversed (interpreters: $\beta = 0.225$, controls: $\beta = 0.182$, both significant), suggesting that the advantage measured at the first occurrence of the task was subsequently lost. Refitting the model with *Conductor* as the group baseline yielded beta estimates of 0.208 and 0.149 respectively (both significant) for DT1 and DT2, suggesting that that group, which was the slowest in the baseline task, has the lowest multitasking cost when it comes to RT, and retains that advantage in DT2. However, group differences are not large enough to warrant a significant effect.

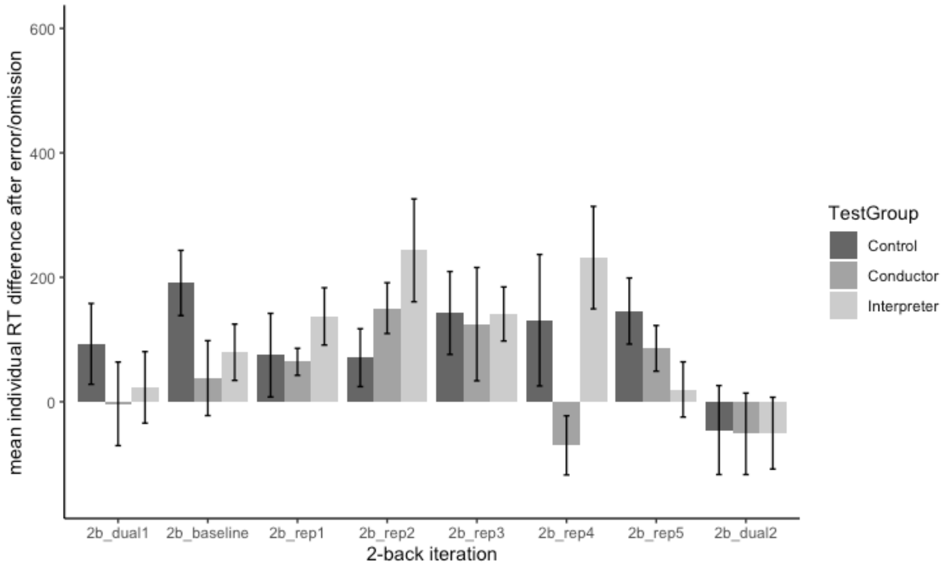
Last, that model was refitted with DT1 as the baseline to compare the dual tasks without using the single-task RT as benchmark, even though the fit of that version with and without a random slope was inferior to that of the model with the original (single-task) baseline. The model (RT4'_d) included a random intercept by subject; in this case, a random slope by condition introduced singularity and degraded the model fit. This model supported the lack of significance of the conductor's advantage over controls in DT1 (*Conductor*: $\beta = -0.083$, SE = 0.079, t = -1.188), but indicated that interpreters performed significantly faster (*Interpreter*: $\beta = -0.183$, SE = 0.066, t = -2.776, p = .007). However, this more granular picture also showed that controls performed significantly faster in DT2 than in DT1 ($\beta = -0.167$, SE = 0.023, t = -7.226, $p < .001$), and performed faster than both interpreters ($\beta = 0.136$, SE = 0.031, t = 4.326, p < .001) and conductors ($\beta = 0.105$, SE = 0.032, t = 3.287, p = .001) in that second dual task.

7.2.4 2-back: Post-error slowing (PES)

Figure 13 shows average PES by group and by iteration. It is important to keep in mind that the number of errors is small across the sample in all the single 2-backs, and that therefore the values are based on relatively few observations. Overall post-error vs. pre-error differences appear to show differences in the type of processing between the groups; however, the group distributions are spread out very widely. Additionally, the presence of negative measures, mostly in the dual tasks, raises questions, as it suggests post-error acceleration.

Figure 13

Mean RT difference between post- and pre-error trials in the 2-back task, by group



Systematic acceleration after errors did not appear logical, unless prompted by a skipped response (this point is discussed section 8.1.3.1); Therefore, the data was re-analysed taking into account the type of error, namely, either a wrong answer or an absence of response ("0"). Below (Figure 14 and Figure 15) are the compared findings:

Figure 14

2-back: Average RT difference between trials before and after a skipped response

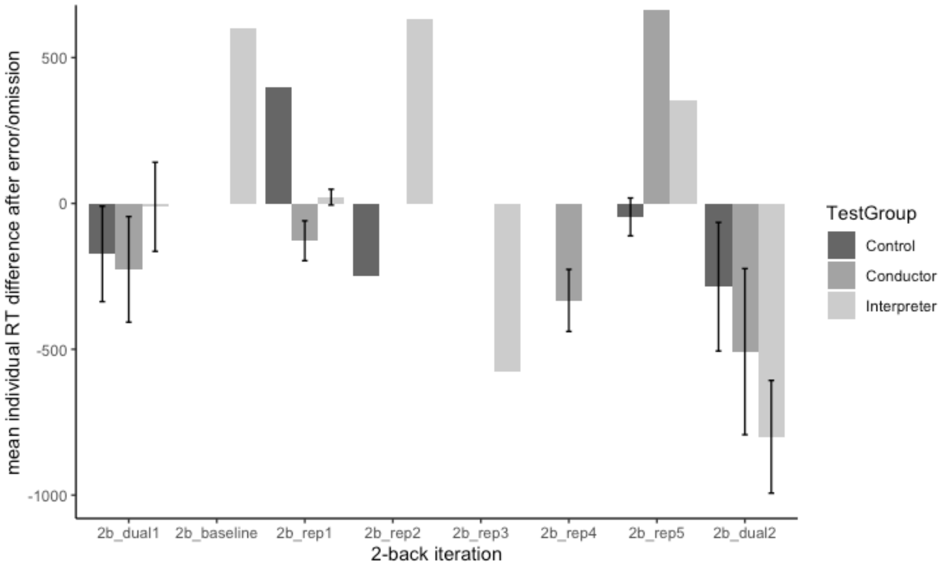
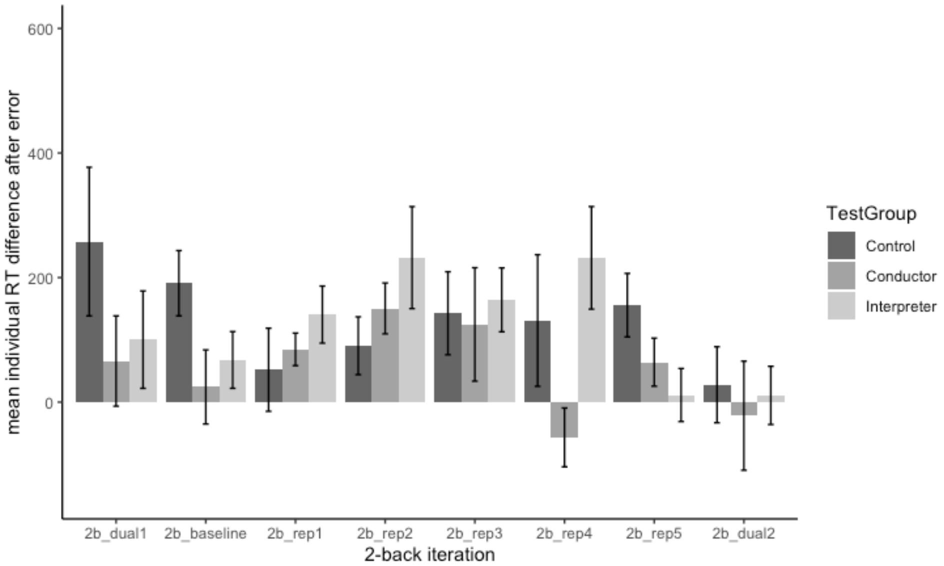


Figure 15

2-back: Average RT difference trials before and after errors only



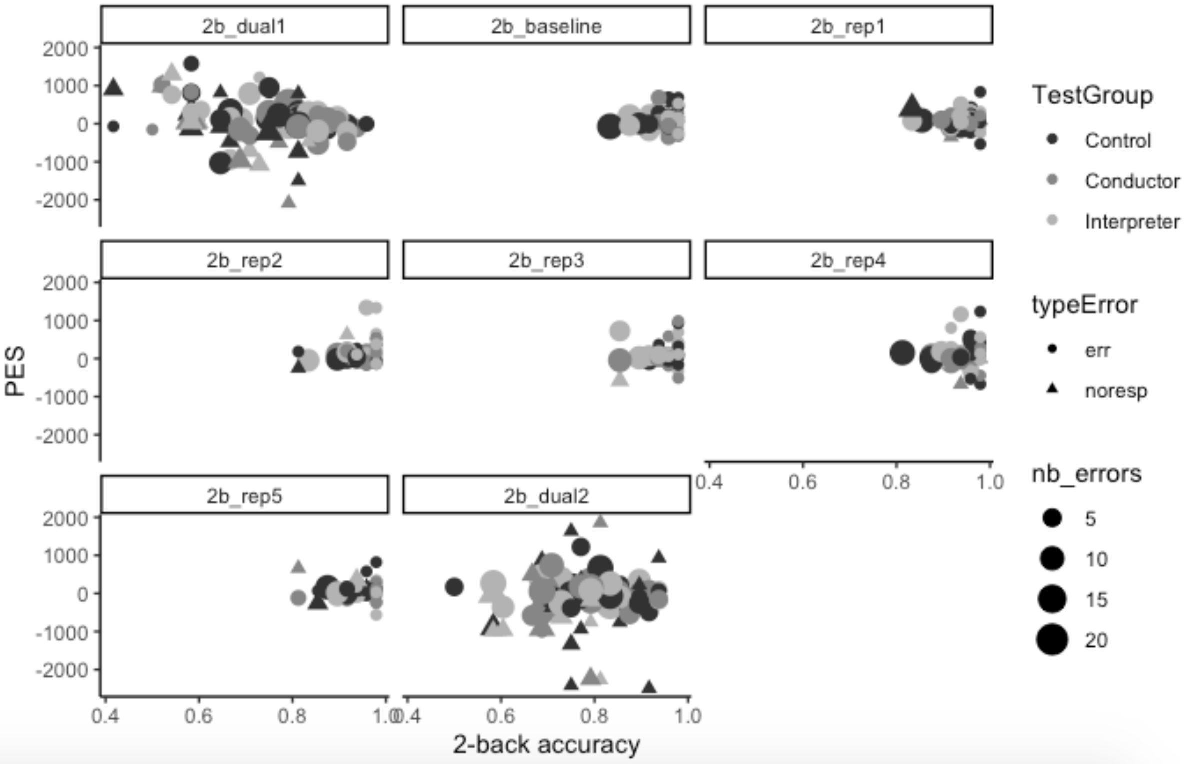
It appears that post-0 trials follow a different pattern than post-error trials. Once post-error trials only are considered, only conductors as a group show post-error acceleration instead of slowing (in Rep4 and DT2 at least). However, the standard error for all groups is too large to allow drawing a univocal conclusion. Controls, on the other hand, seem to show equal or higher levels of PES than interpreters in DT1, baseline, rep5 and DT2.

Plotting individual post-error RT vs. pre-error RT against individual accuracy by iteration shows a great extent of individual variation within the groups (Figure 16). More errors obviously result in lower accuracy, therefore post-error measurements in participants with high levels of accuracy are based on very few items.

In the first dual task, it appears that more low-performing participants show post-error slowing than high-performing ones (missing PES data are linked to the fact that post-error RT was retained for comparison with pre-error RT only where there was only one error, not successive errors in a row). The bulk of participants is clustered around 0 in most iterations, meaning that their RT does not change after an error. Some outstanding individual patterns are likely to influence the group means significantly.

Figure 16

2-back: individual mean accuracy and RT difference (ms) between post-and pre-error trials, by iteration and error type



For the analysis of PES, since there was no difference in the patterns of results between models fitted with RT in ms and log-transformed RT data[54], the data in ms was used for greater clarity. LMMs were fitted on the pre-and post-error RT data to include the variable

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[54] Complex models in ms tended to be slightly more conservative regarding the significance of effects.

Position, that is, pre- or post-error RT. Models were fitted incrementally in order to verify that the included fixed effects were indeed relevant to account for the observed values. In a first step, models were fitted on the baseline and dual tasks only. However, probably due to the limited number of observations, no effect was significant beyond the general slowing compared to the baseline RT in the dual tasks. In a second step, observations from all iterations and from the whole sample were considered. Only *Position* was set as a fixed effect, and a random intercept was set by *Subject* and by *Iteration*, as this was the maximum random structure supported by the data and explained more variance than a random effect by subject only (Model PES1i). The model indicated a significant increase for *Position*: post ($\beta = 45.47$, SE = 19.85, $t = 2.291$, $p = .022$) against the intercept for the sample ($\beta = 731.64$, SE = 55.47, $t = 13.190$). In an incremental approach, the fixed effect iteration was added (Model PES2i). The globally higher RT with *Position*: post remained ($\beta = 45.31$, SE = 19.82, $t = 2.286$, $p = .022$) as well as significant effects of Rep4, DT1 and DT2 (i.e., not taking into account post-error response times) with higher RT than the baseline. An interaction term was set between *Position* and *Iteration* (Model PES3i), and the effect of *Position*: post disappeared. No significant effect was found either for any interaction between position and iteration. The only remaining significant effects were for DT1 and DT2 (p < .001).

In view of this, a fixed effect for *Error type* (no response vs. error) was added to model PES2i prior to adding any further interactions. This further divided the number of observations considered for the various effects, and random effects other than the random intercept by subject were not supported anymore for this model and more complex ones. This new model (PES4i_o) indicated significant post-error acceleration ($\beta = -241.32$, SE = 58.66, $t = -4.114$, $p < .001$) against the baseline, which in that case corresponded to RT in items prior to a missing response (pre-0). The intercept was considerably higher than in the previous models where the baseline was pre-error RT regardless of the error type ($\beta = 1038.21$, SE = 60.44, $t = 17.179$). There was a significant effect for the interaction *Error type*: Error, with a lower estimate for RT in items prior to an error vs. items prior to a missing response ($\beta = -451.37$, SE = 46.06, $t = -9.800$, $p < .001$), and a higher estimate for items after an error than after a missing response ($\beta = 324.00$, SE = 62.20, $t = 5.209$) (all effects: $p < .001$). Effects of iteration were seen for Rep4, DT1 and DT2 against the baseline.

In order to account for PES against the baseline of pre-error RT, considering the discrepancy between RT pre-omission and baseline RT in the models including all trials, the baseline for error type was set to “Error” rather than “No response”. This allowed to account for the observed phenomena with greater clarity. First, the initial model, with random intercepts for *Subject* and *Iteration*, was refitted only with *Position* and *Error type* as fixed effects (PES5i) in order to look at the pattern across all observations (intercept: β = 694.07, SE = 49.67, t = 13.973). The effect of *Position*, namely, PES (β = 82.89, SE = 20.67, t = 4.011), *Error type*, namely the estimated RT difference before omissions (β = 455.21, SE = 46.10, t = 9.876), and the interaction between them, namely, estimated RT difference after omissions (β = -324.19, SE = 62.29, t = -5.205) were all significant (p < .001), indicating that PES was found on average; responses after omissions, on the other hand, were much faster, even compared to the baseline; and RT before omissions was indeed much higher on the whole. Model PES4i, with an interaction term between *Position* and *Error type* and the added fixed effect *Iteration*, was therefore also refitted, yielding similar values and significant effects (p < .001): PES (β = 82.68, SE = 20.65, t = 4.007), *Error type* (β = 451.37, SE = 46.06, t = 9.800) and interaction between *Position* and *Error type*: no response (β = -324, SE = 62.20, t = -5.209). In addition, there was a significant pre-error RT increase across the sample on average in rep4 (β = 104.30, SE = 50.28, t = 2.074, p = .038) and in DT1 (β = 305.25, SE = 39.72, t = 7.686, p < .001) and DT2 (β = 291.35, SE = 38.83, t = 7.503, p < .001). In the full model, an interaction term was set between *Position*, *Error type*, and *Iteration* (PES6i). The values were similar, but the no effect reached significance, except for higher pre-error RTs in DT1 and DT2 against the baseline. The small number of observations by iteration likely plays a role in that loss of significance. PES values (n.s.) were reduced in DT1 and negative in DT2 compared to the baseline. Model comparison showed significant goodness of fit for the model without error type (PES3i) as well as the models with error type, but with improved AIC and BIC values for model PES4i, with fixed effect *Iteration*, *Position* and *Error type* and an interaction term only between *Position* and *Error type*.

The models were re-fitted with fixed-effect *Condition* rather than *Iteration* in order to collapse observations across iterations and form a picture of single-task against dual-task performance throughout the experiment. *Subject* was entered as a random effect with random intercept only, the maximum random structure supported by the data. The model was fitted first without the fixed effect *Error type* (PES3c). There was a clear difference between conditions, with (collapsed) post-error RTs significantly higher (β = 87.14, SE = 30.39, t = 2.868, p = .004) than the single-task pre-error baseline (β = 631.98, SE = 33.36, t = 18.916) and for the dual condition, a comparatively higher pre-error RT estimate (β = 334.16, SE = 29.44, t = 11.350, p < .001) and overall acceleration post error, not reaching significance ($\beta = -73.11$, SE = 40.1, $t = -1.823$, $p = .068$). Once error types were factored in (PES6c), the picture was more precise.

In the single condition (baseline estimate: $\beta = 626.887$, SE = 31.682, $t = 19.787$), there was significant PES across the sample after actual errors ($\beta = 87.157$, SE = 30.423, $t = 2.865$, $p = .004$). There was also an increase ($\beta = 171.198$, SE = 109.210, n.s.) in RT estimate before omissions as opposed to RT before errors, and a decrease (n.s.) for the interaction between *Error type*: no response and *Position*: post ($\beta = -6.524$, SE = 150.820), with high SE in both cases. The effect of *Condition*: dual was significant, with higher pre-error RTs ($\beta = 254.866$, SE = 30.477, $t = 8.363$, $p < .001$). The interaction between *Condition* and *Position* was not significant ($\beta = -7.956$, SE = 41.381), but indicated that overall post-error responses could be faster than pre-error ones in the dual condition. However, the RT estimate before omissions in the dual condition was significantly higher than the baseline ($\beta = 335.727$, SE = 120.363, $t = 2.789$, $p = .005$) and the RT estimate after omissions in the dual condition significantly lower than the baseline ($\beta = -375.742$, SE = 166.188, $t = -2.261$, $p = .024$).

Adding these models to the comparison showed that both were good fits, with the last (PES6c, including error types) further improving the model fit, indicating a strong difference in RT between items after missing responses and after errors in the dual tasks, as well as a strong difference between RT in items before those respective types of errors. PES is observed in the single condition, but not in the dual condition.

Test group was added to the model in a next step, with interpreters as the baseline, in order to test hypothesis 3a (of more PES in interpreters). The models were first fit using *Iteration* as a fixed effect to account for factors in the groups' performance across all reps, and using *Condition* as a fixed effect in a second step to test the hypothesis. Random effects beyond *Subject* were not supported.

The simple model included only *Group* and *Position*, with a random intercept set by *Subject* and by *Iteration* (PES7i). There were no effects, with near significance for *Position*: post. A reduced model: *Group* x *Position* + *Iteration* (PES8i), then a full model with interaction between all fixed effects (PES9i), were fitted. With the fixed effect *Iteration*, no effects were significant except for the effect of *Iteration* in DT1 and DT2. When the model was fitted with the fixed effect *Condition* (PES9c), collapsing the data across iterations, and only when interpreters were set as the baseline for the variable *Group* (the intercept, i.e., pre-error RT in interpreters in single tasks, was 554.79), beyond the effect of *Condition*: dual, there was also a significant effect of *Position*: post, in line with the hypothesis at hand (Table 6 below). There was no effect of *Group*, and no effect of the interaction between *Position* and *Condition* (post and dual), but a marked negative trend. Group estimates against the baseline (RT pre-error) were the highest for conductors, and also higher for controls than interpreters; the interaction *Position* x *Condition* x *Group* is also positive for both controls and conductors, but the effect is not significant.

Table 6

Post-error and post-omission slowing by group and condition. Baseline: Interpreters.

Predictors	*Estimates*	*SE*	*CI (95%)*	*t*	*p*
(Intercept)	554.79	53.06	450.78 – 658.79	17076	**<0.001**
Position: Post error	121.60	48.84	25.88 – 217.32	17930	**0.013**
Conductors	136.49	82.58	-25.36 – 298.34	23743	0.098
Controls	118.21	78.01	-34.69 – 271.10	18994	0.130
Condition: Dual	381.53	47.59	288.25 – 474.82	44235	**<0.001**
Post error: Conductors	-76.31	77.22	-227.66 – 75.04	-0.99	0.323
Post error: Controls	-41.81	70.57	-180.12 – 96.49	-0.59	0.553
Post error: Dual	-115.66	64.62	-242.32 – 11.00	-1.79	0.073
Conductors: Dual	-92.38	72.99	-235.43 – 50.68	-1.27	0.206
Controls: Dual	-67.78	69.99	-204.96 – 69.40	-0.97	0.333
Conductors: Post error Dual	73.54	98.92	-120.35 – 267.43	0.74	0.457
Controls: Post error Dual	73.76	95.93	-114.26 – 261.78	0.77	0.442
Random Effects					
σ2	237777.87				
τ00 Subject	39316.84				
ICC	0.14				
N Subject	67				
Observations	2426				
Marginal R2 / Conditional R2	0.080 / 0.210				

Note. Model PES9c_I was fit using Maximum Likelihood Estimation and included a random intercept by subject (SD = 198.3).

In a last step, *Error type* was added to the equation, first with *Iteration* (PES10i) to picture performance across the routine, then with *Condition* (PES10c) as a fixed effect to test the relationship between dual performance and PES vs. the single tasks. In Model 10i, most effects disappeared. The only significant effects were, again, for *Iteration*: DT1 ($\beta = 286.199$, SE = 88.084, $t = 3.249$, $p = .001$) and *Iteration*: DT2 ($\beta = 280.598$, SE = 85.979, $t = 3.264$, $p = .001$) and the interaction between *Group*: Control and *Iteration*: rep4 with an estimate of

$\beta = 337.77$, SE = 161.67, $t = 2.089$, $p = 0.0368$, suggesting that the significant overall slowing in rep4 observed in whole-sample models was driven by controls.

In Model 10c, with iterations collapsed by *Condition*, the parameter of interest, that is, the effect of *Position*, is again significant: the estimate for post-error RT is higher ($\beta = 121.66$, SE = 48.75, $t = 2.496$, $p = .012$) compared to the baseline estimate (pre-error RT: $\beta = 550.59$, SE = 50.31). The effect of *Condition* (dual) is significant: $\beta = 305.73$, SE = 48.64, $t = 6.286$, $p < .001$. Other effects and iterations are not significant except for the interaction between Condition: dual and *Error type*: no response ($\beta = 389.52$, SE = 197.61, $t = 1.971$, $p = .049$), indicating that RT pre-omissions were higher than pre-error in the dual tasks. The second parameter of interest is the interaction between *Position* (post), and *Condition* (dual), which is slightly negative, but not significant ($\beta = -53.34$, SE = 65.87), while the interaction between *Position* (post), *Condition* (dual) and *Error type* (no response) is very negative, but also nonsignificant. The effect of *Position* only is negative in conductors and controls, but none of these are significant effects. The models were refitted with controls and conductors as baseline for verification, and no effect of *Position* was found against the baseline in that case (the estimate was negative in conductors), indicating that only interpreters showed significant PES in the single condition.

Models were then compared incrementally to previous best fits to verify if the added effects were relevant. While the fullest models including error type with *Iteration* (Model 10i) and *Condition* (Model 10c) provided the best fit of all models including *Group* as a fixed effect, they did not yield AIC and BIC values as low as the full model by *Condition* with *Error type* and without the fixed effect *Group* (Model PES6c).

Table 7

PES model comparison (best fits)

Model	*npar*	*AIC*	*BIC*	*-2LL*	*deviance*	χ^2	*df*	*p*
Model PES 0	3	37249	37266	-18621	37243			
Model PES 3c	6	37059	37093	-18523	37047	196.10	3	< .001
Model PES 6c	10	36963	37021	-18472	36943	103.50	4	< .001
Model PES 10c	26	36985	37135	-18466	36933	109.18	11	< .001
Model PES 10i	85	37046	37539	-18438	36876	141.19	35	< .001

Considering the low granularity of the baseline RT with respect to possible differences in RT values in the dual condition, the full models with fixed effects *Position* x *Error type*, and then

Position x *Error type* x *Group*, were refitted by *Iteration* and by *Condition* respectively with the baseline for *Iteration* changed to DT1, and the baseline for *Condition* changed to “dual”.

There was significant post-error slowing across the board when the whole sample was considered. By *Iteration* (model PES6_d), post-error RT was 112.416 ms (SE = 41,542, $t = 2.706$, $p = .007$) above the baseline ($\beta = 891.514$, SE = 37.855). RT before omissions was significantly higher ($\beta = 331.736$, SE = 71.692, $t = 4.627$, $p < .001$), and acceleration after omissions was significant ($\beta = -254.413$, SE = 98.489, $t = 2.583$, $p = .01$). RT before omissions in DT2 was significant also ($\beta = 354.065$, SE = 100.340, $t = 3.529$, $p < .001$) while acceleration after omissions (-267.193) approached, but did not reach, significance ($p = 0.054$) due to a high level of dispersion (SE = 138.8). In comparison to the RT baseline for DT1, all other tasks were significantly faster ($p \leq .001$), from -191.993 (rep4) to -302.595 (the baseline, i.e., the first, single 2-back task). There was no other effect from the *Position* x *Iteration* interaction, that is, no significant changes in post-error slowing across the sample in comparison to DT1. By *Condition* (model PES6c_d), the values were slightly different due to the collapsing of DT1 and DT2 and single iterations, but the effects were identical (Table 8.)

Table 8

Model summary: RT before and after errors and omissions, by condition

Predictors	*Estimates*	*SE*	*CI (95%)*	*t*	*p*
(Intercept)	881.75	30.33	822.31 – 941.19	44406	**<0.001**
Position: RT Post error	79.20	44344	24.23 – 134.17	29983	**0.005**
Error Type: Omission	506.93	51.13	406.71 – 607.14	33482	**<0.001**
Condition: Single	-254.87	30.48	-314.60 – -195.13	-8.36	**<0.001**
RT post * Omission	-382.27	69.78	-519.03 – -245.50	-5.48	**<0.001**
RT post * Condition	352.47	41.38	-73.15 – 89.06	0.19	0.848
Omission * Condition	-335.73	120.36	-571.64 – -99.82	-2.79	**0.005**
RT post * Omission * Condition	375.74	166.19	50.02 – 701.47	46054	**0.024**
Random Effects					
σ2			228942.92		
τ00 $_{\text{Subject}}$			33123.65		
ICC			0.13		
N $_{\text{Subject}}$			67		
Observations			2426		
Marginal R2 / Conditional R2			0.112 / 0.225		

Note. Model PES6c_d was fit using Maximum Likelihood Estimation and included a random intercept by subject (SD = 182).

Last, *Group* was added as a fixed effect to both models. The default baseline for the *Group* variable was "Control". In model PES10_d, accounting for performance by *Iteration*, the estimate (RT before error, DT1) was $\beta = 915.843$, SE = 70.868, $t = 12.923$. There were significant effects of *Iteration* for all single reps except rep4 (β = -73.047), with RT differences ranging from -226.314 ($p = 0.026$) for Rep5 to -358.652 ($p < .001$) for the baseline 2-back task. The effect of *Position* (post-error slowing) was significant only with regard to the baseline estimate (i.e., DT1: $\beta = 179.737$, SE = 80.047, $t = 2.245$, $p = .025$); interactions with the other iterations were non-significant (post-error slowing was on average smaller in DT2 than DT1: $\beta = -127.745$, but there is large variation between individuals, SE = 108.483). The effect of *Error type*: no response was also, with increased RT before omissions ($\beta = 362.569$, SE = 117.704, $t = 3.080$, $p = 0.002$). Other effects and interactions were non-significant, including the effect of *Group*. To compare the patterns between the groups, the *Group* baseline was changed (this did not modify the model fit): For interpreters, RT difference with rep4 was significant too, while the effects of *Position* disappeared. For conductors, RT before errors differed significantly from DT1 only in the baseline 2-back and reps 2 and 5; there was no effect of *Position* or *Error type* except for DT2, with significantly higher RT before omissions.

The patterns were similar when iterations were collapsed by *Condition* (model PES10c_d): With controls as the baseline, the dual task pre-error RT estimate is 873.07 (SE = 56.20, $t = 15.535$). Post-error slowing is significant ($\beta = 108.80$, SE = 54.70, $t = 1.989$, $p = .047$), as well as *Error type*: no response (difference with RT before omissions: $\beta = 517.97$, SE = 85.79, $t = 6.037$, $p < .001$) and post-error RT after omissions ($\beta = -325.87$, SE = 116.65, $t = -2.794$, $p = .005$). The effect of *Condition* (single) was significant also, with $\beta = -201.34$, SE = 54.56, $t = -3.690$ and $p < .001$. This was the case as well for *Error type*: no response in the single condition ($\beta = -447.09$, SE = 198.88, $t = -2.248$, $p = .025$), pointing to much faster RTs before omissions in controls, but this particular phenomenon was probably based on extremely few observations (on average less than 1 error per participant and between 0 and 8 omissions by group) in the single tasks. With interpreters as the baseline, the effects were similar with the exception of *Position*, indicating an absence of significant PES in the dual tasks, and in conductors, there was no effect of *Position* or for the RT before omission in the single tasks). Overall, these patterns indicate that controls, and DT1, account for most of the observed PES in the dual tasks.

7.3 Beep count task

7.3.1 Data preparation and descriptive statistics:

In addition to missing beep counts in DT1 (two controls, one interpreter), beep counts with an accuracy below 3 SD from the sample means were removed (DT1: one interpreter;[55] Beeps and key press: one conductor, one interpreter). Further participants' data had to be excluded a priori from the analysis in specific conditions (dual tasks only): In the first dual task the two interpreters who had misunderstood the 2-back instructions did complete the dual task, but their multitasking performance cannot be compared with the other participants' and they were excluded from the beep count analysis as well. In the same task (DT1), one control focused on beep counting only and did not provide 2-back responses. In the second dual task (DT2), one interpreter gave up on the 2-back entirely as well and focused on beep counting only. After exclusion of these non-multitasking participants in the relevant conditions, the data for beep accuracy was as follows:

Table 9

Beep count accuracy by group and iteration

TestGroup	*Iteration*	*n*	*Beep acc. (< 3 SD)*	*(SD)*
Control	2b_DT1	19	0.895	0.077
Conductor	2b_DT1	20	0.881	0.093
Interpreter	2b_DT1	24	0.824	0.123
Control	Beeps_baseline	21	0.996	0.018
Conductor	Beeps_baseline	19	0.993	0.016
Interpreter	Beeps_baseline	25	0.988	0.031
Control	2b_DT2	21	0.909	0.092
Conductor	2b_DT2	20	0.910	0.060
Interpreter	2b_DT2	25	0.916	0.076
Control	Beeps_key	21	0.968	0.053
Conductor	Beeps_key	19	0.995	0.014
Interpreter	Beeps_key	25	0.987	0.033

No conductor had complete breakdowns in the beep counting performance in the dual condition, as opposed to participants from the other groups. In addition, the initial group SD was smaller in conductors (0.093 vs. 0.226 in interpreters and 0.279 in controls), suggesting higher consistency in the level of performance in that group. However, once only the

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[55] Excluding outliers above 3 absolute deviations from the median would remove one further participant whose performance was out of proportion with the rest of the sample (interpreter, score: 0.52), but we decided against it for the sake of consistency in the exclusion procedures.

participants who did perform the task successfully are taken into account, controls have a higher group score average. Figures 17 and 18 display the means and score distribution by iteration and by group.

Figure 17

Beep count accuracy: Group distribution by iteration

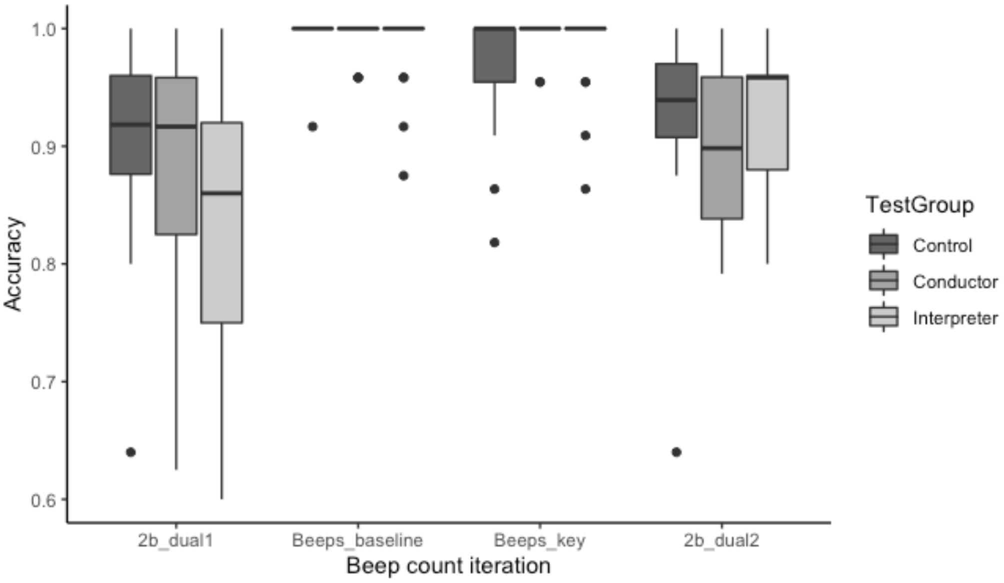
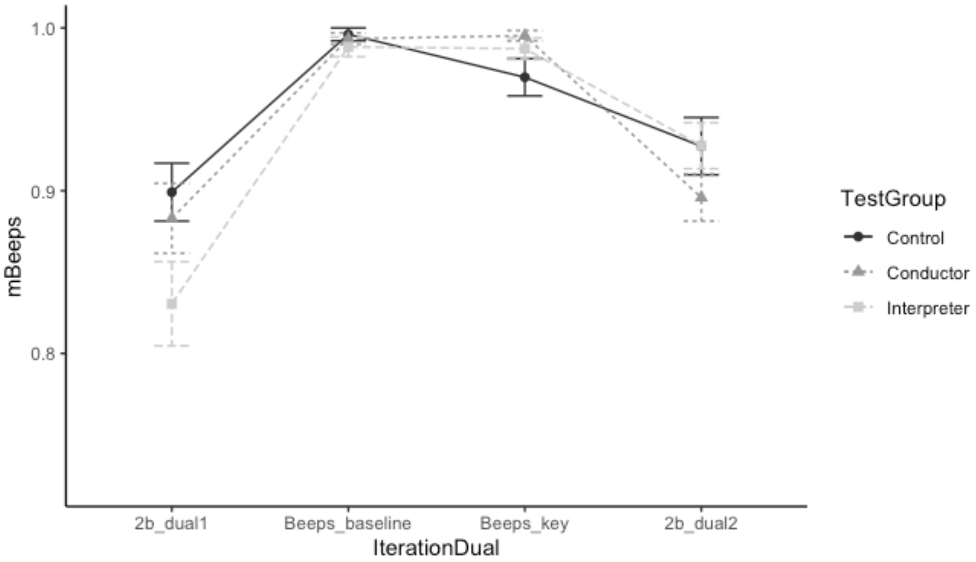


Figure 18

Beep count: Mean accuracy by group and iteration



7.3.2 Beep count in baseline and dual 2-back condition: multitasking cost

Table 10 compares beep count accuracy scores between the baseline beep count task, DT1 and DT2; The difference between the baseline and the dual tasks is plotted in Figure 19 and the difference between DT1 and DT2 in Figure 20.

Table 10

Beep count accuracy: MT cost and gain (score difference between iteration, in %).

TestGroup	*n*	*MT cost, baseline-DT1*	*(SD)*
Control	20	10.1	7.1
Conductor	20	10.6	8.4
Interpreter	24	15.3	15.7
		MT cost, baseline-DT2	
Control	21	8.6	9.5
Conductor	20	7.6	6.9
Interpreter	25	5.7	8.6
		Gain DT1-DT2	
Control	20	3.3	10.3
Conductor	20	4.3	13.0
Interpreter	23	11.5	17.4

Figure 19

Beep count accuracy: MT cost between baseline and DT1 (left) / DT2 (right)

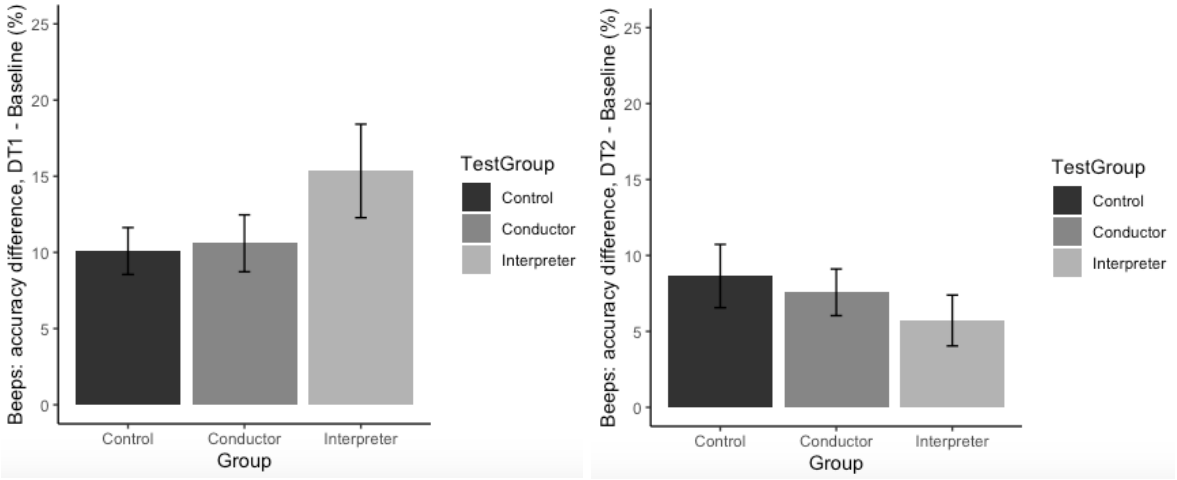
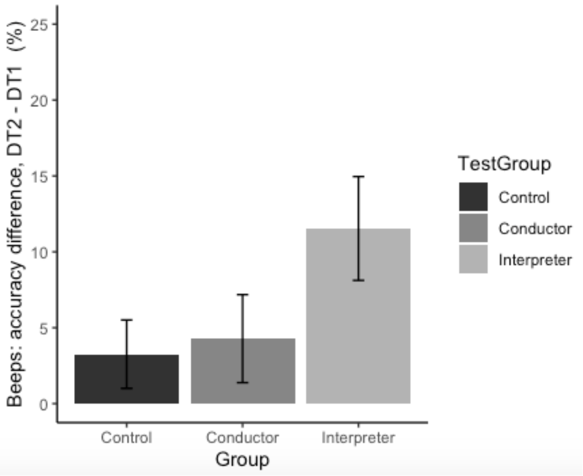


Figure 20

Beep count accuracy: Gain between DT1 and DT2



There appears to be a trade-off between both tasks in the dual task (2-back and beep count) with interpreters giving priority to the 2-back and controls to the beep count in the first dual task; both groups eventually seemed to make progress and "catch up" in the task where they had the lower accuracy rate. All groups appear to show – on average – very similar scores in both tasks in the second dual task. Conductors are the most constant, with high 2-back and beep count accuracy overall.

Prior to fitting global models, pairwise tests were carried out on the whole sample (N=67) to compare beep count performance across tasks in the single and dual condition: Baseline against DT1 and DT2 respectively. The normality of the distribution of mean differences was ascertained through Shapiro-Wilk tests, and dependent 2-group Wilcoxon signed-rank tests were carried out in addition to paired samples t-tests for verification purposes where the normal distribution criterion was not fulfilled. The tests were one-tailed to test the directional multitasking cost hypothesis, assuming a decrease in beep count accuracy between the single and the dual condition. Results were significant in all cases ($p < .001$). The detailed results are available in Appendix C. The means of the differences between the baseline tasks and the first dual task (DT1) was 12.2. The difference in beep count accuracy between the beep count baseline and DT2 was 7.3, pointing to a multitasking cost in both cases. Again, on average, progress is seen in DT2 compared to DT1. This was confirmed by a comparison of the two dual tasks.

To test hypothesis 1b and 2b for beep count accuracy, a linear mixed-effects model was fitted to test the relationship between beep count score and the fixed effect *Iteration* (3 levels: single-task baseline, DT1 and DT2) and *Group* (3 levels: Control, Interpreter, and Conductor, baseline: Control), with an interaction term set between *Group* and *Iteration*. A random intercept was entered by *Subject* (Model B4). By including a random slope for *Iteration* and for *Condition* (task type: single/dual), we assumed that the effect of time and the effect of condition varies across subjects in the population. However, a random slope was not supported by the data. The dataset for this dependent variable was smaller, with one observation by iteration for each subject, and the supported random structure was therefore minimal (see Barr et al., 2013). Models were fitted incrementally with the same random structure in order to verify that the included fixed effects were indeed relevant to account for the observed values, with fixed effect *Iteration* only (Model B1), and *Group* and *Iteration* without the interaction term for comparison purposes (Model B3). Model B2, with fixed effect *Group* only, presented a singular fit due to the closeness between fixed and random effect and was discarded. In Model 1, with fixed effect *Iteration* only, there was a significant effect ($p < .001$) of both dual tasks against the baseline, with negative estimates indicative of a multitasking cost across the sample (intercept: $\beta = 0.985$, SE = 0.010, $t = 102.970$, DT1: $\beta = -0.121$, SE = 0.012, $t = -9.877$, DT2: $\beta = -0.074$, SE = 0.012, $t = -6.180$).

In the full model (Model B 4) there was no effect of *Group* (conductors: $\beta = -0.011$, SE = 0.024, $t = -0.446$, $p = .656$, interpreters: $\beta = -0.020$, SE = 0.022, $t = -0.899$, $p = .370$) or of any interaction between *Group* and *Iteration* (For DT1, conductors: $\beta = -0.001$, p = 0.969, and interpreters: $\beta = -0.050$, $p = .089$. For DT2, conductors: $\beta = 0.011$, $p = .719$, and interpreters: $\beta = 0.025$, $p = .370$). The effect of *Iteration*, however, was significant for both dual tasks against the baseline (DT1: $\beta = -0.103$, SE = 0.022, $t = -4.754$, $p < .001$, DT2: $\beta = -0.087$, SE = 0.021, $t = -4.194$, $p = < .001$).

In order to test hypothesis 3b, regarding goal maintenance in conductors vs. other groups, the models were refitted with conductors as the baseline. In the full model (B 4_C, intercept: 0.985, SE = 0.017) all effects were the same, with significant effects ($p < .001$) only for DT1 ($\beta = -0.104$, SE = 0.021, $t = -4.919$) and DT2 ($\beta = -0.076$, SE = 0.021, $t = -3.588$). The model was also fit with *Condition* rather than *Iteration* as a fixed effect (B 4c_C) to test the multitasking cost hypothesis. This model supported a random intercept by *Iteration*. The effect of *Condition*: dual was significant against the single-task baseline ($\beta = -0.090$, SE = 0.029, $t = -3.108$, $p = .021$). Again, there was no effect of *Group*, and the interaction between *Condition* and *Group* was not significant (interpreters: $\beta = -0.015$, SE = 0.025; controls: $\beta = -0.006$, SE = 0.027).

A comparison of the models (Table 11) showed that this new baseline appeared to improve the significance of the model fits, while the AIC, BIC and -2LL statistics stayed the same. The full model with fixed effect *Iteration* (Model B 4_C) shows the best values of the complex models, however, these were not significantly improved over the simple model with *Iteration* as the only fixed effect (Model 1), indicating that the group parameter was not necessarily a factor of variance:

Table 11

Model comparison: Full model for beep count accuracy, by iteration and condition

Model	*npar*	*AIC*	*BIC*	*-2LL*	*deviance*	χ^2	*df*	*p*
Model B1	5	-434.25	-417.94	222.13	-444.25			
Model B4_C	11	-433.20	-397.31	227.60	-455.20	10.947	6	0.09004

Note. The full models included fixed effects *Group * Iteration* and *Group * Condition* respectively. Models were fit using Maximum Likelihood Estimation and included a random intercept by subject.

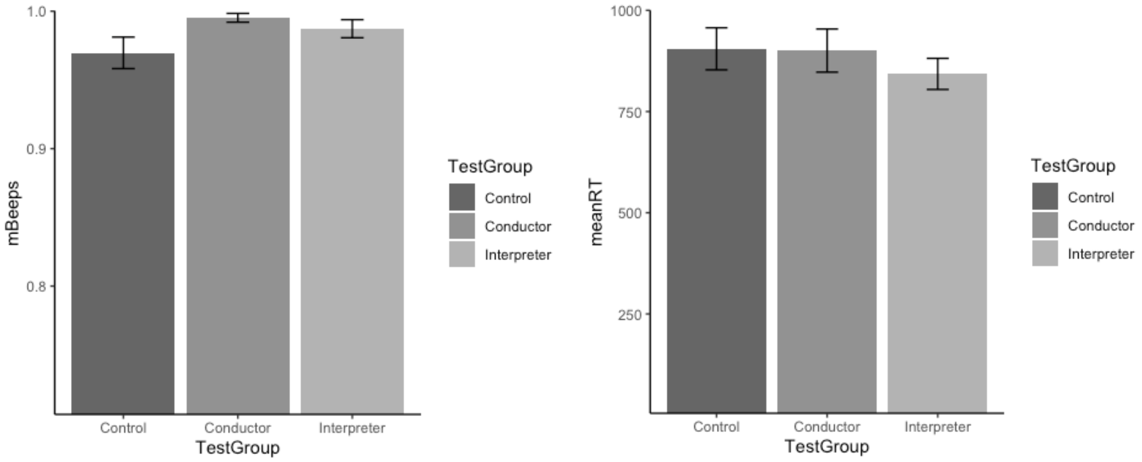
Difference in estimates between models fitted with controls or conductors as the baseline suggest that the multitasking cost is lower in conductors than in controls, but the difference between the groups is not significant. Multitasking performance will be analysed at a later stage, taking into account the performance in the parallel task (2-back accuracy).

7.3.3 Beeps and key presses

Descriptive statistics for beep count accuracy and RT in the beep + key press task are shown in Figure 21.

Figure 21

Beep and key press: Group means, beep count accuracy (%, left) and RT (ms, right).



Accuracy in the beep count in the beeps + key press task was similar to the baseline beep count task. Prior to fitting models, a two-tailed paired samples t-test on the whole sample

(N=67) was performed to compare the performance between baseline beep count task and the key-press condition, as well as a two-tailed dependent 2-group Wilcoxon signed-rank test for verification purposes, as the normal distribution criterion was not fulfilled. The detailed results are available in Appendix C. The means of the differences between the baseline and the task with key presses was 0.012, and the difference was non-significant (*p* = .195). As this exercise and the baseline beep count task had been randomised in the testing routine, tests were carried out to verify whether the task order had an influence on beep count accuracy. A comparison across the sample (Welsh two-sample t-test and Mann-Whitney U test for verification) between participants who performed the baseline first and participants who performed the beep + key press task first did not show a significant difference between them in any of the two tasks (0.016, *p* = .201 and 0.027, *p* = .125, for the baseline and key press task respectively).

A LMM (Model Bkey1) was fitted to compare beep count scores between the baseline and key-press conditions, with a random intercept by subject, the maximal random structure supported (Table 12). There was a significant positive effect of the condition for the conductor and the interpreter groups, the remaining effect of condition against the baseline (controls) being negative.

Table 12

Beep count accuracy, baseline and beep + key press task.

Predictors	*Estimates*	*SE*	*CI (95%)*	*t*	*p*
(Intercept)	0.996	0.007	0.983– 1.009	105.620	**<0.001**
Iteration: Beeps_key	-0.028	0.009	-0.045 – -0.011	-3.209	**0.002**
TestGroup: Conductor	-0.003	0.010	-0.022 – 0.016	-0.268	0.789
TestGroup: Interpreter	-0.008	0.009	-0.26 – 0.009	-0.916	0.361
Beeps_key * Conductor	0.030	0.013	0.005 – 0.055	2.368	**0.021**
Beeps_key * Interpreter	0.027	0.012	0.004 – 0.051	2.338	**0.022**
Random Effects					
σ2			0		
$\tau 00_{\text{Subject}}$			0		
ICC			0.28		
N_{Subject}			65		
Observations			129		
Marginal R2 / Conditional R2			0.050 / 0.312		

Note. Model Bkey 1 was fit using Maximum Likelihood Estimation and included a random intercept by subject (SD = 0.023). There is no estimated impact of the random effect by subject.

A fixed effect for task order (baseline administered first) was added to the model (Bkey 2).

While there was no significant effect for the factor itself and its interactions, there was a similar picture with a significant negative effect for the beeps + key press task against the baseline (β =-0.027, SE = 0.012, t = -2.279, p = .026) but a positive group effect in the beep + key press task for interpreters (β = 0.037, SE = 0.017; t = 2.195, p = .031) as well as a positive trend, not reaching significance, for conductors (β = 0.032, SE = 0.017, t = 1.936, p = .071). Effects in both models were small but an anova for comparison indicated significant improvement over the null model for model Bkey 1 and not for Bkey 2, confirming the lack of relevance of task order.

A LMM was fitted on the beep count accuracy data for all beep count tasks (baseline beep count task, beep + key press task, DT1 and DT2), with the fixed effects *Group* and *Iteration*, an interaction term between the fixed effects, and a random intercept by *Subject*. In that comparison, there were significant effects for DT1 and DT2 only.

No simple RT task was administered as a baseline RT measure, since the beeps + key press task task was itself the baseline for further task combinations with a motor task, which do not fall within the scope of the present study. However, a juxtaposition of response times with the dual 2-back – a task using different stimuli, which cannot be directly compared – shows higher mean response times for the beeps + key press task, a choice-RT task (with a covert count), than for the single 2-back (Table 13).

Table 13

Mean response time, key accuracy and beep count accuracy across tasks, by group

Task	*Group*	*N*	*RT (sd)*		*Key Acc (sd)*		*Beep Acc (sd)*	
Beeps_baseline	Control	21	-	-	-	-	98.4	1.8
Beeps_baseline	Conductor	20	-	-	-	-	94.3	3.9
Beeps_baseline	Interpreter	26	-	-	-	-	90.7	7.0
Beeps_key	Control	21	904.9	238.1	99.3	1.7	87.9	5.3
Beeps_key	Conductor	20	900.5	238.4	100.0	0.0	91.2	8.1
Beeps_key	Interpreter	26	842.9	195.9	99.4	1.5	89.3	8.4
2b_baseline	Control	21	701.7	226.3	95.2	3.9	-	-
2b_baseline	Conductor	20	765.6	328.3	96.9	2.6	-	-
2b_baseline	Interpreter	26	633.1	134.3	95.6	4.0	-	-
2b_DT1	Control	21	1059.4	281.2	74.4	13.4	64.3	7.7
2b_DT1	Conductor	20	968.0	312.5	77.2	12.5	60.4	9.3
2b_DT1	Interpreter	26	894.6	268.4	77.1	10.9	46.1	12.3
2b_DT2	Control	21	910.9	210.4	79.7	11.2	68.4	9.2
2b_DT2	Conductor	20	938.5	235.1	79.5	8.5	68.4	6.0
2b_DT2	Interpreter	26	885.0	297.8	79.3	10.4	70.4	7.5

Key press accuracy was at ceiling for the task, making a robust analysis of post-error slowing impossible. Only 6 subjects (3 interpreters and 3 controls) made 1 error each, and only 2 of them (2 controls) did not make the error on the first item of the task.

Although the beep + key press and the 2-back were different tasks, all processing speed measures, that is, RTs for the baseline and dual 2-back and the beep count + key press exercise were analysed together in an LMM, with task (*Iteration*) and *Group* as fixed effects and an interaction term, and a random intercept by *Subject*. The model was fitted using log-transformed and non-transformed RT values; since the effects were the same, estimates in milliseconds are provided here for better readability. There was a significant difference ($p < .001$) between the RT in the single 2-back and in both dual tasks, with an increase of 348.96 ms for DT1 and 205.27 ms for DT2 against the baseline (β = 704.66 ms), but also a significant difference between the single 2-back and the beep + key press task (β = 185.16 ms). Other significant effects were the interaction between *Group* and *Iteration* for interpreters in DT1 and DT2, with significantly lower RTs (β = -137.63 ms and -103.76 ms respectively), which disappeared when a random slope was added to account for the individual variation of subjects between tasks.

To compare the groups in the beep + key-press task, a one-way ANOVA was performed with log-transformed RT as the dependent variable and *Group* as the independent variable. There was a small, but significant difference between the groups: F (2, 1393) = 5.749, p = .003. Post-hoc multiple comparisons (Tukey-Kramer Test) found that interpreters differed significantly from controls (mean difference: -0.068, p = .013, 95% C.I. = [-0.124 – -0.011]) as well as from conductors (mean difference: -0.071, p = .009, 95% C.I. = [-0.127 – -0.015]). There was no difference between conductors and controls.

7.4 Control variables

Control variables were added as fixed effects to test their potential relationship with the dependent variables in addition to the grouping variable, and to see if they contributed to describing the observed data. The subject-level variables examined here are gender (categorical), age, non-verbal IQ (due to its possible relation with WM functions), bilingualism and musicianship (all scored on a continuum). This section details the associations between the subject-level variables and processing speed in a first step; subsequently, the associations between these variables and performance as measured by both 2-back and beep count accuracy taken together are analysed.

7.4.1 Variables associated with processing speed

7.4.1.1 Age

Adding *Age* to fitted RT models before or after adding the fixed effects tested previously (*Group* and *Iteration*) did not modify the pattern of results, therefore age was taken out of the models. In a dataset comprised of baseline 2-back, D1 and DT2 only, the reduced model (without interaction terms between group, age, and iteration) showed a significant effect of DT1 and DT2 only. The full model, with interaction terms between *Group*, *Age,* and *Iteration*, and a random intercept by subject only, showed significant effects, depicted below in Table 14, but once a random slope was added, all effects disappeared, with only *Age* almost reaching significance ($\beta = 0.009$, $p = .076$). A comparison of the RT models showed that the models including *Age* did not describe the data as well as models without it.

Table 14

Model summary: Full model with Age for RT data: Baseline 2-back, DT1, DT2.

Fixed effects	*Estimate*	*Std. Error*	*CI (95%)*	*t value*	*Pr(>$\lvert t \rvert$)*
(Intercept)	6.070	0.186	5.71 – 6.44	32.583	**< 0.001**
Group: Conductor	0.475	0.274	-0.06 – 1.01	1.735	0.087
Group: Interpreter	0.146	0.255	-0.35 – 0.65	0.571	0.569
Iteration: DT1	0.411	0.098	0.22 – 0.60	4.195	**< 0.001**
Iteration: DT2	0.319	0.082	0.16 – 0.48	3.879	**< 0.001**
Age	0.010	0.004	0.00 – 0.02	2.243	**0.028**
Conductor x DT1	-0.227	0.133	-0.49 – 0.03	-1.708	0.088
Interpreter x DT1	-0.070	0.128	-0.32 – 0.18	-0.551	0.582
Conductor x DT2	-0.417	0.122	-0.66 – -0.18	-3.427	**< 0.001**
Interpreter x DT2	-0.007	0.114	-0.23 – 0.22	-0.063	0.950
Conductor x Age	-0.010	0.006	-0.02 – 0.00	-1.741	0.086
Interpreter x Age	-0.006	0.006	-0.02 – 0.00	-1.123	0.265
DT1 x Age	-0.002	0.002	-0.01 – 0.00	-0.722	0.470
DT2 x Age	-0.003	0.002	-0.01 – 0.00	-1.803	0.071
Conductor x DT1 x Age	0.002	0.003	-0.00 – 0.01	0.819	0.413
Interpreter x DT1 x Age	-0.000	0.003	-0.01 – 0.01	-0.046	0.963
Conductor x DT2 x Age	0.009	0.003	0.00 – 0.01	3.355	**< 0.001**
Interpreter x DT2 x Age	0.002	0.003	-0.00 – 0.01	0.641	0.521
Random Effects					
σ^2	0.18				
$\tau_{00\ \text{Subject}}$	0.04				
ICC	0.18				
N_{Subject}	67				
Observations	7618				
Marginal R^2 / Conditional R^2	0.080 / 0.249				

Note. The model was fit using Maximum Likelihood Estimation and included a random intercept by subject (SD: 0.2037). Effects disappeared once a random slope was added.

Adding *Age* to the model previously fitted to analyse the key press task alongside the baseline and dual 2-back, there was no significant effect of *Age* when *Age* was considered with *Iteration* only nor when *Group* was added without interaction terms. Model comparison shows that this reduced model with *Iteration*, *Group* and *Age* is a better fit than the equivalent model fitted without *Age*, but that the best description of the data is provided by the random slope model without *Age*. Adding an interaction term between *Age* and *Iteration* does not modify the pattern of effects.

Once interaction terms are added between all the fixed effects (*Group*, *Iteration* and *Age*), the picture changes, suggesting a group-dependent effect for age. The overall effect of *Age* on RT becomes significant ($\beta = 0.009$. $p = 0.016$) against the baseline, and in the beep + key press task (associated with lower RTs: $\beta = -0.005$, $p = 0.012$), but not in the dual tasks. Beyond usual effects of *Iteration* (consistent across models), once age is accounted for, an additional effect of *Group* (speed advantage) is predicted for conductors in DT2 ($\beta = -0.425$, $SE = 0.119$, $t = -3.578$, $p < 0.001$) as well as a trend in DT1 ($\beta = -0.231$, $p = 0.074$). With age, conductors show slight, but significant, slowing in DT2: $\beta = 0.009$, $SE = 0.003$, $t = 3.459$, $p < 0.001$).

With all tasks and iterations (all 2-back tasks and the beep and key press task), a complex picture emerges. Adding *Age* to the full model with all interactions improves the fit for that dataset, but a random slope is not supported. There is a slight, but significant effect of *Age* against the baseline, as well as in DT2 and Beeps + Key (advantages in both cases). With Age added to the equation, conductors are faster in both dual tasks (and slower with age in DT2), slower in Rep4, and perform faster with age in rep2; interpreters are significantly faster in rep3, rep4 and rep5, but slower with age in those iterations.

7.4.1.2 Gender

Adding *Gender* to the models yielded some differences in DT1 and 2 and beep + keys for conductors notably, due to slower performances in the very few women conductors in these conditions, but the fit of the models was poorer than without the effect.

7.4.1.3 Bilingualism

In the dataset without the 2-back reps, *Bilingualism* was associated with faster RTs in the dual tasks in interpreters and conductors and with slower RTs in the dual tasks in controls. Bilingualism explained away the advantage for both groups in DT2, where they were significantly slower once bilingualism was taken into account, suggesting that the slowing effect was attributed mainly to bilinguals in the control group. However, adding *Bilingualism* to the models deteriorated the respective model fit.

7.4.1.4 Musicianship

In the dataset without the 2-back reps, there was a significant effect of *Musicianship* in both the model with and without interactions, and the fit was improved compared to the full model without the added effect of *Musicianship*.

In the full dataset, the fit was also improved by adding the fixed effect *Musicianship*. The effect remained for DT1 and DT2; *Musicianship* significantly improved RT in the baseline 2-back task in controls (β = -0.003, SE = 0.001, t = -2.312, p = .024) as well as in rep3, rep4 and rep5 and the beep + key press task, but constituted a slowing factor for interpreters in that task (β = 0.003, SE = 0.001, t = 3.110, p = .002). Both interpreters (β = -0.082, SE = 0.039, t = -2.128, p = 0.033) and conductors (β = -0.335, SE = 0.142, t = -2.368, p = .018) were faster than controls in DT1.

7.4.1.5 Non-verbal IQ

In the dataset without the 2-back reps, adding non-verbal IQ (*NVIQ*) to the effects did not improve the model fit. However, applied to the dataset with all iterations, the full model with *NVIQ* best described the data. Once *NVIQ* was taken into account, the effects remained unchanged for DT1 and DT2 against the baseline, as well as Rep3 (β = 0.379, SE = 0.184, t = 2.059, p = .040) with significant slowing also for beeps + key press (β = 1.489, SE = 0.232, t = 6.424, p < .001). Conductors were significantly slower than controls in the baseline (β = 2.581, SE = 0.803, t = 3.215, p = .002), but faster in both DT1 (β = -3.158, SE = 0.293, t = -10.789, p < .001) and DT2 (β = -1.413, SE = 0.280, t = -5.050, p < .001) as well as interpreters (DT1: β = -2.284, SE = 0.305, t = -7.483, p < .001; DT2: β = -1.178, SE = 0.280, t = -4.210, p < .001). Interpreters were also faster in Rep3 (β = -0.821, SE = 0.266, t = -3.082, p = .002). Conductors were noticeably faster in the beeps + key press task: β = -2.341, SE = 0.332, t = -7.044, p < .001. Regarding *NVIQ*, the parameter was associated with slightly higher RTs overall against the baseline (β = 0.012, SE = 0.005, t = 2.333, p = .022), but with lower RTs in DT1 (β = -0.015, SE = 0.002, t = -7.728, p < .001), DT2 (β = -0.008, SE = 0.002, t = -4.680, p < .001) and rep3 (β = -0.004, SE = 0.002, t = -2.182, p = .029), as well as in the Beep + key press task (β = -0.012, SE = 0.002, t = -5.409, p < .001). This suggests that controls are faster with NVIQ, but significantly slower once that variable is accounted for. Conversely, *NVIQ* was associated with lower RTs in conductors in the baseline ($\beta = -0.024$, SE = 0.007, t = -3.154, *p* = .002), but conductors with higher *NVIQ* were comparatively slower in DT1 ($\beta = 0.028$, SE = 0.002, t = 10.298, *p* < .001) and DT2 ($\beta = 0.013$, SE = 0.003 t = 4.929) as well as the beep + key press task ($\beta = 0.022$, SE = 0.003 t = 6.964). The same applied for interpreters in DT1 ($\beta = 0.020$, SE = 0.003, t = 7.168), DT2 ($\beta = 0.011$, SE = 0.003, t = 4.363) and Rep3 ($\beta = 0.008$, SE = 0.002, t = 3.053, p = 0.002).

7.4.1.6 All control variables.

7.4.1.6.1 Comparison of added effects

Model comparison between all the added effects (Table 15) shows that the full model with *NVIQ* above best describes the complete dataset with all 2-back iterations.

Table 15

Model comparison: LMMs of log-transformed 2-back RT, with added subject-level variables

Model	*npar*	*AIC*	*BIC*	*-2LL*	*deviance*	χ^2	*df*	*p*
Null model	3	21000	21024	-10496.8	20994			
Red. model (Iteration+Group)	13	18797	18902	-9385.5	18771	2222.540	10	<0.001 ***
Red. model + Age	14	18797	18910	-9384.4	18769	2.145	1	0.1431
Red. model + Gender	14	18799	18912	-9385.4	18771	0.0000	0	1.0000
Red. model + Bilingualism	14	18799	18912	-9385.5	18771	0.0000	0	1.0000
Red. model + Musicianship	14	18788	18901	-9379.8	18760	11.361	0	<0.001 ***
Red. model + NVIQ	14	18799	18912	-9385.5	18771	0.0000	0	1.0000
Full model (Iteration*Group)	29	18687	18922	-9314.5	18629	141.938	15	<0.001***
Full model + Age	56	18533	18986	-9210.6	18421	207.776	27	<0.001 ***
Full model + Gender	56	18587	19040	-9237.5	18475	0.0000	0	1.0000
Full model + Bilingualism	56	18590	19042	-9238.8	18478	0.0000	0	1.0000
Full model + Musicianship	56	18652	19105	-9269.9	18540	0.0000	0	1.0000
Full model + NVIQ	56	18481	18934	-9184.4	18369	170.951	0	<0.001 ***

Note. Models were fit using Maximum Likelihood Estimation and included a random intercept by subject.

In the dataset without the 2-back reps, the best fit is provided by the reduced model with added effect *Musicianship* and a random slope by subject for the variable *Iteration* (Table 16).

Table 16

Model summary: Full model with Musicianship for RT data: Baseline 2-back, DT1, DT2.

Fixed effects	*Estimate*	*Std. Error*	*CI (95%)*	*t value*	*p*
(Intercept)	6.59	0.05	6.49 – 6.70	125.36	**< 0.001**
TestGroup: Conductor	0.19	0.07	0.06 – 0.33	2.79	**0.007**
TestGroup: Interpreter	-0.07	0.05	-0.16 – 0.03	-1.31	0.193
Iteration:_DT1	0.27	0.04	0.19 – 0.35	6.69	**< 0.001**
Iteration:_DT2	0.19	0.03	0.13 – 0.25	5.92	**< 0.001**
Iteration: Beeps + key	0.25	0.04	0.17 – 0.33	6.10	**< 0.001**
Musicianship	-0.003	0.00	-0.00 – -0.00	-4.10	**< 0.001**
Random Effects					
σ^2	0.15				
τ_{00} Subject	0.07				
τ_{11} Subject.Iteration2b_dual1	0.09				
τ_{11} Subject.Iteration2b_dual2	0.06				
τ_{11} Subject.IterationBeeps_key	0.10				
ρ_{01}	-0.64				
	-0.62				
	-0.71				
ICC	0.28				
N Subject	67				
Observations	9014				
Marginal R^2 /Conditional R^2	0.093 / 0.343				

Note. Log-transformed RT. The model was fit using Maximum Likelihood Estimation and included a random intercept by subject (SD: 0.2607) and a random slope by iteration. Grey: RT for the key press in the beep count task. Adding the beep + key press iteration as a parameter did not modify other effects.

7.4.1.6.2 All effects analysed

In the full dataset, the data does not support a model with all effects, with or without the beeps + key press task. In the reduced dataset without single 2-back reps (i.e., including the data from the baseline 2-back, DT1 and DT2 only, with and without the beeps + key exercise), the model containing *Age*, *Gender*, *Bilingualism*, *Musicianship* and *NVIQ* as fixed effects that where thus considered as overall RT predictors (in addition to *Iteration* and *Group*), without interaction terms, and with a random slope by Iteration for each subject, only *Musicianship* has a significant effect, with a global advantage against the baseline (no difference from individual, previous models for those variables). *Group* (conductors, overall slower once *Musicianship* is taken into account separately) and *Iteration* (higher RTs in DT1-2, beep keys; lower in reps 2,3,4, and 5) show the usual overall significance. That model offers the best fit over the models fitted without the added effects and over the full model with interactions.

For each dataset: Baseline and dual 2-back only, complete 2-back, and complete dataset with the beep + key press task, models with added effects were fitted iteratively, with 2, then 3, then 4 effects etc., comparing the best fit every time prior to adding an effect. *Iteration* was set as a fixed effect from the beginning, as the hypothesis at hand was to test changes in RT between the various single and dual iterations. In all cases, *Group* provided the best fit as the second effect, therefore, RT could be studied in detail as a function of *Iteration* and *Group*, to test hypotheses 1b and 2a (section 7.2.3.2 above) prior to fitting further effects.

For the reduced 2-back dataset, the best fit as a third effect, improving the model, was *NVIQ* (AIC: 8931.8, BIC: 9070.6, *-2LL*: -4445.9, deviance = 8891.8, $\chi^2 = 79.971$) closely followed by *Age* but with more predictive power. The best fit as a fourth effect was *Musicianship*, which also significantly improved the model's overall goodness of fit (AIC: 38 8852.5, BIC: 9116.2, *-2LL*: -4388.3, deviance = 8776.5, $\chi^2 = 115.299$). Attempts to add a new effect to that model were successful only for *Age*, as the correlation matrixes including *Bilingualism* and *Gender* could not be produced.

The most complete model with interactions, and the best fit to the data among those models, therefore included the fixed effects *Iteration*, *Group*, *NVIQ*, *Musicianship* and *Age* (AIC: 8805.0, BIC: 9318.4, *-2LL*: -4328.5, deviance: 8657.0, $\chi^2 = 119.557$). Though this complex model describes the data reasonably well, the small relative size of the subgroups created by each interaction probably greatly undermines its predictive power compared to simpler ones, especially considering possible confounds between musicianship and age due to the composition of the conductor group. It is also important to bear in mind that this model was fitted without a random slope, which provided better goodness of fit to simpler models of the same dataset. In any case, it is interesting to observe the possible interplay in the current sample of NVIQ, musicianship and age across groups and iterations, and within each of those. Conductors are slower and interpreters faster against the baseline, but the effect is not significant. However, a number of significant effects appear in the model: interpreters are significantly faster in DT1 and less so in DT2 (reduced estimate and $p = .078$). Age, as well as musicianship, are associated with faster RTs in DT1, but less so in interpreters (comparative slowing effect). There is an overall RT advantage with musicianship in interpreters, but smaller in the DT1 (comparative slowing effect). NVIQ has a small slowing effect in interpreters, especially in DT1, and a significant speeding effect against the baseline (i.e., in controls). Other significant effects are very small and all related to the interplay between age and at least two other variables in the DT1, except for a RT advantage with NVIQ and musicianship and age in interpreters overall.

The best fit in the full dataset was a model comprising fixed effects and interactions for *NVIQ* and *Age* in addition to *Iteration* and *Group* (AIC: 18071.7, BIC: 18961.2, *-2LL*: -8925.8, deviance: 17851.7, $\chi^2 = 23902$). In the complete dataset for the 2-back only, *NVIQ*, *Musicianship* and *Age* or *NVIQ*, *Age* and *Gender* provided a comparatively good fit, but with probably no predictive power considering the number of subgroups due to the added iterations.

Patterns in the models advocated for re-fitting the RT models with added effects with interpreters as the baseline: In fact, a comparative slowing in bilinguals among the controls as opposed to the other groups, probably contributed to making bilingualism less relevant as a variable to describe the data. In addition, changing the baseline seemed relevant to analyse specifically the differentiated relationship – if any – between interpreting, bilingualism and processing speed, However, doing so in the dataset with the baseline 2-back, DT1 and DT2 with or without the beep + key press task did not yield further insight when bilingualism was observed in isolation nor in interaction with other effects.

7.4.2 Variables associated with multitasking (2-back and beep-count accuracy)

In a subsequent step, multitasking performance during DT1 and DT2 was assessed by considering and analysing accuracy in both task components taken together. Performance in both task components across the three experimental groups is depicted below, for accuracy measures only (Figure 22) and with RT (Figure 23). To some extent, variation within groups and within the sample is reduced in DT2, although RT was noticeably increased in a few individual performers.

Figure 22

Boxplot of 2-back and beep count accuracy by group during DT1 (left) and DT2 (right).

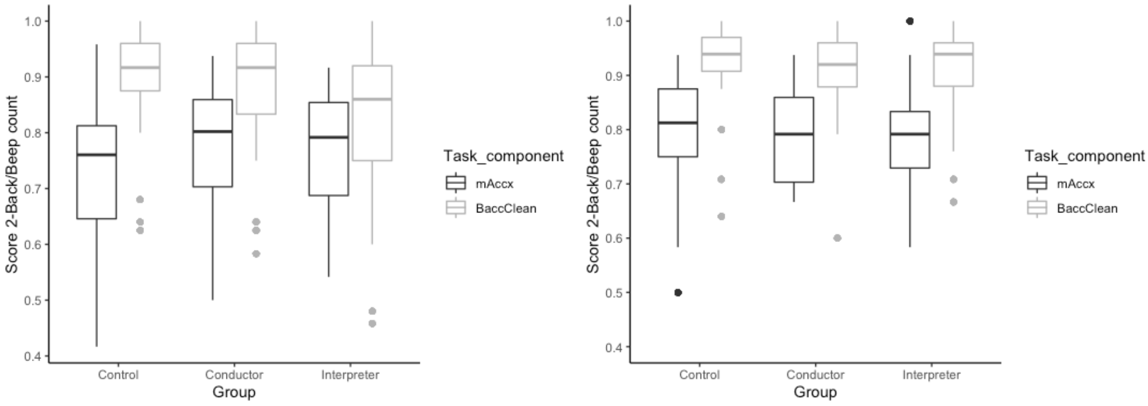
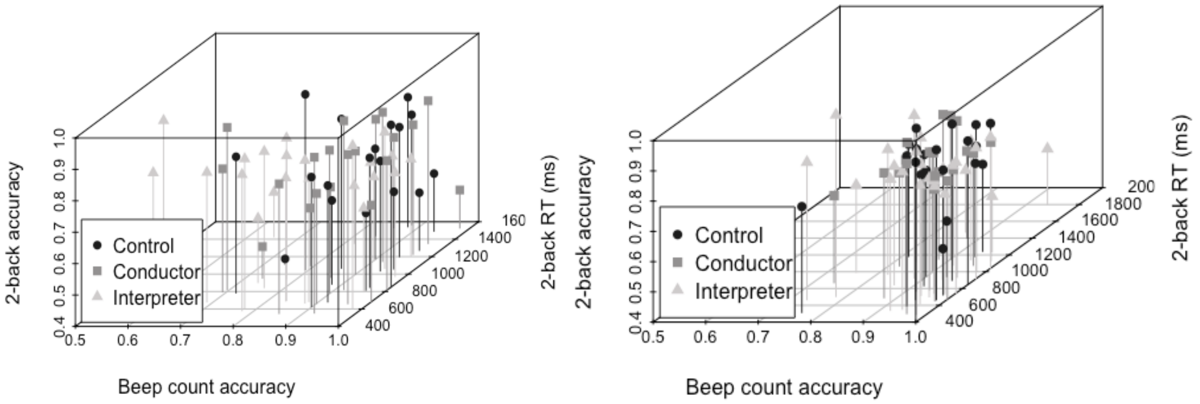


Figure 23

3D-scatterplot of 2-back, beep count accuracy and RT by group during DT1 (left) and DT2 (right).



To provide an account of specific levels of performance within the sample, we performed a median split on several variables to create categories; post-error slowing was computed for each task iteration, as well as the overlap between categories. We then tallied the number of participants from each group in these subgroups. The simple categories were as follows: Faster than the median ("Fast"), more accurate than the median in the beep count ("GM"), more accurate than the median in the 2-back ("Best2b"), slowing after errors ("PES"), slowing after omissions ("P0S"), and generalised PES ("gPS"), that is, slowing after both kinds of non-correct trials. The categories were also combined in order to display the number of faster performers or performers with post-error slowing – and the type of post-error slowing – among accurate performers (Table 17) and highlight common occurrences of post-error slowing, fast RTs, and good multitasking (Table 18). Insights from the distribution patterns will be drawn in the discussion.

Table 17

All tasks: Number of participants by group, type of PES, upper performance categories, and category combinations

Task	*Group*	*n*	*Fast*	*PES*	*P0S*	*gPS*	*Fast PES*	*Fast P0S*	*Fast gPS*	*Best2b*	*Best2b Fast*	*Best2b PES*	*Best2b P0S*	*Best2b gPS*	*GM*	*GM Fast*	*GM PES*	*GM P0S*	*GM gPS*
2b	CT	21	11	12	0	0	6	0	0	8	2	5	0	0	-	-	-	-	-
	Cond.	20	8	8	0	0	4	0	0	11	6	4	0	0	-	-	-	-	-
	Int.	26	13	11	1	0	6	0	0	13	7	4	0	0	-	-	-	-	-
2b rep1	CT	21	10	9	1	0	5	0	0	4	2	0	0	0	-	-	-	-	-
	Cond.	20	7	6	1	0	2	1	0	9	2	0	0	0	-	-	-	-	-
	Int.	26	15	10	1	1	6	1	1	10	7	0	0	0	-	-	-	-	-
2b rep2	CT	21	9	5	0	0	3	0	0	5	0	0	0	0	-	-	-	-	-
	Cond.	20	8	9	0	0	2	0	0	6	3	0	0	0	-	-	-	-	-
	Int.	26	15	14	1	1	8	0	0	6	4	0	0	0	-	-	-	-	-
2b rep3	CT	21	10	7	0	0	5	0	0	6	3	0	0	0	-	-	-	-	-
	Cond.	20	9	6	0	0	2	0	0	9	5	0	0	0	-	-	-	-	-
	Int.	26	13	14	0	0	8	0	0	7	2	0	0	0	-	-	-	-	-
2b rep4	CT	21	10	9	0	0	5	0	0	10	5	3	0	0	-	-	-	-	-
	Cond.	20	8	4	1	0	0	0	0	12	5	1	1	0	-	-	-	-	-
	Int.	24	14	10	0	0	6	0	0	13	8	4	0	0	-	-	-	-	-
2b rep5	CT	21	10	15	1	1	8	0	0	9	3	4	0	0	-	-	-	-	-
	Cond.	20	7	8	1	0	6	0	0	17	7	7	0	0	-	-	-	-	-
	Int.	26	16	8	1	1	6	0	0	16	10	3	0	0	-	-	-	-	-
DT1	CT	21	7	12	5	3	5	0	0	8	4	4	1	1	10	5	7	3	2
	Cond.	20	10	12	4	4	7	1	1	10	7	6	2	2	11	6	7	2	2
	Int.	26	13	15	2	2	8	0	0	10	8	6	0	0	8	3	6	0	0
DT2	CT	21	10	9	6	2	3	4	1	12	8	4	3	1	11	5	3	3	1
	Cond.	20	8	12	3	2	5	1	1	9	6	5	1	1	7	4	6	0	0
	Int.	26	15	12	0	0	4	0	0	12	8	5	0	0	15	10	6	0	0
Beeps	CT	21	-	-	-	-	-	-	-	-	-	-	-	0	20	-	-	-	0
	Cond.	20	-	-	-	-	-	-	-	-	-	-	-	0	16	-	-	-	0
	Int.	26	-	-	-	-	-	-	-	-	-	-	-	0	21	-	-	-	0
Beeps key	CT	20	10	2	2	2	0	0	0	-	-	-	-	0	13	7	0	-	0
	Cond.	20	8	0	0	0	0	0	0	-	-	-	-	0	17	8	0	-	0
	Int.	26	14	0	0	0	0	0	0	-	-	-	-	0	21	12	0	-	0

Note. Groups: Controls (CT), Conductors (Cond.), Interpreters (Int.). Categories: median-split RT (Fast), median-split 2-back accuracy (Best2b), median-split beep count accuracy (BestGM), positive slowing post errors (PES), positive slowing post omissions (P0S), positive general PES, i.e., after both errors and omissions (gPS). Dual tasks are highlighted.

Table 18

Multitasking: Number of participants by group, type of PES, upper dual performance categories, and category combinations

Iteration	*Group*	*n*	*ST*	*ST Fast*	*ST PES*	*ST P0S*	*ST gPS*	*ST Fast PES*	*ST Fast P0S*	*ST Fast gPS*
DT1	CT	21	4	3	2	1	1	1	0	0
	Cond.	20	7	4	4	1	1	3	0	0
	Int.	26	2	1	1	0	0	0	0	0
DT2	CT	21	9	5	2	2	0	1	2	0
	Cond.	20	4	3	4	0	0	3	0	0
	Int.	26	6	4	2	0	0	0	0	0

Note. Groups: Controls (CT), Conductors (Cond.), Interpreters (Int.). Categories: Accuracy in both 2-back and beep count above median (ST), median-split RT (Fast), positive slowing post errors (PES), positive slowing post omissions (P0S), positive general PES, i.e., after errors and omissions (gPS).

We used multiple multivariate regression analyses to examine both accuracy outcomes of the dual task together and try to form a picture of the interplay between subject-level variables and performance in a dual-task setting[56]. Although this provides a way to account for multitasking performance as such, one major drawback of these models is that they do not allow for introducing random effects in order to take individual factors in sets of repeated measures into account. They therefore increase the risk of type I errors (false positives). In addition, creating subgroups for the analysis decreases the cell size and increases the risk of violating the normalcy assumption. Due to the large number of independent variables, and consequently, of significance tests, and the increased likelihood of making a Type I error, only results significant at the $p < .001$ level are reported (Pillai's trace, Wilks' Lambda, Lawley's trace, and Roy's largest root test statistics showed equal significance levels).

In a first step, subject-level variables were added incrementally to the fixed effect Iteration. Group was the best fit of all possible second fixed effects. Adding more effects and interactions tended to improve the model fit. The complete model included all effects with an interaction term for each with *Group* only (as this was the maximal supported structure). In order to test whether processing speed is associated with better performance in the dual task, and the changes after training, a median split was performed on the RT observations for each iteration, and an additional variable for *processing speed* with two factors, "high" (above median) and "low" (below or at median), was created and included in the model with an interaction term between processing speed and the Group variable. It appears that RT is

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[56] Subject-level variables were also examined in relation to the individual accuracy scores, but this approach appears to be more appropriate to test the hypotheses at hand.

correlated with higher accuracy in the 2-back task (the same task) in all groups in the dual tasks, except for controls in DT2 (all parameters significant). There is no significant association with higher performance in the beep count task in DT1 for all groups, and a significant association with higher performance in that task in DT2 for interpreters. A variable *post-error slowing PES* with two factors ("true" for mean RT post-error higher than mean RT pre-error for the iteration, or "false") was also created and included in the analysis. There was a significant effect of PES on accuracy in all cases in the 2-back (the same task), with PES = "true" associated with higher accuracy in interpreters and conductors and with lower accuracy in controls in DT1 and in DT2. The association with beep count accuracy was positive in controls and negative in conductors in DT1 (interpreters n.s.) and negative in controls and positive in conductors and interpreters in DT2 (as for the 2-back task).

In order to test the relationship between goal maintenance and multitasking, where one of the outcomes (beep count accuracy) was the goal maintenance measure, the first step of the analysis required testing whether participants who performed better in the beep count during multitasking tended to also perform well in the 2-back task. To distinguish the effect of goal maintenance during multitasking from the phenomenon of ‘good multitasking’ and from that of the sheer priorisation of tasks, we also needed to verify in a second step if the pattern was different for people who performed better in the 2-back task. For the purpose of these analyses, we performed a median split to divide participants by level of performance in the tasks.

We first refitted the multitasking model, with both 2-back and beep count accuracy as dependent variables, adding the median-split beep count accuracy as an independent variable, and considered its effects on the 2-back accuracy DV. There was a significant difference in 2-back performance between participants who performed above the median in the beep count and participants who did not, as well as between groups. Controls were the only ones in which the association between higher beep count accuracy (GM: goal maintenance for the beep count) and 2-back accuracy was positive both in DT1 ($\beta = 0.020$, SE = 0.007, $t = 2.999$, $p = .003$) and DT2 ($\beta = 0.125$, SE = 0.008, $t = 15.723$, $p < .001$). For the conductors, the association was positive in DT1 ($\beta = 0.046$, SE = 0.009, $t = 5.166$, $p < .001$). The association was negative and significant ($p < .001$) for the interpreters in both DTs (DT1: $\beta = -0.043$, SE = 0.009, $t = -4.869$; DT2: $\beta = -0.159$, SE = 0.011, $t = -14.375$) and for the conductors in DT2 ($\beta = -0.135$, SE = 0.011, $t = -11.915$). This means that the best performers in the beep count showed worse 2-back accuracy. This suggests that controls who gave priority to the beep count task were effectively multitasking better than controls who did not. The same applies to conductors in the first DT, but that the reverse was true for interpreters, and for conductors in the second DT.

In a next step, we added a median-split 2-back accuracy IV to the model and considered its effects on the beep-count accuracy DV. In DT1, performance above the median in the 2-back was negatively associated with beep count performance in controls ($\beta = -0.022$, SE = 0.006, $t = -3.911$, $p < .001$), and non-significant in conductors (positive) and interpreters (negative). In DT2, the association was positive in controls ($\beta = 0.083$, SE = 0.008, $t = 9.828$, $p < .001$) and negative in conductors ($\beta = -0.052$, SE = 0.012, $t = -4.427$, $p < .001$) and interpreters ($\beta = -0.031$, SE = 0.011, $t = -2.835$, $p = .005$). This also transformed the relationship patterns observed between performance in the upper half of the beep count accuracy scores and 2-back accuracy, which matched these new relationships (with a significant positive association in conductors in DT1). Table 19 reports the multivariate effects and their relative explanatory power for the combined accuracy outcome of the dual tasks. The complete table of effects on each DV (2-back accuracy and beep count accuracy) of the IVs is found in Appendix . However, it should be underlined that some of the effects predicted on either DV (2-back or beep count accuracy) were inconsistent with the results of more robust modelling on the isolated DVs. This is probably due to the model being more sensitive to group effects without regard for individual variation, and the results should therefore be interpreted in that light. In order to make variables more comparable and the analyses more robust, we refitted all models on the centred covariates.[57] While most effects and the corresponding multivariate tests were significant in the original multiple multivariate regression analyses, the significance mostly disappeared in the second analysis. The estimates and summary of coefficients for the centred version of the full model are provided in Appendix E.

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[57] Multiple multivariate models with random effects, (e.g., multivariate random coefficient model), which constitute comparatively recent advances, could be considered for future analyses, especially if more multitasking performance variables are added.

Table 19

Complete multivariate regression analysis: Significant multivariate effects (at p<.001 level)

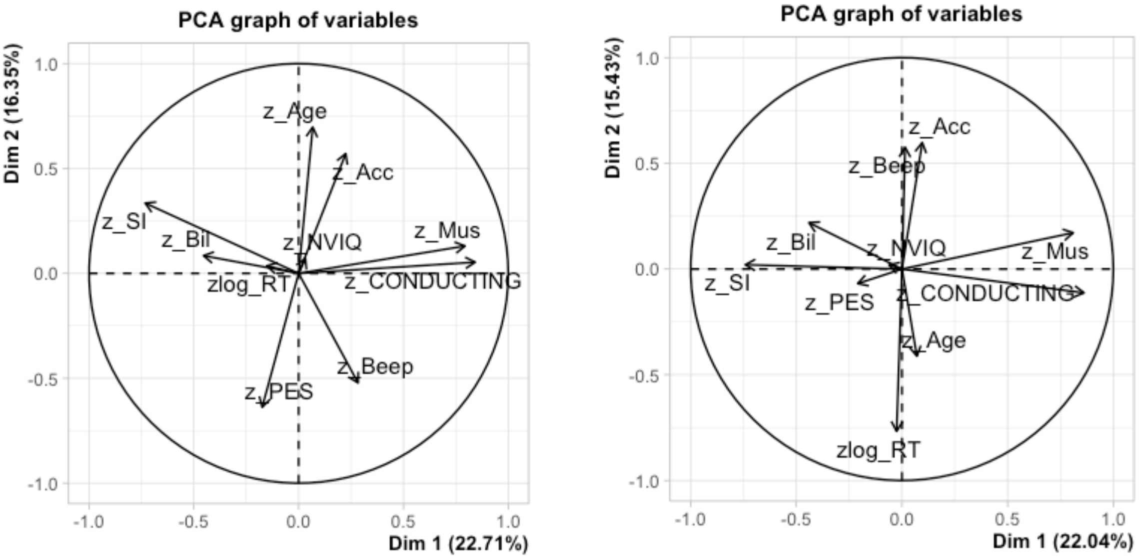
Variable(s)	*Pillai's Trace*	*F*	*df*	*Error df*
TestGroup	.018	27.214	4	11814
Iteration	.121	404.788	2	5906
Age	.017	50.297	2	5906
Gender	.005	13.419	2	5906
Bilingualism	.022	65.812	2	5906
Musicianship	*.0003*	*0.837*	*2*	*5906*
NVIQ	.005	14.285	2	5906
Fast	.078	249.942	2	5906
PES	.0676	213.960	2	5906
GM	.336	1494.737	2	5906
Best2b	.487	2804.517	2	5906
Group*Iteration	.019	27.997	4	11814
Group*Age	.055	82.842	4	11814
Group*Gender	.009	13.187	4	11814
Group*Bilingualism	.053	80.426	4	11814
Group*Musicianship	.048	73.329	4	11814
Group*Standardised	.035	52.323	4	11814
Group*Fast	.043	65.413	4	11814
Iteration*Fast	.010	29.511	2	5906
Group*PES	.013	19.180	4	11814
Iteration*PES	.051	160.201	2	5906
Group*GM	.044	66.303	4	11814
Iteration*GM	.037	114.425	2	5906
Group*Best2b	.010	15.485	4	11814
Iteration*Best2b	.031	95.177	2	5906
Group*Iteration*Fast	.084	129.913	4	11814
Group*Iteration*PES	.011	16.322	4	11814
Group*Iteration*GM	.0136	20.190	4	11814
Group*Iteration*Best2b	.0129	19.194	4	11814

Note. Italics: non-significant effect (Musicianship: *(p* = 0.433).

As a last step, we performed an exploratory analysis of correlation levels between factors contributing to multitasking, considering all participants' performance and the best multitaskers' performance in the dual tasks at hand, namely, the performers in the top half of the score distribution in both task components. Using the *FactoMineR* package (Lê, Josse, & Husson, 2008), we performed a principal component analysis on the dummy, centered variables used for the multivariate analysis and plotted the dual task results against the two dimensions explaining the most variance in the dataset. A dummy variable was created for interpreting and conducting experience, in order to include it in the visualisation of relationships. DT1 and DT2 in all participants (Figure 24), the first dimension was closely aligned with conducting and musicianship and on an opposite axis with interpreting ("SI"). In DT1, the second dimension was closely aligned with age, and to a lesser extent with 2-back accuracy, on an opposite axis with PES. Lower RTs were closely aligned with bilingualism and interpreting. In DT2, the second dimension was very closely aligned with beep count and to a lesser extent 2-back performance, and on an opposite axis with RT. The little variance explained by the PCA suggests that the data is explained to a large extent by individual variation. The underlying values (loadings and contribution of the respective variables) are provided by way of example for for DT1 in Appendix F.

Figure 24

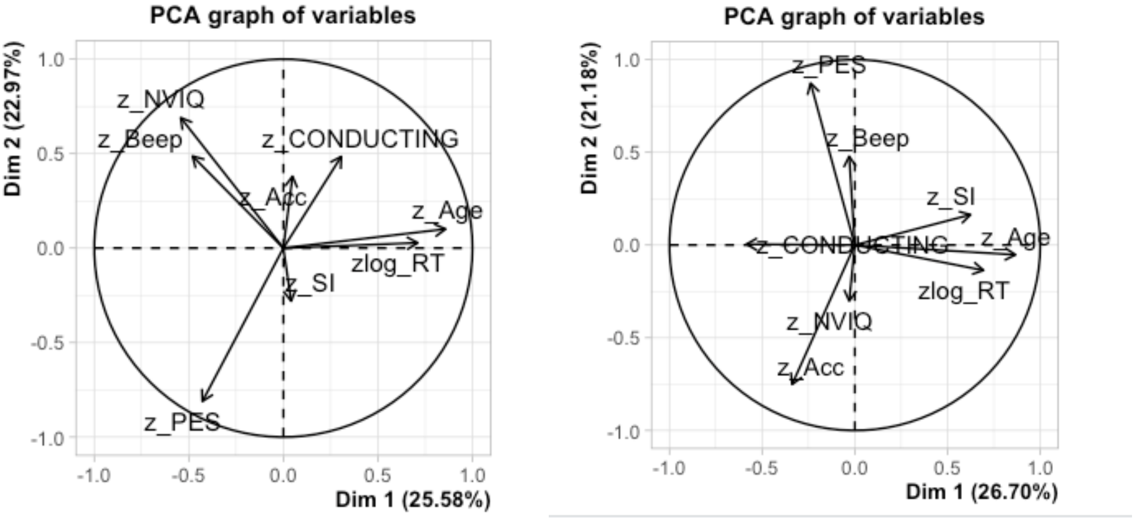
Principal component analysis: all participants, DT1 (left) and DT2 (right).



The same analysis was performed on participants whose performance was in the upper half of both accuracy distributions (Figure 25). Especially in DT2, there appears to be more consistency in the subset of good multitaskers than across the whole sample, suggesting that they may present some shared characteristics beyond their superior performance in both task components.

Figure 25

Principal component analysis: Best multitaskers in DT1 and DT2.



The analysis was carried out with the addition of the Bilingualism and Musicianship variables (Figure 26), and then again with Interpreting and Conducting removed from the analysis and the Group variable only added as a qualitative supplementary variable to visualise the differences.

Figure 26

Principal component analysis: Best multitaskers in DT1 and DT2, with musicianship and bilingualism.

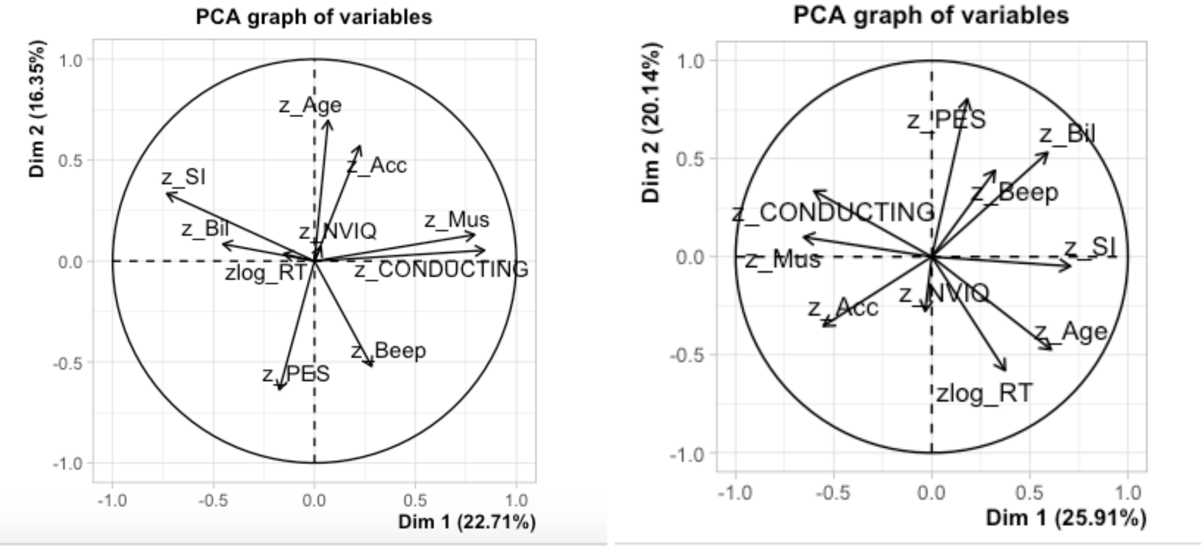
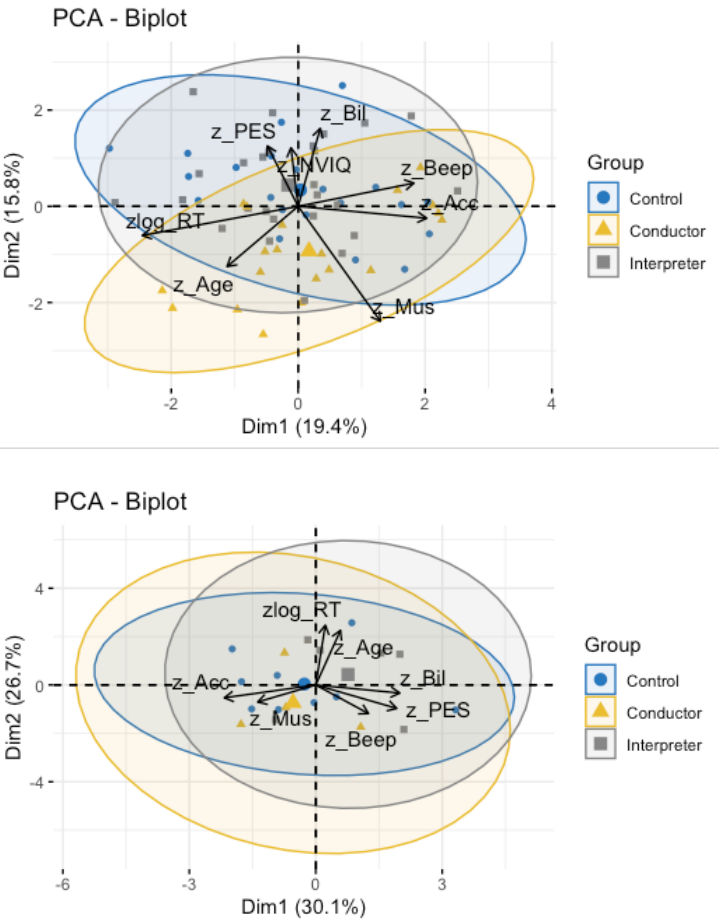


Figure 27

DT2 with ellipses by group: All participants (above) and good multitaskers (below).



7.5 Real multitaskers

7.5.1 Performance above chance in continuous multiple tasks.

Among the participants whose scores were included in the analysis in the respective dual tasks, 2 had scores in the 2-back task below or at 50% in the 2-back in DT1 (one control, one conductor), and one at 50% in DT2 (control; that participant had not been able to perform the 2-back task at all during DT1). All other participants performed above chance in the 2-back component. Regarding the beep task, which is a continuous (double) serial generation task, assessing performance above chance is not as clear-cut, but as a conservative estimate, we used the lowest score in the baseline task (0.67) as a cut-off to assess above chance performance in the dual task. 2 interpreters were below that threshold in DT1.

However, assessing only the values included in the clean dataset would lead to a foregone conclusion on this specific question. Therefore, the same verification was also carried out on the raw data, which included the observations excluded from the analysis (2 non-multitaskers and 3 outliers for the beep count = 5 additional data points in D1, and one non-multitasker = 1 data point in DT2). Of all the 67 participants in the sample, 7, or 10.44%, did not multitask in DT1: 4 controls (19,0%), 4 interpreters (15.4%), 1 conductor (5%), and 2 in DT2 (3.0% of the sample, namely, 1 control and 1 interpreter, or 4.8% and 3.8% of the groups respectively). According to that evaluation, the vast majority of the participants (89.6%) was therefore able to carry out two tasks concurrently, without a total breakdown in performance.

Table 20

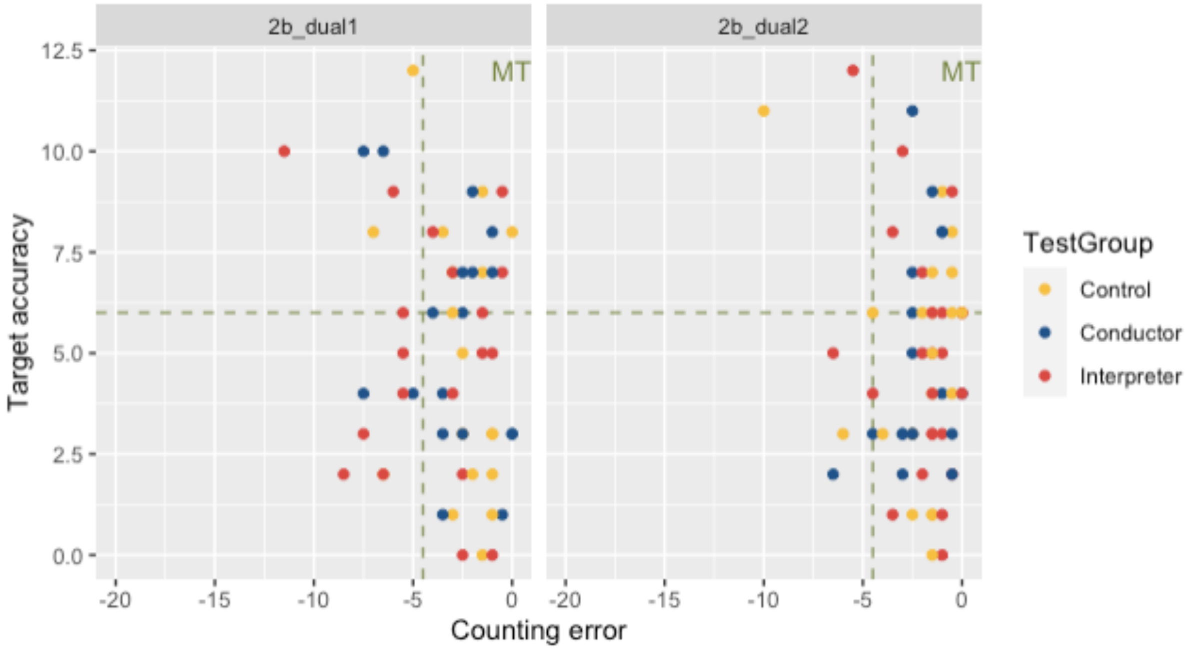
Initial beep count accuracy and 2-back accuracy distribution across the sample.

	Min.	*1st Qu.*	*Median*	*Mean*	*3rd Qu.*	*Max.*	*NA*
Beep acc.							
Baseline	66.7	100	100	98.5	100	100	
DT1	54.0	79.2	89.8	86.4	94.5	100	7
DT2	60.0	89.6	93.9	91.2	95.9	100	1
Beeps + key	59.1	100	100	97.3	100	100	
	Min.	*1st Qu.*	*Median*	*Mean*	*3rd Qu.*	*Max.*	*NA*
2-back acc.							
Bas.	83.3	93.7	96.8	95.9	97.9	100	3
DT1	41.7	68.8	79.2	76.3	85.4	95.8	7
DT2	50.0	73.4	80.2	79.5	85.4	100	1

Table 20 depicts the summary values for both accuracy scores. We decided to delineate (Figure 28) focused multitasking performance by plotting the participants' performance in the beep count and target accuracy in the 2-back task. Participants who recognised at least half of the target items can be considered to not have resorted to probabilistic strategies (considering that 75% of the items are non-target in the 2-back task). By the same token, the number of beeps played in a given task block ranged from 20 to 29, so we established a cut-off at 4.5 in total counting error. This did not modify the criteria for real multitasking in the beep count task, in that it was equivalent to the lowest performance in the baseline. Participants who identified at least half of the 2-back targets and performed above the lowest baseline score in the beep count were 19 (6 controls, 7 conductors, 6 interpreters) in DT1 and 25 (10 controls, 7 conductors, 8 interpreters) in DT2.

Figure 28

Real multitaskers: Performance in the beep count and 2-back target items above chance.



7.5.2 “Supertaskers”

Watson and Strayer (2010, 2012; Strayer & Watson, 2014) define “supertasking” as the ability to perform in a continuous multiple task without apparent cost in comparison to performing each task separately. The criteria they establish for their studies are the following:

- performance in the top quartile of the baseline, to avoid false reduction of multitasking cost through mediocre performance in the baseline. In the present study, the 3rd quartile is 97.9 in the baseline 2-back, and 100 (a perfect score) in the beep count task;

- a score in the dual task removed less than one baseline standard deviation from the score in the baseline, in this case less than 4.9% (baseline SD) in multitasking cost in the 2-back task, and less than 04.96% (baseline SD) in the beep counting task.

No participants fit this description in DT1: Taking Watson and Strayer’s criteria, 1 participant showed no multitasking cost in the 2-back task (1 conductor), and 13 participants showed no multitasking cost in the beep count (5 controls, 5 conductors, 3 interpreters), but none showed no multitasking cost in both tasks. However, while Watson and Strayer’s condition that the baseline score be high (to make sure that the multitasking cost is computed on the basis of a participant’s best endeavour to perform in the baseline) is justified, it makes sense to assess whether there were good multitasking performances at all in the sample, regardless of their performance in the baseline task, considering the continuous and concurrent constraints of the dual task set, and the fact that the baseline task was administered after the first DT. In this case, in DT1 5 controls, 6 conductors, 4 interpreters performed within the desired score range in the beep count, and 1 control and 1 conductor did so in the 2-back task; however, here again, none performed in the desired score range in both tasks.

Regarding DT2, 11 participants fit Watson and Strayer's criteria in the beep count task: 4 controls, 3 conductors and 3 interpreters. 1 interpreter fits the criteria for both tasks to be called a "supertasker" in the original sense. Since the baseline task was carried out after the first dual task, we also considered all performers in the desired score range regardless of their baseline score to find out the best multitaskers. This leads to an increase in the number of supertasker candidates for each task in the beep count task (20 participants: 6 controls, 6 conductors and 8 interpreters), but with no changes for the 2-back task and no difference in the actual number of supertaskers.

In order to investigate the best performers in the sample, we also filtered out the participants who scored in the top quartile for both tasks in the dual tasks. In DT1, this was the case for 4 participants: 1 control, 2 conductors, 1 interpreter. In DT2, 7 participants performed in the top quartile for both tasks: 4 controls, 2 conductors and 1 interpreter.

Table 21 below depicts participants with > 89% accuracy in both tasks of all dual task sets of the original testing routine (the cut-off was decided as a function of performance distribution in the various tasks). This yielded one noticeable outcome: The larger number of real multitaskers in the 2nd iteration of the dual 2-back (as well as two "lost" good multitaskers between DT1 and DT2).

Table 21

Best multitaskers in original testing routine, by subject number.

Gp. Task Identifier		2-back + beeps DT1	2-back + beeps DT2	Text + beeps	Motor tracking + beeps	Motor tracking + beeps/key
Control	107			X		
	124			X		
	214	X	X			X
	400		X			
	849		X			
	867		X			
Conductor	132				X	
	201	X				
	216			X	X	
	318		X	X	X	X
	607	X	X			
	609		X	X		
	898		X			
Interpreter	145			X		
	156		X			
	267		X			
	478				X	
	750				X	
	783	X				

8 Discussion

The key findings from this study indicate that while no significant difference was found between the three groups in terms of accuracy in the dual-task components, the groups showed distinct patterns indicative of group-related strategies, control habits and short-term training effects. In a first step, the present discussion focuses on the results for the various sets of analyses, starting with the hypotheses regarding multitasking ability in general to zoom in on the group differences and control processes during multitasking. In a second step, the broader theoretical implications of these findings are discussed. Last, methodological limitations as well as suggestions for further investigation are highlighted.

8.1 Tested hypotheses

8.1.1 Concurrent multitasking

The first research question investigated whether behavioural indications of concurrent multitasking could be found. In the multitasking paradigm at hand, verbal WM was expected to be taxed by both task components. On the one hand, a strategy of verbalisation – specifically, subvocal rehearsal – appears to be often acquired with training in the *n*-back task (Chooi & Logie, 2020) and commonly adopted for the letter component in a dual 2-back task (Jaeggi et al., 2007), although it should be noted that in that study the stimuli are auditory. On the other hand, the beep count required rehearsal in order to maintain two parallel counts active and update them continuously. Monitoring and updating of the WM content, and probably specifically verbal WM content, was therefore required for both tasks. In the best of cases, resetting WM content for the 2-back would mechanically lead to a participant needing to guess the response for at least two trials (the current and the next one), while resetting WM content for the beep count would lead to participants resorting to guess the final estimate for each beep type, risking major accuracy loss. Therefore, the only strategic instruction provided was to keep counting the beeps. This was also relevant for the use of the beep count as a goal maintenance measure in a dual-task setting (e.g., Bier et al., 2017). Two hypotheses were tested: Hypothesis 1a predicted that performance would be above chance in the continuous multitasking paradigm at hand, and hypothesis 1b predicted that a cost in accuracy and response time would be observed compared to the respective single tasks.

8.1.1.1 Continuous multitasking is possible

In this sample, in the first dual task, 60 participants out of 67 (89.6%) performed above chance in both tasks (i.e., above 0.5 in the 2-back or above the minimum baseline score in the beep count), consistent with hypothesis 1a regarding the possibility of continuous multitasking. In their study using the dual 2-back "gatekeeper" exercise, Heathcote et al. (2015) considered that participants performing at an accuracy rate below 55% in the visual or auditory 2-back did not engage in the task. They found that 66 out of 311 participants (21.2%) did not multitask. Using the same metric to determine multitasking performance in the present study, two participants with 52% and 54% 2-back accuracy are added to the number of non-multitaskers, bringing their total to 16.4% of participants. With all the caveats that apply in the context of a comparatively smaller sample than in Heathcote et al., a similar or higher number of people were able to perform the present continuous multitasking task in all the groups (with 19% below 55% 2-back accuracy among control and interpreters and 10% among conductors). The tasks used in the two studies cannot be directly compared: The Gatekeeper task involves the combined processing of one 2-back visual and one 2-back auditory cue for each response.[58] In the present paradigm, there is at least one beep to process between two 2-back responses, forcing participants to update the dual beep count during 2-back updating. It can be assumed that the verbal WM load is similar; but in addition, in the present paradigm, the task components serve distinct goals, which need to be maintained concurrently. Remarkably, in the second iteration of the dual task at the end of the testing routine, only 2 participants (3%) could not perform above chance or above 55% accuracy. These findings suggest that concurrent multitasking is indeed possible, although behavioural measures do not provide insight into the concurrent or successive nature of the underlying processes. In addition, the ability to concurrently multitask appears to be highly amenable to even limited amounts of training.

8.1.1.2 Multitasking cost

While performance was at ceiling in the single tasks across the sample, *t*-test and (generalised) linear mixed-effects model results indicated that there was a clear performance decrement in the dual condition for all the task components: Lower beep count accuracy, and lower accuracy and higher RT in the 2-back. The effect of dual condition, or of the dual iterations when all iterations were considered, was consistent for all measures and models.

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[58] The Gatekeeper includes 3 possible auditory clues, 3 possible visual clues, and proactive lure patterns.

These findings are in line with hypothesis 1b regarding the presence of a multitasking cost and consistent with the literature, insofar as dual tasking, concurrent or not, is used as a paradigm to explore limitations on performance (Jaeggi et al., 2003; Meyer & Kieras, 1997a). In concurrent multitasking, the expectation is that a risk of performance breakdown, that is, the impossibility to carry out one of the tasks, has to be taken into consideration. In the task presumed to be free of goal-related conflict, beep count with choice key press as a function of the beep type, there was little to no multitasking cost at all in accuracy, which is consistent with the idea that multitasking cost depends on the degree of competition between the tasks at hand (e.g., McLeod, 1977; Navon & Gopher, 1979; Wickens, 1991). However, RTs were higher than expected. It should be borne in mind that this phenomenon could simply be attributed to the nature of the stimuli (auditory, vs. visual for the 2-back task), and further explored through targeted comparisons between baseline and covert count tasks across stimuli types. However, though there was only one set of stimuli, with the same properties relevant for both beep counting and key presses, and the key-press task was a simple choice reaction-time task, in effect the same as a 0-back task, the combined task was a complex task and appeared to place some demand on the key press response. Multitasking cost could not be computed in the absence of a dedicated baseline (in this case, a beep discrimination task with choice-reaction key presses and without a covert count). The key-press task was expected to have an adjuvant effect on the beep count; However, the presence of a possible outcome conflict (Navon & Miller, 1987; Pashler, 1994) in the context of dual treatment of the same information (the relative tone pitch), supports the idea of shared representations generating conflict and introducing a need for control (e.g., Feng et al., 2014; Musslick et al., 2016; Musslick & Cohen, 2019). Indeed, an adjuvant effect of processing the tone pitch for the key press task was found only partially regarding the ability to count the respective tones: Overall accuracy scores were not significantly different from the baseline beep count task, though group differences emerged. While conductors and interpreters did globally appear to benefit from accompanying the count with a key press, controls performed slightly worse. It appears that in that group, the effect of combining two responses, although structurally compatible (a motor response and covert rehearsal) induced a higher cost than the association of beep type with a given response could have contributed to reinforcing the maintenance of the beep count task goal. In both expert groups, however, beep count accuracy was significantly higher than in controls, and the baseline task, when the count was accompanied by the key press task. In interpreters, who had slightly lower scores in the baseline task compared to the other groups, this improvement in performance was seen even when the task was administered prior to the baseline task – conductors performed slightly better when the baseline had been administered first. While the difference between the groups is unexpected, this points to a different management of component task boundaries in expert groups and suggests that their complex task experience may play a role in helping them establish hierarchical, integrated representations of task goals when the constraints inherent to the task allow it (Freedberg et al., 2014).

Despite the overall multitasking cost in the dual tasks, however, there was progress not only in the single condition of the 2-back task between the baseline task and rep5 (the last single-task 2-back iteration), but also in the dual condition, where the margin for progress was larger and 2-back accuracy improved significantly. Therefore, we notice that there was a performance gain between the first occurrence of the dual task at the beginning of the testing session and the second one at the end of the session, following repeated training in one of the task components (2-back) and exposure to the second one (beep count) in the single condition. Across the sample, multitasking cost measured in terms of accuracy against the baseline tasks decreased on average in DT2 (MT cost in the 2-back: 16.3%, beep count: 12.2%) in comparison to DT1 (2-back: 19.5%, beep count: 7.3%); even comparing DT2 to rep5, where performance had improved in comparison to the baseline, still showed lower multitasking cost in the 2-back task than between the baseline and DT1. Improvements in dual tasks after training were observed in other studies, (e.g., Bender et al., 2017). The rate of improvement in the present study (3.2% and 4.9% for the two outcomes) was lower than the one observed in Bender et al. (5%), but these authors used a visual-motor tasks did not place a continuous load on WM.

In DT2, individual perfect accuracy scores were observed in the 2-back, which was not the case in DT1. Contrary to DT1, there were no scores below 50% in DT2, and a mean improvement ranging between 2.2% and 5.3% depending on the groups was measured. However, it is important to note that median group scores improved only by 1% overall, suggesting that while participants were in general better at preventing performance breakdown, no substantial group progress was made across the sample, but improvements were registered for a few individual participants in all groups. This could be due to various reasons: First, some participants had more margin for improvement due to comparatively low performance in one of the two components of the first dual task. Secondly, individual differences in cognitive flexibility are not entirely explained by group differences (see Jaeggi et al., 2014). Thirdly, differences in control strategies likely play a role in this pattern, and will be explored further when the corresponding research question (RQ3) is discussed. In the beep count task, there were occurrences of perfect scores in both dual tasks for all groups, except for interpreters in DT1, whose scores were the most widely distributed (i.e., more scores in the middle and lower range) for that task component. In spite of the limited margin for progress, all groups improved and saw their score distribution reduced in DT2.

8.1.1.3 "Supertaskers" hypothesis

A number of individuals performed particularly well in both task components in the dual condition. However, contrary to hypothesis 1c, this study did not unequivocally replicate Strayer and Watson's findings regarding the amount of "supertaskers" in the population, though one participant from the interpreter group did meet the criteria in DT2. It should be pointed out, however, that the present sample was too small for the results to invalidate that hypothesis. Statistically, according to the various studies by Strayer, Watson and colleagues (Watson & Strayer, 2010; Strayer & Watson, 2012; Medeiros-Ward et al., 2015), there should have been about two supertaskers (i.e., 2.4-4%) in the present study and possibly detectable in both dual tasks, but the sample here was considerably smaller than the samples in these authors' studies, and the number of expected multitaskers was therefore well within the margin of error. In addition, the task type was different, with constraints placed on WM by both task components. Furthermore, it is conceivable that supertasking might not generalise to all kinds of multiple tasks, but only to those that rest on subcomponents that have been at least partially rehearsed (e.g., in the case of driving). This suggestion is supported by the fact that similar supertasking is not observed in studies using other tasks, like the Gatekeeper task mentioned above (Heathcote et al., 2015).

It should be highlighted that multitasking cost alone cannot be used to identify proficient multitaskers: Multitasking cost formulas, such as the one used by Baddeley (1997) and Miyake and Friedman (2000) are very useful to determine the added performance decrement in both task components of a dual task, but logically depend on the baseline performance. By that measure, poor single-taskers can show little multitasking costs and appear to be excellent multitaskers (Watson & Strayer, 2010). The present sample was no exception, with a handful of participants performing less well in the baseline beep count task than in the dual-task beep count task component. The inherently continuous character of the dual task, which is very unforgiving once the participant has lost track of the count, is a factor to consider. Two participants also performed better in the 2-back component during DT2 than in the baseline, after single-task training during the testing session. Therefore, similarly to Watson and

Strayer (2010), we used absolute in addition to relative within-subject measures of performance to determine highly proficient multitasking ability. These authors' criteria, (performance in the top quartile in the single task and dual task score within 1 SD of the baseline score), however, were too stringent to characterise performance in the task at hand (with 1 supertasker in DT2); raising the maximum difference in performance to 2 SD from the baseline score identified a few more highly proficient multitaskers, 3 (one from each group) in DT1 and 4 (2 controls, 1 conductor, 1 interpreter) in DT2. Relative to the sample, and regardless of baseline performance, there were 4 participants in the top quartile of the distribution for both tasks in DT1 (2 conductors, 1 control, 1 interpreter) and 7 in DT2 (4 controls, 2 conductors and 1 interpreter). These were able to perform the concurrent continuous task comparatively well, and in absolute terms, to obtain scores comprised within the distribution for the respective single tasks.

Beyond the best multitaskers in the sample, for the present purposes, we needed to identify good multitaskers and real multitaskers more generally. In the 2-back task, target items represented 25% of all items in each block. Target accuracy was consistently lower than new item accuracy, probably due to acquired bias based on the rarer frequency of targets (see, e.g., Wadhera et al., 2018). Therefore, we considered participants who identified at least half of the target items correctly in the dual 2-back tasks to have successfully remained on-task. For the beep count, we established a cut-off at a counting error of 2, (either 1+1, with an error of 1 per beep type, or 2-0), to define successful remaining on-task. 10 participants performed above both thresholds in DT1 (3 controls, 5 conductors, 2 interpreters) and 10 in DT2 (5 controls, 3 conductors, 2 interpreters). These were considered proficient multitaskers. In relative terms, performers in the top half of the score distribution in both task components were taken into account to analyse factors of successful multitasking. They were 13 in DT1 – 4 controls, 7 conductors, 2 interpreters – and 19 in DT2 – 9 controls, 6 interpreters, and 4 conductors.

An analysis of these combined good multitaskers, merging both groups described above (total in DT1: 5 controls, 7 conductors, 3 interpreters; total in DT2: 9 controls, 5 conductors, and 7 interpreters) and comparing both dual tasks reveals that, in line with Watson and Strayers' notion of individual multitasking proficiency, there was remarkable consistency overall in proficient multiple performance. All five controls in the good multitasker group in DT1 were again in the group in DT2, and two out of three interpreters; in conductors, three of five good multitaskers during DT2 had already been in the group in DT1. When participants were not represented in that good multitasker group in both tasks, they were usually still part of the "real" multitaskers who performed above chance and additionally correctly identified at least half of the 2-back targets during the other dual task.

These categories reveal that there were generally a greater number of good performers in the second dual task, including at the highest level. However, the respective representation of each group changes between both dual tasks, with more conductors than participants from other groups multitasking well in DT1 and more controls – and fewer conductors – in DT2. The discussion of RQ2, on the possible advantage of complex task experts in multitasking, will seek to shed light on that phenomenon.

8.1.2 Multitasking in complex tasks as a domain-general advantage

The second research question of the present dissertation examined whether interpreters and conductors performed more accurately and faster than controls in new continuous complex tasks. While the small differences in accuracy in the first DT were not significant, distinct RT patterns emerged.

8.1.2.1 Complex task expertise and multitasking cost

8.1.2.1.1 Lower multitasking cost in experts

Generally, a trade-off between the two task components was observed in the dual tasks. Conductors had the lowest combined multitasking cost (i.e., accuracy loss in both task components) in DT1 especially; but the group effect for conductors on dual 2-back accuracy became non-significant after model outliers were removed, indicating that the effect was driven by individual performances and suggesting that the accuracy models lacked power to detect smaller effects. Across single and dual task iterations, no significant difference in 2-back or beep count accuracy emerged between the three groups. The increase of 2-back RT in DT1 was smaller in conductors than in interpreters, and in both expert groups than in controls, while in DT2, with multitasking cost reduced for all groups, conductors had again the smallest increase, followed by controls, then interpreters; progress between both dual tasks was the largest in the control group. However, the smaller RT cost in conductors is also impacted by the fact that they were slower as a group in the baseline task. Group effects observed for both expert groups depend on the random structure of the RT model – in spite of acceptable power especially when all 2-back iterations are considered – suggesting that the effects may be false positives and driven by the assumption that a few individuals' pattern of performance in the dual against the single 2-back is representative of the whole group. Barr et al. (2013) advocate for adopting the maximal possible random structure when a random effect is assumed to be present in the underlying population (in the present case a random slope by condition) in order to avoid Type I errors. Therefore, even though all increases in RT between the single and dual tasks were significant, the group differences were not consistently so, pointing so far toward a rejection of hypothesis 2b regarding the differences in multitasking cost between experts and controls. This pattern of results points to the fact that there was individual variation, beyond the effect of professional experience, that the model was unable to take into account.

One noticeable phenomenon is the adaption effect apparent in DT2, where groups (and participants at an individual level) “catch up” on the exercise they performed less satisfactorily in the first time. Between DT1 and DT2, in spite of the absence of significant group differences, it appears that there were more individuals whose 2-back performance improved in the control group. In the beep count task, descriptive statistics indicate that interpreters had the highest multitasking cost in beep count accuracy in DT1, but the lowest in DT2; while all groups improved and had a lower cost in the second dual task, interpreters as a group improved the most. This catch-up effect could be due to higher automaticity of one of the tasks after training, but may also have other implications which will be detailed in the general discussion below.

8.1.2.1.2 Better performance in experts in the dual condition, especially before training

Hypothesis 2a predicted that performance in both tasks of a dual-task set, in their first occurrence, is higher in conductors and interpreters than in controls. In absolute numbers, there are more proficient multitaskers (performing above the median in both task components) among conductors than other groups in DT1: One-third of the group, against one-fifth of the control group, but also against less than one-tenth of interpreters. More conductors, therefore, appear to have been able to make use of complex task management skills across domains. This could be explained by similar processes underlying conducting and the task at hand (e.g., simultaneous visual and auditory processing) although the required treatment of the various stimuli for each task component differed from their domain of expertise and the stimuli were unrelated to each other. Still, there may have been an advantage for some of the musicians in pitch processing and WM for pitch against other groups (Varga, Marton, Jakab, & Láng, 2022); In addition, this advantage may also have transferred to other verbal WM tasks (Fennell, Bugos, Payne, & Schotter, 2021). Although fewer conductors had performance breakdowns during the first dual task than participants in the other groups, and descriptive statistics as well as model estimates indicate higher 2-back accuracy and lower RTs for interpreters and conductors in DT1, inferential statistics do not confirm group differences in terms of accuracy in either of the task components. Additionally, when all 2-back iterations are considered, the group effect for interpreters and conductors in DT1 RT is significant only in the absence of a random slope, indicating a possible type I error or an effect that is too weak to be confirmed in the sample at hand. However, when dual-task iterations are considered in isolation rather than compared to the baseline, the LMMs show significantly lower RTs in interpreters in DT1 (as well as lower RTs in conductors than in controls, but the difference is, again, non-significant). The advantage is lost in DT2, with interpreters apparently adapting to the task through increased caution; In addition, controls are the only group with a significant RT improvement between DT1 and DT2, and there are more controls among proficient multitaskers in DT2. Separate measures do not allow us to conclusively corroborate hypothesis 2a for DT1, and invalidate the hypothesis for DT2; however, in order to draw a more comprehensive picture, it is necessary to look at RT and its relationship to accuracy in the dual-task performance.

8.1.2.2 Complex task expertise and processing speed

It should be noted that processing speed as measured in the present experiment is heavily task-related. Cepeda, Blackwell, and Munakata (2013) note that measures of processing speed in more complex tasks tend to be more strongly confounded with executive control measures, and that it is therefore difficult to completely distinguish the effect of “pure” speed of processing from the actual task-inherent processes.

8.1.2.2.1 Processing speed is associated with better performance in the dual condition

According to hypothesis 1d, higher processing speed was expected to be associated with better performance in the dual tasks. In the single 2-back task, descriptive statistics suggested that the speed-accuracy trade-off did not manifest in the same way in both expert groups: while conductors were on average slower and more accurate, interpreters were on average faster but less accurate (with performances almost at ceiling, the difference in accuracy was very small). The RT range was also smaller in interpreters, indicating more disparity in conductors in that respect. Controls as a group showed an intermediary pattern between both experimental groups. An LMM of accuracy as a function of iteration, group and response time and taking individual variation into account indicated that the speed-accuracy trade-off was similar in all three groups in the single task. In the dual task, however, the relationship between 2-back RT and accuracy was reversed, with smaller response times correlated with higher accuracy compared to the baseline, lending support to hypothesis 1d and the idea that faster (e.g., Dux et al., 2009), and/or more automatic processing (Shiffrin & Schneider, 1977), is beneficial to multitasking performance. This effect was seen even more strongly in conductors and interpreters in the first DT, and again in interpreters in the second DT. When compared to interpreters, however, both other groups showed speed-accuracy trade-off in DT1 and DT2. Together, these results suggest that interpreters had the best speed/accuracy ratio in the dual tasks, with conductors also performing better than controls once RT is taken into account. With the DTs considered in isolation (without comparison to the baseline task), the picture was more precise. In DT1, controls were the only group with an apparent (n.s.) speed-accuracy trade-off, while both experimental groups had better accuracy with higher speed, and better accuracy overall once the RT effect is included in the model. The speed/accuracy ratio remains significantly better in interpreters than conductors, and in both experimental groups compared to the controls. In DT2, controls significantly gain in accuracy compared to DT1 and also become more accurate when performing faster. The same effect (albeit n.s.) is found in interpreters; conversely, conductors are significantly less accurate than in DT1, and they do not show as much gain in accuracy when they respond faster. Overall, in DT2, both experimental groups (the difference between conductors and interpreters is not significant) perform less accurately than controls. All groups perform with higher accuracy when faster, but compared to controls, both experimental groups show a relative speed-accuracy trade-off; Conductors more so than interpreters, but the difference between conductors and interpreters is again not significant.

Thus, the differences between the model with and without RT show that while 2-back accuracy alone did not differ significantly between expert groups and controls, both expert groups were better at performing at once faster and more accurately than controls in the first 2-back task, in line with hypothesis 2a. In addition, the differences between the model including RT and fitted with and without the single tasks show that in comparison to the single tasks, interpreters had a better speed/accuracy ratio than the other groups; and the speed/accuracy ratio in both experimental groups was better than in controls. This indicates a stronger reversal in the accuracy pattern associated with speed in the interpreter and conductor groups in both dual tasks, although in absolute terms controls gained more in terms of accuracy and speed-to-accuracy ratio between DT1 and DT2 and performed better in the second dual task. Taken together, these results suggest that complex task experts may indeed more easily combine two novel tasks efficiently, but that controls are more flexible in adjusting to the dual-task paradigm at hand and show greater performance improvements. Thus, it would appear that domain-general procedural learning has taken place to some extent in experts, but that they face more constraints on short-term adaptation – or that there is a limited margin for progress and a ceiling in our ability to continuously multitask, a point which we can endeavour to clarify.

In dual-tasking settings, some studies suggest that increased processing speed is associated with better dual performance, a result that they attribute to the possibility of processing information in more rapid succession in a processing bottleneck (e.g., Dux et al., 2006, 2009). In the case of theories proposing shared representations as the origin for the need for control, higher processing speed after single-task training would be attributed to greater automatisation (Shiffrin & Schneider, 1977) associated with pathway strengthening (Cohen et al., 1990), reduced persistence of representations in shared networks (Musslick & Cohen, 2019) and the forming of dedicated representations (Musslick et al., 2016). According to all these theories, higher processing speed should be observed in DT2 compared to DT1 in the present study, and higher speed should be generally associated with facilitated dual task execution. However, diverging predictions can also be made on the basis of these theories regarding the association between processing speed and accuracy. If processing speed facilitates processing in a control bottleneck, lower processing speed (higher RTs) would be associated with worse performance in a time-constrained multitasking setting. By contrast, according to a theory positing that control is induced by shared representations, control might result in less speed, but not necessarily less accuracy, especially in the untrained dual task (DT1).

The pattern of performance associated with processing speed is uneven across the groups as well as the iterations of the dual task and depends on the task component. The lack of a consistent effect throughout is probably also due to the continuous nature of the dual task, which does not allow freeing WM at any stage. Processing speed was measured only in the 2-back component, however, its association with accuracy in the 2-back as well as in the beep-count task during multitasking was considered. RT was not consistently lower in DT2 than DT1, while accuracy in the task components tended to improve. Controls improved the most, but this brought them to the same level as the other groups. As we have seen, in the 2-back controls were the only group not to show higher accuracy with speed in DT1; their performance accuracy also tended to be lower than in the other two groups, supporting the suggestion of a beneficial effect of speed on performance during the dual task, which is in line with hypothesis 1d. In DT2, speed was positively correlated with accuracy in all groups, but in conductors the effect was smaller rather than increased in comparison to DT1, suggesting that some amount of conflict remained unsolved beyond the effects of acceleration. There was no association at all between 2-back RT and beep count accuracy in conductors and controls, but higher RTs in interpreters in DT2 were significantly correlated with higher accuracy in the beep count. This phenomenon likely illustrates a trade-off between the task components, but does not suggest a central bottleneck as the most likely origin of conflict.

8.1.2.2.2 Processing speed in bilinguals and interpreters

We hypothesised that interpreters, as expert bilinguals, would show a processing speed advantage (hypothesis 2c). The data seem to support this hypothesis, even though the models predicted small effects. Interpreters were significantly faster than the other groups in the beeps and key press task and in the single 2-back task, especially in the last 2-back reps. In the single 2-back there was in general a trade-off between speed and accuracy across all groups, with interpreters favouring speed over accuracy especially at the beginning of the testing routine. In the sample as a whole, the highest increase in accuracy was achieved in the third task repetition, rep3 (i.e., the fourth administration out of six of the single task), suggesting that the best strategic balance was achieved at that point in training. Accuracy differences between groups (both expert groups performed slightly more accurately than controls) were not significant, and group means were influenced by the presence of isolated scores on the lower side of the respective distributions. Inspection of the distributions suggests that the global improvement in accuracy during rep3 was driven by controls, for whom this iteration is the only one where the group's mean accuracy exceeds the expert groups'. Interpreters as a group appear to have progressed in terms of accuracy during rep1, and significantly reduced their speed/accuracy trade-off by rep2, with significant RT improvements starting with that iteration for that group. Conductors show the highest accuracy overall, with performance almost at ceiling throughout the single reps, and reach their best accuracy/RT ratio at rep5, but their RT significantly improves as of rep3. The processing speed advantage in interpreters was mostly significant compared to conductors, but less so compared to controls. In the dual tasks, a processing speed advantage over controls was seen only in DT1, with controls catching up in DT2. The evolution between both dual tasks is not entirely consistent with findings by Strobach et al. (2015) but these authors used a dual-tasking rather than a continuous multitasking paradigm, which limits the comparability of the outcomes.

Overall, interpreters tend to show higher processing speed than other groups, in line with hypothesis 2c and with an abundance of findings on bilinguals (Marton et al., 2017) or interpreters specifically (e.g., Santilli et al., 2019). However, the link between bilingualism and RT was not homogenous across the board. A salient feature is that the effect of bilingualism is different between the groups. In interpreters, but also in conductors,[59] bilingualism was associated with lower response times, whereas it was associated with slower performance in controls, which seems consistent with the idea that other domains of expertise also influenced performance (for instance interpreting vs. translating), but the results are sensitive to considerable individual differences. These results underline the complexity and variety of the bilingual experience and its cognitive correlates and challenges of accounting for them (e.g., Gullifer et al., 2018; Marton & Gazman, 2019; Titone et al., 2017; Valian, 2015b).

8.1.2.3 Effect of complex task expertise on other variables affecting performance

In order to introduce nuance beyond possible group effects and account for other subject-level variables likely to affect performance in a multitasking setting, these variables were introduced in the models as well as their interaction with the group variable. Literature on bilingualism and on expertise in other domains, like musicianship, has identified possible associations with cognitive abilities in older adults; expertise in a cognitively demanding domain may also influence the potential relationship between intelligence and multitasking, by making that relationship more or less relevant.

8.1.2.3.1 Experts and age

Age does not seem to have robust effects in the present study. The effect of age on 2-back or beep count accuracy is not significant, and age does not contribute to explaining variance in performance across the sample or in any of the groups – a small detrimental effect on beep count accuracy across the board in DT1 (but not DT2) disappeared once more relevant variables such as the group variable was introduced. While this does not follow the same direction as findings regarding the association of age, including in interpreters, with performance in WM tasks (Timarová et al., 2014, Signorelli et al., 2012), it is necessary to

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[59] Bilingualism was also associated with higher 2-back accuracy in conductors in DT1; however, adding Bilingualism to the 2-back accuracy model deteriorated the model fit, therefore this cannot be regarded as conclusive.

point out that the present exercises did not tax WM storage capacity, but the participants' ability to update concurrent sets of WM representations – as well as goal representations – and maintain them active. Age shows no association with RT performance in the sample as a whole but shows a group-dependent effect. It is associated positively with speed in controls in DT2 and in the beep and key press task, whereas it is associated with higher RTs in the last single 2-back iterations in interpreters and in DT2 in conductors, findings which do not support a mitigating effect of expertise on the effect of age; however, these effects also need to be interpreted in light of the overall group effect on RT, and therefore suggest that there was more acceleration in younger interpreters and conductors. These results may indicate a strategic choice of accuracy over RT in older participants, but in the absence of a clear accuracy advantage, they are consistent with accounts of the effect of age in *n*-back performance at least regarding RT (Gajewski et al., 2018) and studies suggesting that slowing with age can be seen in interpreters and that if interpreting experience entails cognitive benefits, these might not necessarily generalise beyond that specific activity (García, 2014; Santilli et al., 2019).

8.1.2.3.2 Experts and non-verbal IQ

NVIQ was investigated as an additional variable, notably to ascertain whether it showed an effect on multitasking that differs from that of the specific expertise studied. Beep count accuracy does not vary with NVIQ, except for interpreters (unfavourably) in the beep and key press task. Regarding 2-back accuracy, there is no effect of NVIQ in the various iterations. The only noticeable effect is found in an analysis by condition, where NVIQ is linked with higher 2-back scores in the single condition and lower scores in the dual condition (with conversely less performance decrement in the dual task with NVIQ in conductors). There is no effect of NVIQ in RT across the sample on the various tasks, except for an RT advantage in the beep and key press task. When groups are considered, it appears that the effect of NVIQ on performance indeed differs between controls and the other groups, with NVIQ associated with higher RTs in the baseline and significant acceleration in DT1 and DT2 in that group, while controls and interpreters are slower with higher NVIQ in both dual tasks, Conductors with higher NVIQ are also slower in the beep and key press task, but they are faster in the baseline 2-back.

These results do not suggest a robust link between NVIQ and dual task performance in general (as suggested e.g., by Ben-Shakhar & Sheffer, 2001), although dual-task performance in controls seems to benefit from higher NVIQ in terms of RT only. Regarding group differences, it should be noted that the results are probably driven by individual patterns of performance in participants removed from the respective group means in NVIQ, and therefore do not allow to make conclusive claims. However, the association between NVIQ and slowing in experts in the dual tasks (fostering or at least not impairing accuracy), raises questions, regarding for instance the level of caution and the possible link between measures of fluid intelligence and proactive control strategies (see Burgess & Braver, 2010); Given the relationship between RT and cognitive control in complex tasks, including NVIQ measures in models of post-error slowing may be relevant.

8.1.3 Complex task expertise and cognitive control during multitasking

RQ3 investigated indications of proactive and reactive control during multitasking in the three groups and potential differences associated with the domain of expertise. Interpreters were expected to show more PES, which is regarded as a measure of conflict monitoring, suggesting that they rely more on reactive control (hypothesis 3a). Conductors were expected to rely more on proactive control. This in turn would manifest in better performance in maintaining the beep count throughout the tasks (hypothesis 3b).

8.1.3.1 Interpreters and conflict monitoring

First of all, the nature of the 2-back, with ceiling performance in the single task, makes PES a variable that can be measured on a limited number of observations. In order to increase the robustness of that measure, it would be recommendable to increase the number of blocks by iteration, wherever the testing context allows that. Due to the little number of observations by single task rep, effects could only be identified on collapsed data by condition.

The results of the analysis indicate that the RT pattern between items before and after wrong responses differed significantly depending on the type of error. Omissions appear to be treated differently from erroneous key presses, both in single and dual tasks – but more so in the dual tasks. It is striking that RTs before omissions were significantly higher than RTs before errors. This appears to be revealing of participants' attention drifting away from the 2-back task component, or possibly reduced reactivity (e.g., Strayer et al., 2013) or increased caution (e.g., Tillman, Strayer, Eidels, & Heathcote, 2017) with increased cognitive load. In any case, there was significant acceleration overall after missing items, especially in DT2. A decrease in post-error slowing could point to greater automation, that is, less control, but systematic acceleration did not appear logical, except if the error was a skipped response due to interference from the parallel task (a covert response), in which case reactive control would be associated with increased vigilance, that is, reallocation of attention to the task, and with a quick answer in the next item. In order to verify this assumption, the two error types – errors and omissions – were analysed separately. The difference between post-omission and post-error RT differences and their interactions in the models, and increased RTs before omissions, make the case for distinguishing between those types of errors in complex tasks and focusing on PES strictly speaking – that is, slowing after providing a wrong response – as a measure of conflict monitoring. By contrast, in the case of omissions, renewed vigilance – potentially triggered by the stimulus change – is likely to result in comparatively short RTs in the subsequent item. It was therefore assumed that post-omission acceleration might be more revealing of conflict monitoring than post-omission slowing. A follow-up analysis of the present data suggests that participants who slowed down after errors were slightly more numerous to speed up than to slow down after an omission. However, the relationship between PES and performance in the tasks sometimes also applies to general slowing (i.e., post-error and post-omission), but does not seem to apply to post-omission acceleration, although the cell size does not allow to determine this with sufficient certainty. Thus, it would appear that acceleration after skipped responses may indeed be related to a refocusing of attention after it has drifted away from the task at hand, but it is unclear whether it could constitute a relevant indicator of conflict monitoring in the present case. Acceleration or slowing after an omission might primarily depend on whether the participants were slow in their responses before the omission. The cell size here again does not allow to draw conclusions, as there are far fewer omissions than errors. Group differences may also exist in that regard. Data exploration reveals that there were more participants who accelerated after omissions among the better half of beep accuracy scores than participants who did not (but less than participants with post-error slowing), suggesting that these participants prioritised the beep count task over the 2-back. The decoupling between post-error slowing and post-omission acceleration could also mean that the latter indicates in some cases that the 2-back task has stopped being performed altogether during the preceding item: Slowing due to processing of concurrent task in WM may lead to delays beyond task requirements and therefore omissions. Therefore, conflict monitoring associated with post-error slowing but not with post-error acceleration in a multitasking context, might provide an indication that control is allocated in a traffic-control (i.e., flexibly distributed) rather than a switchman-like (i.e., all-or-nothing) manner.

In view of the above considerations, slowing after errors was the measure considered to test hypothesis 3a. In the single 2-back condition, the data indicates that interpreters were the only group to show significant PES overall, suggesting a tendency to rely on reactive control, in line with the hypothesis. This seems to be the case throughout the single reps, except for the last. There the trend is reversed, tending to post-error acceleration, which may point to growing automatisation of the task (Schneider & Chein, 2003). It is also noticeable that the evolution of post-error against pre-error RT in interpreters diverges from that of conductors. As a group, interpreters show increasing PES with each new single task rep until rep2 (the third iteration of the single 2-back task overall) and then roughly maintain their level of PES until rep4, after which their PES decreases into a small, but positive, average in rep5 and again in DT2. Conductors follow a similar pattern until rep2, but their amount of PES subsequently decreases; they show clear post-error acceleration in rep4 and in DT2 (but higher PES than interpreters in rep5). This points to the development of different control strategies with training in the two groups.

In the dual condition, on the other hand, controls show more PES than both the conductor and interpreter group, among whom PES is not significant. Although no specific hypothesis was made with regard to controls, this is inconsistent with the hypothesis of higher conflict monitoring in interpreters, and could point to a different control pattern or less control in that condition in interpreters. The effect is in all probability driven by DT1, where PES in some controls was especially high. However, PES in that task was not associated with better accuracy in controls, to the contrary of interpreters (the effect was non-significant in conductors). Interpreters again tended to perform better with higher PES in DT2, but the effect is non-significant. In that task, PES disappears in controls (the difference is smaller in the other two groups, but that is presumably due to the fact that they had less PES in DT1). To sum up, while it seems that interpreters tend to resort to conflict monitoring as a control strategy, the results do not suggest that interpreters as a group rely on more reactive control than other groups in order to complete the dual tasks. However, they seem to have adapted between both dual tasks by increasing their level of caution, since faster processing and overreliance on post-error adjustments tended to be detrimental to the simultaneous processing of both components in the first dual task.

In contrast, conductors appear to show a distinctive pattern, with consistently low or negative PES values in the 2-back task throughout the testing session, and lower PES is not associated with lower accuracy in their case. This finding seems consistent with our hypotheses as well as observations by Jentzsch et al. (2014). This pattern would be compatible with a tendency to exert control more parsimoniously in general throughout the task, but they could also point toward a tendency in the group to rely on other, proactive control processes. It should be highlighted that the groups' level of observed PES may be related to their baseline RT. In fact, interpreters, who show significant PES in the single tasks, are comparatively faster than the other groups, while conductors, who are consistently slower, show less variation in pre- and post-error RT. This supports the idea that conductors proactively adopt a more cautious attitude in general, focusing on increasing their chances of accuracy across the board, while interpreters favour the best speed-accuracy ratio by relying on reactive control. Findings by Damaso, Williams and Heathcote (2020) regarding difference in slowing or speeding patterns after errors are consistent with this suggestion. However, the idea that conflict monitoring may be more visible in the case of interpreters because they perform at a speed that leaves no margin to process extraneous events, while other groups may still monitor conflict without it visibly modifying their RT, cannot be discarded entirely (see Danielmeier & Ullsperger, 2011), even though follow-up analyses of the present dataset revealed no consistent relationship between RT and PES.

8.1.3.2 Conductors and goal maintenance

It was expected that conductors would rely on proactive control and experience higher goal maintenance (hypothesis 3b), a measure manifest in accuracy in the beep count task. The goal maintenance measure was therefore confounded with accuracy in the beep count task, and ascertaining the association between that construct and performance in the dual task beyond successful multitasking was a delicate exercise. Beep accuracy models did not lend conclusive support to hypothesis 3b: Conductors' performance in the single beep count task does not differ from the other groups', and their edge over other groups in DT1 is non-significant. However, in absolute terms, beep count accuracy scores were very good in many conductors and controls and still suggest a high level of goal maintenance. If processing speed in complex tasks is also indicative of control processes (Cepeda et al., 2013), higher RTs in conductors may reveal a higher tendency to proactively rely on control rather than only reactively in the presence of conflict signals, but this assumption requires further investigation. Indeed, non-significant PES in conductors may not necessarily mean that there was no conflict monitoring (due to the demands of the dual task) or less reliance on reactive control in that group: A principle of minimal intervention in motor control, helping to limit motor variability in musicians (see Jentzsch et al., 2014) may also apply here. Integrated models of cognitive and motor control suggest that similar control strategies can apply to both (Alexander & Brown, 2015); Here this would suggest that some conductors did rely on a strategy to modulate control signals that was highly flexible from the start, as is required in ensemble performance (see Clayton et al., 2020) but also – and proactively – geared towards limiting strong modulations.

In order to see whether goal maintenance in the beep count task was predictive of better goal maintenance overall, we fitted LMMs treating performance in the first two quartiles in one of the dual task components as a predictor to accuracy in the other task component. These did not yield similar results in both directions. While this may appear surprising, it simply reflects the fact that the performance on both tasks does not follow a linear correlation in the sample. In DT1, while 2-back performance and beep count accuracy were positively correlated with each other for instance in controls in DT1, in conductors and interpreters higher 2-back accuracy was positively correlated with accuracy in the beep count (n.s. in the case of interpreters), but better performers in the beep count component had worse accuracy in the 2-back task (again n.s. in interpreters). This does not support a multitasking advantage associated with goal maintenance in conductors. In addition, in DT1, there was more consistency between performance in both task components within participants among controls than among other groups. In DT2, there was no mutual effect of the accuracy outcomes in controls, while in interpreters and conductors, higher 2-back accuracy was correlated negatively with beep count accuracy; however, higher beep count accuracy was strongly correlated with 2-back accuracy in conductors, and non-significantly so in interpreters. It would seem, therefore, that conductors who prioritised the beep-count task in DT2 performed better in the 2-back task, while this may not necessarily be true in the other groups.

Beyond the skill of conducting, musicianship seemed to provide controls with an edge in baseline response time; furthermore, adding musicianship to the beep accuracy model indicated that the "musicianship" effect was a factor of increased beep count performance in the conductor group, though the model was not the best fit. Musicianship as a factor may thus be relevant to various measures in the experiment, either in relation to the nature of the beep counting task or to better coordination between the concurrent processes. If a large enough sample made it possible, it would be worthwhile to further differentiate between the subskills of trained musicians within a given domain of expertise (see also Wöllner & Halpern, 2016). Various instruments appear to train different components of music processing and performance, with harmonic instruments (i.e., instruments that can play chords and multiple melody lines) being associated with a number of cognitive advantages, such as fluid intelligence and divided attention (Porfitt & Rosas, 2020); Pianists who are primarily experienced accompanists might also show higher divided attention than piano soloists; And conductors' skills may to some degree be shaped by their musical genres and repertoire of predilection.

8.1.4 Follow-up analyses and covariates

In most models of the performance outcomes in the dual tasks, the group variable and most grouping variables did not show a consistent predictive effect: It appears that in the case of multitasking performance, and as suggested also by consistent multitaskers among the participants, differences are highly dependent on individual variation. This corroborates remarks by Henrard and Van Daele (2017) who found a high degree of variability in bilinguals and specifically in interpreters in a battery of executive function tasks: this was the case even though that specific study included three large groups of interpreters, translators, and controls respectively, aged 25 to 65 years (n = 60 each). This variability, as in the present study, increased the chance of a lack of significant effects in statistical models that do not rely simply on group average but include subject-level variation. Multitasking ability may be differentially fostered by professional experience, but closer investigation would require a longitudinal study with various continuous multitasking paradigms.

As a follow-up to the testing of the hypotheses, in order to provide an account of variables associated with good multitasking, we first looked at variables associated with both accuracy outcomes taken together; in the present case, effects were not strong enough to be conclusive. In a second step, we focused on performance in the higher half of accuracy scores in both task components.

8.1.4.1 Characteristics of good multitaskers

An exploratory analysis (principal component analysis) of good multitaskers in the sample suggested that in DT1, two unrelated dimensions closely aligned with 2-back RT on the one hand, and 2-back accuracy on the other, had the most explanatory power for the performance, but suggested that speed and accuracy were not related in this subgroup. This would mean that good multitaskers did not show a trade-off (but no direct association either) between speed and accuracy. In addition, 2-back accuracy itself was a factor with comparatively little weight in the model, suggesting that the subgroup shared stronger commonalities above and beyond their performance. Age was closely correlated with higher RTs; being an interpreter was correlated with PES and negatively correlated with the task outcomes, while being a conductor was correlated with both higher RTs and 2-back accuracy, and to a small degree with beep count accuracy and NVIQ. NVIQ was closely correlated with the beep count accuracy, and both showed a correlation with accuracy, as expected in a depiction of good multitasking performance. The analysis outcome suggests that control processes in conductors and interpreters were indeed different, with interpreters relying on reactive mechanisms, but that this latter control strategy – and being an interpreter, which was not weighted heavily in the model – was much less conducive to high performance in the DT1.

In DT2, the picture had shifted considerably; the two dimensions with the most explanatory power were closely related to age (and to an extent RT) on the one hand, and beep count accuracy on the other. Being a simultaneous interpreter was also closely related to that first dimension, and to some extent to the second dimension, indicating a strong relationship with higher RTs, and some association with beep count accuracy. Being a conductor was negatively correlated with that first dimension; NVIQ, this time around, had little explanatory power, but was directly opposed to beep count accuracy, and rather closely related to 2-back accuracy, while PES was correlated with beep count accuracy; Conducting was correlated to limited extents with PES and 2-back accuracy. This picture indicated that good multitaskers among conductors were likely to show some reactive control this time around, while good multitaskers among interpreters tended to slow down during DT2, were presumably older, but did not show indications of reactive control; indeed, they performed especially better in the beep count than in the 2-back, pointing rather to successful priorisation and goal maintenance.

While this comes with a risk of giving disproportionate weight to the conducting and interpreting variable, bilingualism and musicianship were added to the picture. They did not add explanatory power to the analysis, but considering these factors in the analysis highlighted that bilingualism and musicianship were more closely aligned with interpreters and conductors in DT1 than DT2. In DT1, musicianship was positively correlated with both accuracy outcomes, while it was correlated only with 2-back accuracy in DT2. Bilingualism was associated only with interpreting in DT1, and (lower) RT, which lost most of its predictive power; in DT2, bilingualism was closely associated with beep count accuracy and PES. This highlights the observed difference between the effects of bilingualism on RT across the groups in the first dual task, with the expected higher processing speed seen only in interpreters as opposed to controls. However, in the second dual task, bilingualism appears to have contributed to shaping individuals' control strategy. In order to make controls more salient (other than not being interpreters or conductors), a further analysis used all three groups as additional categorical variables only and looked at the interplay of individual characteristics and performance in DT2. Bilingualism and PES are strongly associated, both when taking all participants and good multitaskers into account; However, while across the sample PES is negatively associated with both accuracy outcomes (and positively with processing speed), in good multitaskers PES is closely associated with performance in the beep count. PES being an error-dependent measure, in this paradigm it is likely that it reflects the priority given to beep-counting while performance in the 2-back is adjusted reactively on the basis of conflict monitoring. This provides for comparatively good 2-back scores when compared to the bulk of participants, but for a negative relationship on a closer look between these higher beep count and 2-back scores.

The analysis suggests that cognitive flexibility may have played a role across the sample to allow good multitasking performance in DT2, as well as a tendency towards a stronger association between speed (smaller RTs) and the accuracy outcomes, suggesting growing automation. Insights regarding the consistency of MT performance remind us, however, that the changes in the picture do not reveal changes in control strategies within individuals so much as a change in the composition of the interpreter and conductor group among good multitaskers during DT1 and DT2.

8.2 General discussion

Beyond the exploration of group differences, this study sought to shed light on two major questions: In the presence of a complex continuous task, do we task-switch or can we multitask continuously? And what control processes do we apply during multitasking? Regarding the first question, the empirical study investigated the issues analysed in Chapter 2 by providing a continuous dual-task framework. While the results indicated a clear multitasking cost across the board both in RT and accuracy, some participants were able, even without prior training in any of the tasks, to perform satisfactorily in both. With training, multitasking cost was reduced.

The present paradigm looked at “spontaneous” multitasking performance as well as potential short-term training effects in the form of an adjustment to the constraints of the dual task at hand. Therefore, it did not constitute a training paradigm over several sessions and the results may not reflect on improved performance on the longer term. However, within the duration of the testing session, on-task learning can take place (Botvinick, 2007; see also e.g. Morales et al., 2015), especially with repeated exposure to certain task components and their combination. Measures of cognitive control were thus used to shed light on the mechanisms potentially associated with differences in performance and patterns of evolution between subjects and across the groups.

While this study could not univocally pinpoint individual characteristics sufficient to explain the phenomenon of high spontaneous multitasking capacity, forms of musical experience, for instance, could have had a beneficial effect; However, it remains to be clarified to what extent this influenced domain-specific processes and domain-general control. In general, participants across the sample made up for their comparative weaknesses between the first and the second occurrence of the dual task: Trade-offs in performance between both task components were compensated. However, there was little improvement in the task component that was the less problematic during the first dual task. This may simply be due to the fact that there was less room for improvement in one task component than in the other, necessarily making improvement in that component comparatively smaller. However, the remaining gap between performance in the dual and single task in both components could indicate additional possibilities that are not mutually exclusive: The performance ceiling in the dual task may be structurally lower than in the single task across participants, and it could be that only a few of them are able to effectively reduce the multitasking cost further. This would be in line with the hypothesis that a subset of the population has multitasking capacities that the rest does not have (Watson & Strayer, 2010). Alternatively – or in addition – participants appear to have engaged in a greater effort to compensate for the poorer performance. This suggests that an internal system allowed participants to keep track of the comparative performance impairment during the first dual task and to regulate their performance accordingly during the second task. This, in turn, is consistent with the idea of a control-mediated, and more specifically a conflict-mediated, learning process (Botvinick, 2007) and highlights the role of control in a multitasking situation.

Although differences in processing between the first and last occurrences of the 2-back task in single and dual condition are visible, behavioural data allows only a superficial peek into the different control processes possibly at play.

8.2.1 Multitasking abilities and the issue of transfer: Implications for professional training

While expert groups had, on the whole, a better speed-to-accuracy ratio than controls in the first, untrained, dual task, their accuracy overall was not significantly higher than controls. In addition, as regards multitasking capacity, while more controls than in other groups had difficulty with DT1, controls were able to catch up and even surpass both other groups.

There might be a paradox in experts, where a potential capacity to regulate inner timing (for instance) or coordinate WM processes might be counteracted by a certain rigidity in the actual processes that they are used to combining. Concretely, task-specific connection pathways may have been created with experience that cannot be used to the same extent in other domains. For example, is possible that multitasking in an interpreting setting is fostered inter alia by enhanced coordination of the articulatory processes (Hervais-Adelman et al., 2014): This might help interpreters in other contexts depending on the extent to which the context calls for articulatory coordination and control. Therefore, not only might the multitasking ability of interpreters only partly be domain-generally transferable to other settings, but interpreters may additionally be inclined to resort to cognitive strategies that may not be the most efficient in the context at hand. Thus, as the present results suggest, complex task experience appears to both provide control habits that may be transferable, coupled with a form of inflexibility compared to non-experts. Multitasking, on the other hand, appears to call for flexible control processes.

However, interpreters and conductors, as well as controls, showed a clear evolution during single 2-back task training, suggesting that in general control processes are both flexible and shaped by experience. Successful outcomes tended to be more related to RT in the first dual task iteration and PES in the second dual task iteration, suggesting that proactive control might be beneficial in the execution of a new task, while reliance on strengthened representations and reactive control subsequently bestows a greater advantage. The phenomena described above in experts seem to point to demand-based cognitive flexibility (Garcia et al., 2020) on the shorter and longer term, namely, that the improvement in cognitive abilities is driven by the demands of the context at hand and therefore domain-dependent. Such a demand-based learning process is also consistent with the EVC hypothesis (Shenhav et al., 2013) and the idea that control is allocated where significant performance gain, worth the cognitive cost of exerting control, can be expected. That type of system would constitute a valuable framework for pathway strengthening and continuous learning, with conflict between the task goal and specific aspects of current performance mediating control adjustments over repetitions of the task. However, this also suggests that once a component is entirely automated and does not rely on conflicting representations anymore, internal incentives for further improvement, mediated by reactive control, diminish. Cognitive habits may become engrained, for better or for worse. When that happens, relying anew on proactive control, mediated by an external goal (i.e., self-provided instructions, not determined by the task itself), may provide a margin of progress.

Possible implications for training arise from these insights: Relying on explicit instructions and goals when acquiring and consolidating a new competence is necessary to reliably form the related tasks representations and processing pathways. The example of the beep and key-press task suggests that there is advantage in formulating task goals under which the various processes can be accommodated. The high extent of individual variation in factors influencing complex task processing, including general factors such as the degree of motivation (Braver et al., 2014), underlines the importance of these a-priori task representations. However, in a second step, it is also necessary to make sure there is enough repetition to strengthen the associated processes. The challenge resides in ensuring that the degree of flexibility required to face changing demands is reached during this learning process, and that it is not lost with growing consolidation.

Such a mechanism might underlie the respective contributions of “hours on task” and “deliberate practice” to skill acquisition and improvement (see Macnamara, Hambrick, & Oswald, 2014, for a meta-analysis), and studying the respective contributions of reactive and proactive control to the skill acquisition process might clarify the debate on the value of these respective strategies by providing arguments as to why both may be essential to the process.

8.2.2 Proactive and reactive control

Current theories suggest that cognitive control signal modulation is linked to inferior PFC function, and that it can be mediated in two ways: Reactively and bottom-up by – schematically, and inter alia – regions of the posterior fronto-medial cortex and the ACC associated with action monitoring, and proactively and top-down by sustained goal maintenance in the PFC, with the involvement of the pre-SMA (Braver, 2012; Botvinick et al., 2001; Irlbacher et al., 2014; Miller & Cohen, 2001). The present results offer an insight on a potential difference between control mechanisms when it comes to multitasking.

These results suggest that in most cases, a tendency to resort to proactive control, which translates into a more accurate beep count, seems to be associated with reduced indications of reactive control in the 2-back. This complex picture has a few possible explanations: On the one hand, a tendency to exert proactive control could apply to both tasks, favouring longer, most consistent response times in the 2-back. On the other hand, reduced reliance on reactive control here may also be a sign that control is applied preferably in a "switchman" fashion, and that one of its roles is precisely to prevent multitasking. However, the negative association between indications of each control strategy was not systematic. In addition, the distinct phenomena that appear to be attributable to control during multitasking highlight the potential duality of the control process – or the existence of distinct modes of control, whether or not they can be considered to be part of one and the same construct of "control". This raises the question of their compatibility; while proactive and reactive control appear to show a degree of complementarity, they do not appear to operate on a continuum.

Indeed, the outcome of the present dual-task paradigm raises questions. In fact, single task automatisation appears to lead to an improvement in the management of concurrent tasks, but not so much to a considerable improvement of the performance compared to the baseline single task. This underlines two issues. On the one hand, a multitasking setting presents a multiplicity of constraints which in itself calls for the involvement of various WM processes, which may to some extent run contrary to one another. On the other hand, if cognitive control is an emergent phenomenon in interfering pathways, differentiated "automatisation" processes might occur when mediated from the bottom up or from the top down. While the proactive, goal-maintenance-related component of "control" is linked to global executive functioning (Miyake & Friedman, 2017) and WM, consistent with Baddeley (1986), conflict monitoring acts as a signal regulator at the level of lower-level processes (Botvinick et al., 2004). Evidence of a duality of networks to serve these functions (Braver, 2012), also involved in language-related activities requiring control (Hervais-Adelman & Babcock, 2019; Cachia et al., 2017), highlights that the interplay between proactive and reactive control is not linear – with reliance on one reducing reliance on the other – but intertwined. Although task demands and personal preferences may lead to one mode taking precedence over the other (Braver, 2012; Chiew & Braver, 2017), a degree of independence between them, allowing both to be active at a given time, is not precluded (Braver, 2012). Findings by Unsworth et al. (2006) suggesting that post-error slowing is associated with different outcomes depending on working-memory-related variables are consistent with this proposition. This is also in line with recent findings by Mäki-Marttunen, Hagen and Espeseth (2019), suggesting that separate mechanisms for proactive and reactive cognitive control modes allow their independence and simultaneous engagement.

A question that arose from the literature review in Chapter 2 was whether relying primarily on reactive control is beneficial to concurrent multitasking, as representations are open to being disturbed by interference in and from the concurrent task, with little sway over whether the processing of that concurrent task is then completely overridden (in "switchman" mode). It is possible that goal maintenance, by contrast, limits overwriting in WM and allows task representations for both task components to remain active. If goal maintenance is associated with proactive control, it can be assumed that WM can be proactively conditioned to maintain the representations associated with concurrent goals, and that the reactivity or susceptibility of the representations to conflict signals can be reduced. The difference in WM involvement depending on the mode of control is in line with findings by Unsworth et al. (2012), according to which WM capacity did not influence RT increase after errors, but participants with lower WM capacity consistently demonstrated more instances of PES than higher-WM-capacity participants. This idea is compatible with an association between proactive control and WM capacity, while the two features remain distinct. This also goes in a similar direction as Engle and Kane's (2004) executive attention component of WM capacity or the common EF component of WM proposed by Friedman and Miyake (2017). It appears that proactive control relies on maintaining task-related information active in WM. The fact that individuals with higher WM span can be less sensitive to the cocktail-party effect from a concurrent channel during a listening task (Conway et al., 2001) suggests that such a mechanism might support selective attention. In the same way, enhanced proactive control in musicians might be associated with better selective attention (e.g., in the context of signal-in-noise recognition: Yoo & Bidelman, 2019). If proactive control favours selective attention, it might then be detrimental to successful multitasking. Conversely, it could also be the case that proactive control supports the type of attention best suited to reaching the goal at hand – in the case of a continuous dual task, this would be divided attention.

In the present study, however, in addition to insights from the accuracy scores, the relative proportion of participants from the three experimental groups among the high-multitasking group in DT1 and DT2 suggests that while more controls and interpreters achieved good multitasking performance in DT2 compared to DT1, the reverse was the case in conductors. It would appear that there was more fatigue in conductors as a group, or less automatisation of the component tasks. If the pattern of RT and PES in conductors is indeed indicative of their more proactive control mode – although findings in that regard were not clear-cut –, this may support the suggestion by Braver et al. (2007) that proactive control is not conducive to automatisation. It is striking, in that regard, that out of five good multitaskers in the conductor group in DT2, four were comparatively fast performers and four (including three of the fast ones) showed increased PES in the 2-back task, suggesting that they probably resorted to reactive control at least for the 2-back task (the same was true for 2 controls and 3 interpreters). It would appear, therefore, that in a multitasking setting, relying on proactive control (and goal maintenance) for both separate tasks may impede their combination. In addition, the nature of proactive control, apparently associated with maintaining WM representations active, may induce more fatigue than relying on parsimonious reactive control during an already practiced task.

A possible benefit of proactive control for multitasking might thus depend on the compatibility of the goals maintained. Across the groups, beep count accuracy was not impaired, or even improved, when the count was accompanied by key press in dual task; nevertheless, there seems to be an increased latency in response due to response conflict (Navon & Miller, 1987). With accuracy scores at ceiling, it is impossible to corroborate or to infirm conclusively the hypothesis of goal reinforcement. In addition, Duthoo, Abrahamse, Braem, and Notebaert (2013) suggest that proactive control may also efficiently come into play in the case of scenarios when the succession, type, and timing of stimuli can be expected: Therefore, it cannot be excluded that a predictable multitasking setting might benefit from the exertion of that form of control.

In order to perform optimally in the dual task, we thought that it would be beneficial for control to be modulated proactively so that any required adjustments in control do not drastically modify the equilibrium required for continuous multitasking. However, it appears that this is likely to work against potentially needed flexibility; moreover, this equilibrium might not be found in any case in the first occurrence of a new task. On the other hand, it is still unclear whether a heightened level of reactive control during multitasking actually benefits dual task performance, and what it reveals about the functioning of control during multitasking. “Switchman”-like control would divert attention away from the concurrent task, which would also be detrimental to maintaining divided attention and good dual-task performance; these would be fostered by lighter adjustments – “traffic-control”-like – of the control signal. The present results suggest that this is not systematic but remains a possibility, underlining that optimally efficient multitasking performance could require a combination of both (Fischer & Plessow, 2015).

8.2.3 Allocation of control during multitasking

The present results suggest a global gain in dual-task performance and increased automation after the single reps. This pattern of results is consistent with theories regarding "multiplexing and multitasking" (Feng et al., 2014), which posit that some specific, dedicated representations, which do not exist prior to training, are created with practice. Participants would then rely on reactive control to face residual conflict from performance inadequacies or from competing stimuli interfering with the optimal timing of the task. The findings might also be consistent with the idea that there is a single, specific resource for control, which would be less solicited with greater practice due to an easing of timing constraints (Dux et al., 2009; Tombu et al., 2011; Garner et al., 2014). However, we have seen that RT is not necessarily reduced between DT1 and DT2, while dual-task performance improves. In addition, PES values in the 2-back task component are not negatively linked to the accuracy score on the same task, nor on the other task component, which might be expected in the case of a control bottleneck. Looking at beep count accuracy results shows that in DT1, while higher PES is not associated with any significant performance change in controls, and has a negative effect in interpreters, it is associated with better performance in the beep count component in conductors. In DT2, higher PES is accompanied by increased accuracy in the beep count task in interpreters. In addition, examination of the good multitaskers data shows that about half the participants who perform comparatively well in both task components have positive PES values (and most good-multitasker conductors in DT2).

This pattern of results suggests that reactive control may indeed be allocated with a degree of flexibility, taking into consideration other processes involved in a task. This is consistent with the idea that control operates hierarchically (Alexander & Brown, 2015; Branzi et al., 2016; Chiew & Braver, 2017; Colzato et al., 2006). It is also likely that various hierarchical levels of a task are sensitive to different modes of control. For instance, in the case of (non-continuous) dual tasks, rewards such as monetary bonuses have been found to contribute significantly to eliminate dual-task costs by the end of practice (Tombu & Jolicoeur, 2012). It is unclear whether cognitive control in different time frames works the same way (Cohen, 2017), although for instance according to Braver (2012) proactive control also applies to remembering a task prior to doing it. Cohen also raises the question of the sameness or the difference between control signals over domains; in the case of a hierarchical control process, with top-down and bottom-up adjustments at the various levels, whether motor or cognitive, a certain compatibility at the very least would make sense.

However, the present findings cannot elucidate whether control during multitasking, and specifically goal orientation on the one hand, and conflict detected during task execution on the other, modulate the relative synchronisation of activation in networks relevant to the task components (Buschweitz et al., 2012), or the strategic scheduling or deferment of responses (Meyer & Kieras, 1997a), or the relative degree of activation of the pathways relevant to different task components at a given point in time.

The instructions provided to prioritise the beep count over the visual 2-back task component – since the outcome of the beep count task could be affected more by goal neglect – did not always suffice to override tendencies by individual participants to prioritise tasks otherwise or resort to additional strategies. During WM tasks, single as well as dual, participants may have been tempted to adopt various strategies to alleviate the cognitive load, reinforce representations or maintain WM content active. In the present study, participants were not asked to describe their strategies, though several volunteered comments in that regard. With all due caveats, these provide indicative, impressionistic insight into possible paths to explore: Some interpreters reported identifying acronyms in the successive letter probes of the 2-back tasks, a phenomenon that is consistent with suggestions by Henrard and Van Daele (2017), regarding a potential memory advantage in interpreters in tasks requiring the recall of series of letters due to their familiarity with numerous acronyms (see section 3.2.3). While this suggests that recognising meaningful successions of letters may indeed be a strategy used by interpreters, this did not lead to a better performance compared to other groups. Other participants reported visualising letters or beep pitch, with at least one conductor updating the count under the form of an evolving mental pitch. Priorising one task over the other – not always as instructed – was also mentioned, offering a further argument in favour of investigating individual strategies in this type of experimental paradigm.

Regarding the reduction in multitasking cost in DT2, it cannot be excluded that training may have also been accompanied by a strategy change, for example from a verbal to a familiarity-based strategy in the 2-back task (Kane et al., 2017), or by the consolidation of a strategy (e.g., Jaeggi et al., 2007). For instance, while most participants appeared to rely on subvocal rehearsing or other explicit strategies for the auditory-verbal element in Jaeggi et al.'s dual *n*-back especially for the smallest load levels, high performers in that study self-reported less explicit strategies, and some felt they were relying on intuition. This relationship between fluid task execution and various degrees of automatic, implicit or unconscious processing (see e.g., Silva et al., 2018; Gold & Ciorciari, 2020) is a rich domain to explore with similar, adjusted paradigms.

In addition, the results of the present study highlight the extent of individual variation, which drives many of the effects reported. This is consistent with the idea that improvement in complex tasks and in the *n*-back particular are linked with a broad array of individual characteristics (e.g., Jaeggi et al., 2014), which would deserve further exploration. A number of underlying factors interact and come into play in cognitive tasks, influencing performance and improvement with training as well as WM function (Kane, Hambrick, & Conway, 2005), which in turn, plays a role in control preferences (Burgess & Braver, 2010).

8.3 Limitations of the present study: Possible confounds and further variables to explore

The present study seeks to investigate two aspects of multitasking: Specific control-related variables influencing multitasking and possible group effects regarding the ability to multitask. However, a number of other aspects which are likely to play a role in that equation should not go undiscussed, some of which could not be entirely controlled for in the experimental setting and would be worthy of further investigation. They are detailed below.

8.3.1 Ecological and construct validity

The experimental setting in this study is faced with the same challenges as other dual-task paradigms, and more generally other tasks seeking to measure executive functions: the issue of task purity, which affects construct validity (see Friedman & Miyake, 2017), and that of ecological validity. On the one hand, tasks designed to quantify specific variables should allow for their isolation and measurement. On the other hand, real-life cognitive tasks are shaped by complex contexts and rely on a complex and oftentimes variable cluster of cognitive processes. Experimental tasks are, therefore, by design simplified and streamlined versions of possible real-life scenarios.

In the present case, the concurrent dual task is a complex task by nature. For comparability, it is based on combined baseline single tasks. These were designed to rely on various sensory and response modalities to reflect the different skill sets presumably developed by interpreters and by conductors, while reducing stimuli and responses to the smallest common denominator so to say. This approach aimed at making the task manageable to non-specialised subjects, and to limit response-related costs as much as possible in order for the variance on performance to reflect actual differences in cognitive processing. Specifically, the component tasks were designed to involve specific executive functions, that is, monitoring and updating, in a continuous way (see above sections 2.4.3.5 and 5.2.2.1). Furthermore, their design ensures that specific control mechanisms, i.e., conflict monitoring and goal maintenance (see section 5.2.3) can be measured. Therefore, no claim is made that the multitasking skills tested in the present study and the conclusions drawn from the results apply to all forms of real-life concurrent multitasking, nor provide an account of skills transferability beyond the exercises tested.

In addition, the *n*-back task can itself be viewed as a complex task which involves updating, but also maintenance of the relevant representations – thus calling for a fine balance between stability and flexibility in managing WM representations –, as well as executive control to regulate these functions (Rac-Lubashevsky & Kessler, 2016a, 2016b). The control strategies applied to carry out the task often vary through the lifespan (Gajewski, Hanisch, Falkenstein, Thönes, & Wascher, 2018).

8.3.2 Considerations related to sampling

Language: Interpreters were the first group recruited for the experiment. With bilingualism taken into account as a continuous variable rather than a categorical one, they were treated as language experts for whom a working language should be processed in a similar manner to their declared native language. Instructions were provided in English or French, but participants in the three groups also had other native languages.

This study included 69 initially recruited participants, 67 of whom had valid results, forming 3 groups of respectively 26, 21 and 20 persons. This sample size was smaller than expected at the outset of the study: 30 to 40 persons by group was the goal. It proved very difficult to find professionals willing to plan in advance to take two hours off for an experiment. While the subject matter intrigued or interested most contacted persons, making concrete arrangements was often a hurdle and some contacts could not be met in the end. For participants in the study, the final appointment chosen may not always have been the best suited, with participants in a hurry or otherwise not in the best shape to produce a sustained cognitive effort. Be that as it may, the final sample size did not allow for an optimal degree of robustness to compare groups. A-posteriori power analyses using the *simr* package in R (Green & McLeod, 2016) yielded satisfactory values (power > .8 to detect effect sizes of .2) for RT models with all iterations and beep accuracy models; However, for the comparison of 2-back tasks between the baseline and the dual tasks only, the number of items per task, also limited by constraints on the possible session duration, would have needed to be increased for satisfactory detection of patterns once random effects were introduced. Furthermore, a higher number of participants would have offered more consistency across models with additional interactions. Even when modelling was possible, a random slope was not always supported by the data, which in the case of repeated measures and manipulations within subjects may yield false positives (Barr et al., 2013). This issue is, justifiably, a widespread one when it comes to studying specialised professions like interpreters and conductors (e.g., Christoffels et al., 2006; Nager et al., 2003). However, this tradition is not conducive to sustainable research practices. This is evidenced by the frequent inconsistency between study results which cannot be entirely explained by differences in paradigm (Chmiel, 2018; Timarová et al., 2014). Statistical tests that seek to attenuate the risk of Type I error require comparatively large datasets. With small samples, the choice is then reduced to using tests that are likely to yield falsely significant results or facing the risk of a lack of conclusive results once the necessary nuance to best account for the results is introduced. In the present case, most attempts at simple or multiple regression modelling highlighted significant effects which were not observed in multilevel models seeking to account for individual variation. Descriptive data suggests that it is probable that the effects were exaggerated in the first case and minimised in the second; a wider sample would have allowed robust hypothesis testing. Disciplines such as interpreting studies, which attempt to provide a comparative picture of given processes in interpreters within the framework of research on other populations, would benefit from a paradigm shift (exemplified e.g., in Keller, 2018, or Amos, 2020), striving to meet the conditions for comparability with the related fields. The present study makes, in retrospect, an argument for extending the testing phase to warrant such conditions, (so far) accepted – though widely lamented – practice notwithstanding. In all fairness, it should be highlighted that similar issues are not circumscribed to the domain of interpreting research or other smaller fields (see Brysbaert & Stevens, 2018), and that better practice in hypothesis testing across the board would go a long way to make scientific output more reliable (see Wagenmakers, Wetzels, Borsboom, van der Maas, & Kievit, 2012).

8.3.3 Considerations related to the experimental setting

8.3.3.1 General setting

Task order: Although a short break was scheduled between two tasks and the routine was programmed to avoid presenting two tasks relying on the same stimuli and response modality in a row, the task-switching costs that may have been higher for some participants than for others (e.g., Costa and Friedrich, 2012) could not be quantified.

Fatigue: In total, there was ca. 30 minutes of time off task per session. Considering the necessary amount of cognitive effort to complete the whole routine, the duration of the testing session was kept to a minimum (approx. 1h45). Additionally, participants' time constraints called for a shorter rather than longer testing session. Although no exercise was started without the participant stating they were ready, this put participants under greater pressure than a context in which ample time could have been allotted for them to feel in effect ready for each task. This accrued time pressure may have compensated the stress potentially induced by a longer routine in the case of participants in a hurry; However, this context makes fatigue a more relevant variable in the multitasking performance than it might otherwise have been (see Green, Strobach, & Schubert, 2014).

Breaks: Participants may have experienced the effect of breaks differently. For some, and at given times, a break provides a respite, which allows them to start afresh and to concentrate better at the beginning of the next instalment of exercises than at the end of the previous one. For others, or in other cases, the break interrupts their concentration (or potential state of flow, if such a state was reached) and they would not quite be back into full focus at the start of the next instalment of exercises. In spite of the experimenter's best efforts to suggest a five-minute walk at least in the surroundings of the testing room during breaks to each participant, this possibility was not consistently taken advantage of. In ideal conditions, characteristics of each participant's break – including, for instance, their intake of caffeine as compared to their habits in that regard – would be controlled or at least documented. This does not appear to be easily feasible; However, self-accounts of the experienced state of focus before and after breaks could constitute an approximate measure of individual variations in focus.

Practice: The same practice vs. fatigue conundrum applies to the practice trials. While the overwhelming majority of the participants fared better after practice in the baseline tasks, in the dual exercises, some were not able to replicate the scores they had achieved in practice.

The amount of practice before the dual 2-back had been limited to three blocks to limit cognitive fatigue, contrary to usual *n*-back protocols where practice lasts until a given level of accuracy has been reached. The downside to this approach was that a few participants started the dual 2-back exercise while instructions were still not fully understood and had to be excluded from the analysis for that exercise. To see if a performance decrement after practice could indeed be linked to cognitive fatigue, an analysis of the participants' performance pattern during and after practice was carried out, but showed no difference with age, or best performance achieved overall (with all levels represented), though of course some participants who performed less well in the experiment than during practice had reached high scores during practice. However, a trade-off between performance in the task components was noticeable, suggesting that participants shifted priority or strategy.

State of mind and circumstances: There were temperature variations between sessions, with some held on very hot days. Participants had to be tested at various times of the day and in various states of wakefulness, after or before other activities which may or may not have been a cause of stress, distress, or positive feelings. Parallel events in the participants' life, or their amount of sleep, cannot be controlled in any such setting. This aspect is of course not unique to the present experiment, and modelling seeks to account for subject variability in the analysis, but it may bear a particular weight where executive control is concerned and required to such a high degree, making variations in circumstances a greater reliability concern. Cognitive processes are by definition difficult to isolate given that the signal modulation, based on an internal estimation of the expected value of exerting control, is susceptible to personality traits (see section 2.3.2), like for instance locus of control, perseverance or confidence, and to personal stakes (ease in a testing situation/experimental setting…). In the present case, this may come in to play to an important degree and affect the measured group differences. In fact, interpreters and conductors were likely to expect a high level of cognitive performance of themselves and frustration in this regard was reported by several participants in those groups – as well as negative self-assessment and/or trouble concentrating as a result.

Strategy: Beyond the aspects of control studied, differences in strategy (e.g., reliance on verbal rehearsal, visualisation, association, or specific conscious focus) may also have influenced the task outcome and constituted a confound. It would therefore be useful to consistently ask participants at the end of the experiment to self-report on their strategy use in the various exercises of the testing routine, even though strategies are not always explicit (for instance visualisation may occur without intent) and therefore may not be systematically recalled by participants.

Pitch discrimination: The participants' hearing was tested at the beginning of the session. However, some participants whose hearing was otherwise good expressed a priori difficulty in telling apart high and low beep pitches. Nevertheless, these participants showed no difficulty in distinguishing between the two types of tones played in this particular routine. The frequencies for both tones were far enough apart and their timbre and sound spectrum were also different in order to facilitate their identification.

Inner timing: In line with findings suggesting that the acquisition of the ability to multitask in the framework of a given activity (in that case interpreting) is associated with better management of task components (Hervais-Adelman et al., 2015), it would be highly relevant for future studies on multitasking to investigate matters related to inner timing and coordination. Consistent with suggestions by Maes et al. (2015) regarding musicians, certain participants favoured concentration and possibly flow (Csikszentmihályi, 1990) by adopting a rocking movement.

8.3.3.2 Challenges/limitations with regard to Individual exercises

2-back: Before each 2-back exercise, participants were explicitly asked to try not to rehearse the letters to the extent possible, as such attempts are assumed to slow down the process and load verbal working memory in a way that would have been detrimental to the execution of dual 2-back tasks. However, all participants may not have been able to consistently conform to these instructions. While this may constitute a part of individual differences in the capacity for control, which this study seeks to assess, it is also a matter of strategy.

Beep count: Beep order was randomised in most exercises (not the dual text exercise for programming reasons). In other words, for some participants there may have been more times when the number of beeps of one type overtook the other (e.g., 3-4, 4-4, 5-4). The changes in relative proportion may have created an additional element to bear in mind in working memory.

It would be useful to integrate other exercises in order to control for the modality of the goal maintenance measure. In the present case, due to the nature of the task, there may be a difference in the way musicians, bilinguals, and controls process beep count. If musicians show better working memory capacity for pitch, for instance, they may have had an advantage beyond control-related aspects. A routine including other task combinations should be considered. In the larger routine not included in the present analysis in its entirety, various continuous task combinations were used using a motor task and a reading comprehension task as alternatives to the 2-back task in order to test for possible domain-specific advantages.

8.3.4 Suggestions for the way forward

One of the issues highlighted by the present results has to do with the relationship between RT and control processes and the necessity of distinguishing between possible nuances in slowing patterns. In order to provide clearer insight into the various participants' control strategies and potential group differences, provided the data supports such a model, it would be necessary to fit a diffusion model of the RT distributions (Ratcliff, 1978; Ratcliff & McKoon, 2008; for its applications to PES analysis see Dutilh, Vandekerckhove, et al., 2012; for its application to task and response inhibition in a task-switching context see Schuch, 2018). By distinguishing response boundary, that is, the amount of information required by an individual to make a decision, from other processes (such as initial bias towards a response, speed of information accumulation, and non-decision-time), and taking error patterns into account (see also Lerche & Voss, 2016), a diffusion model could highlight potential differences in processing between the groups. This was attempted on the present 2-back RT data using the "EZ(2)" diffusion model (Grasman, Wagenmakers, & van der Maas, 2009; e.g., Pirrone et al., 2017, Domenech et al., 2019). The model is based on the "EZ" diffusion model (Wagenmakers et al., 2007, 2008; Van Ravenzwaaij & Oberauer, 2009; Van Ravenzwaaij et al., 2017), which is lighter than fully-fledged drift-diffusion models. It allows for response bias to be taken into account (in cases like the present one when there are, e.g., fewer target than nontarget items), can be applied to data with less observations, and performs well (Dutilh et al., 2019).

However, fitting such a model was not feasible on the dataset at hand, as the number of trials by iteration was not sufficient (see Lerche, Voss, & Nagler, 2017). The research question on cognitive control concerned specifically proactive vs. reactive control processes; differences in boundary separation estimates for instance could also be revealing of more or less conservative strategies used by the participants, and differences in pre- versus post-error retrieval time and response caution (Dutilh, Vandekerckhove, et al., 2012) would be highly suggestive of the amount of proactive versus reactive control at play. To verify the differences highlighted in the present study, the hypothesis to test would concern specifically increased baseline response caution in conductors and increased post-error response caution in interpreters. Such a model would also better account for the role of baseline response time in slowing patterns. It remains to be seen, however, to what extent it would make sense to use a diffusion model on dual-task RT data in addition to single-task data, since in a continuous multitasking task, as opposed to a dual-task paradigm, the reaction time is heavily influenced by external factors that cannot necessarily be accounted for in the model. In the present case, the beeps occurred at various times during the 2-back stimulus or response processing. Finding out how to introduce and factor in the various intervals between 2-back stimulus onset and beep onset in the model would be a major, if useful, challenge, but might not suffice to account for potential changes associated with WM maintenance (e.g., covert rehearsal) for the concurrent task component. In any case, fitting full diffusion models for the tasks at hand would represent an endeavour worthy of an individual study.

Many studies focus on WM capacity in language/interpreting and musical experts, highlighting differences between types of experts (e.g., D'Souza et al., 2018) and depending on the degree of experience (e.g., Köpke & Nespoulous, 2006; Signorelli et al., 2012). A conscious choice was made to focus in the present study on control mechanisms specifically, independently from WM capacity. However, in the context of concurrent multitasking, it appears that WM capacity is a relevant factor likely to interplay with individual patterns regarding possible strategies and type of preferred control mechanisms. It follows from such insights that it could be relevant to include WM capacity measurements, not only to study performance in continuous multitasking in relation with WM but also to examine whether WM capacity is linked to a propensity to rely on proactive rather than reactive control during continuous multitasking, as seems to be the case in other paradigms (e.g., Kane & Engle, 2003).

This would need to be done using diffusion modelling to dissociate between the processes, or using tasks specifically tailored to tap proactive and reactive control distinctly, such as the AX-CPT (Cohen et al., 1999), where expectations regarding probe sequences are broken in specific ways to tap one or the other control mode. In that respect, a continuous task using a format similar to the gatekeeper test (Heathcote et al., 2014), and manipulating lures based on the same principles as the AX-CPT, would complement the present findings usefully. In addition, if WM appears to play a central role in proactive control, it would be relevant to also investigate control during multitasking in non-verbal tasks, as the role of WM in verbal tasks may be confounded with possible associations with control as such (Hernard & Van Daele, 2017). The testing routine of which the experiment presented here was a part included combinations of different task types, notably the beep count task and key press with a visuomotor tracking task, which, while not entirely devoid of verbal processing for the differentiated beep count, may provide a useful basis for comparison.

Another avenue worth looking into is the relationship between individual proactive or reactive control exertion in various tasks and the capacity to multitask concurrently compared to the capacity to switch tasks. Task-switching is associated with cognitive flexibility, which requires flexibly shifting between goal maintenance and goal updating (Friedman & Miyake, 2017). Differences between task-switching and multitasking abilities within individuals would shed light on the differences between the control mechanisms subserving successful execution of tasks in these conditions. Short-term single-task and dual-task training could also be compared across continuous multitasking paradigms. This would allow to test the relative contribution to performance of task-component-related as opposed to global mechanisms such as coordination mechanisms, and their relation to cognitive control modalities.

Additionally, while providing priority instructions allows insight into goal maintenance, it may work against successful multitasking in the case of continuous, concurrent tasks. An issue that appears to be a determining factor in our capacity to continuously multitask is the relative strength of our internal concept of the complex task at hand. The literature review highlighted the probable relevance of establishing a hierarchy of task-related goals and subgoals (e.g., Halvorson et al., 2013; Freedberg et al., 2014). That hierarchy might even be itself a determining factor in the way we exert cognitive control. It is possible that proactive control exertion, while not facilitating automatisation (Braver et al., 2007), allows a number of goals to be maintained simultaneously, leading to adjustments in their relative priority that in turn foster the integration of multiple processes into one task. This hypothesis was tested in the larger experimental routine that is partially used in the present thesis. Analyses are underway to infirm or support the hypothesis.

Conclusion

An analysis of conductors' and interpreters' performance in a new multitasking paradigm revealed that specific complex task expertise is not systematically transferable to new tasks; However, control habits appear to be forged by experience and to inform not only performance in new tasks, but also the ability to adapt. In this regard, more conductors successfully met the new challenge, but more interpreters and controls were able to improve their performance the second time. In addition, this study supports findings according to which specific musical or bilingual experience modulates the effects of musicianship and bilingualism on cognition (e.g., Costa et al., 2014; Merett et al., 2013). Testing various multitasking modalities and components may yield a finer-grained picture of potentially acquired advantage. In addition, the present results were driven by individual performance patterns more than by group effects, and advocate for a follow-up investigation of possible commonalities between proficient multitaskers. When it comes to complex task performance, it seems that we cannot make the economy of adopting an individual differences approach. As complex tasks performance hinges, inter alia, on goal representations that are not only task-dependent, but also highly dependent on individual experience – in the broadest possible sense –, there is yet much to be understood from the complex interplay of personal factors.

During complex, continuous tasks, it remains unclear to which extent individuals need to switch back and forth between subprocesses, especially when they are untrained; it appears, however, that a continuous production of the task outcome is possible. The ability of participants to improve their performance on the weaker dual task component in the present study highlights the inherent relationship between control and task goals: "Cognitive control provides the interface through which goals influence behaviour" (Gazzaniga, Ivry, & Mangun, 2014, p. 512). This relationship has consequences when the continuity of multiple task performance, and the various goals or subgoals, cannot be maintained. It underpins findings according to which for instance "multitasking" that entail frequent goal-switching, such as media multitasking, has consequences on WM and on the capacity to apply control more generally (Loh & Kanai, 2014; Ophir et al., 2009; Sanbonmatsu et al., 2013; Uncapher et al., 2016). Even accidental multitasking, such as being frequently interrupted, is detrimental (Sana, Weston, & Cepeda, 2013). Accidental multitasking is, however, becoming not only a widespread habit but a way of life, with real-time connection to various sources of incoming information or "notifications". Accidental multitasking takes, more often than not, the shape of unprepared task-switching: Taking out one’s phone to look at the time or the weather can often lead to a number of activities, at the end of which the weather or time has remained unchecked by the time the phone goes back into the pocket. Not allowing the brain to apply the necessary mechanisms to maintain a goal until it is reached, and update goals as required by the tasks at hand, is thus likely to impair our capacity to complete tasks more generally. There may not be a fixed capacity for control; our ability to exert control does however appear to be amenable to training and, conversely, attrition. Throwing light on these fluctuations, between as well as within individuals, is challenging, and calls for research paradigms that strive to accommodate and account for this flexibility.

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Appendices

A. Description of frequently used cognitive tasks

Table A1:

Frequently used cognitive tasks.

Task	Description	Associated function
Keep track task (Yntema, 1963)	Participants are instructed to remember the last word of 4 or 5 distinct category in lists of 15 successive words presented visually.	**Updating / monitoring**
Letter memory task (Morris & Jones, 1990)	Participants are told to rehearse out loud the last 4 letters of a list presented serially, adding with every new letter that newly presented letter and dropping the last of the previously rehearsed letters.	
Tone monitoring task (Modified from the Mental Counters task; Larseon, Meritt, & Williams, 1988)	In a series of tones of 3 distinct pitches, played in random order, participants are asked to respond to the 4th tone of each pitch.	
Spatial 2-back *In Friedman et al. (2008), this form of* n-back *task replaces the tone-monitoring task.*	Participants must indicate whether a box flashing on the screen is at the same spot (out of 10 possible spots) than the one that flashed 2 trials earlier.	
***n*-back task** (Kirchner, 1958)	Sequences of stimuli (e.g., of letters or images) are presented. For each item in the sequence, participants are required to determine if the presented stimulus matches the presented stimulus "n" items ago.	
Antisaccade task (Hallett, 1978)	When a cue flashes on one side of the screen, participants try to suppress the reflexive saccade toward it and instead look in the opposite direction to identify the target.	**Prepotent response inhibition**
Stroop task (Stroop, 1935)	Participants name the colour in which colour words and neutral words are printed, ignoring the dominant tendency to read the words.	
	In another version of this task (digit Stroop), participants indicate the number of digits in a row, ignoring the identity of the digits.	
Stop-signal task (Logan, 1994)	Once participants have built up a prepotent response to categorise words in a particular way, they try to withhold their responses on a small proportion of trials during which they hear an auditory signal.	
Related paradigm: **Go/No-Go task**	Participants press a button as quickly as possible when a stimulus is presented (go trials), unless the stimulus is, e.g., an "X", in which case the response	

(described in Donders, 1868)	should be witheld (no-go trials).	
Simon task (Simon & Wolf, 1963),	Participants press a key on one side when they see one stimulus (e.g., a red square, or an arrow pointing up) and one on the other when they see another stimulus (e.g., a blue square, or an arrow pointing down). The stimulus can be presented on the same side of the screen as the associated response key (congruent trial) or on the opposite side (incongruent trial). The "Simon effect" is the difference in response times between congruent and incongruent trials.	
Word naming (Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994)	Participants name a green target word that is presented either alone or with a red distractor word.	**Resistance to distractor interference**
Shape matching (DeSchepper & Treisman, 1996)	Participants indicate whether a white shape matches a green shape that is presented either alone or with a red distractor shape.	
Eriksen flanker task (Eriksen & Eriksen, 1974)	Participants identify a target letter that is presented either alone or with response-incompatible letters flanking it.	
	A version of this task uses arrows, with the target arrow flanked by arrows pointing in the same direction (congruent trial) or in the other direction (incongruent trial).	
Attentional Network Task (ANT) Fan, McCandliss, Sommer, Raz, & Posner (2002).	Temporal and spatial cues added to the flanker arrow task enable the calculation of individual difference measures for "orienting", "alerting", and "executive attention", which is measured using the interference score. (Task based on the cue reaction time task (Posner, 1980) and the flanker task (Eriksen & Eriksen, 1974).	**conflict monitoring and resolution**
Brown–Peterson variant (Kane & Engle, 2000)	Participants learn and later free recall successive lists that are composed of words drawn from the same category.	**Resistance to proactive interference**
Cued recall (Tolan & Tehan, 1999)	Participants view either one or two lists of four words each and must retrieve the word on the most recent list that belongs to a cued category, ignoring any previous lists.	
AB–AC–AD (Rosen & Engle, 1998)	After learning a list of cue–target word pairs to a criterion, participants learn a new list of targets that are paired with the same cues.	**Resistance to proactive and retroactive/reactive interference**
AX Continuous Performance Task (AX-CPT) (Cohen, Barch, Carter, & Servan-Schreiber, 1999; Servan-Schreiber, Cohen, & Steingard, 1996). Based on the classic Continuous Performance Test (CPT; Rosvold,	The AX-CPT is a delayed-response task requiring context maintenance and updating for successful performance. On each trial, participants must respond to a cue–probe pair (typically, letter stimuli) presented sequentially. One specific combination requires a target response (i.e., the letter 'A' followed by the letter 'X'; AX trial), whereas all other combinations of cue and probe require a non-target response. Target (AX) trials occur at a high frequency (typically 70%), leading to associations between the target cue (the letter A) and target response, and between the target probe (the	

Mirsky,Sarason, Bransome, & Beck, 1956).	letter X) and the target response. These associations subsequently lead to interference for two low-frequency cue–probe pairs (typically occurring at 10% each): AY trials (target cue, non-target probe), where contextual cue leads to a bias towards target response that must be overcome; and BX (non-target cue, target probe) trials, where the contextual information must be used to inhibit the probe-related tendency towards target response. BY (non-target cue, non-target probe) trials also occur at a low-frequency (10%) control condition.	
Plus–minus task (Adapted from Jersild, 1927, and Specter & Biederman, 1976)	Participants alternate between adding 3 and subtracting 3 from subsequent randomised numbers on a list as quickly as possible.	**Shifting**
Number–letter task (Rogers & Monsell, 1995)	Participants are asked to categorise either the letter or the number of a number-letter pair depending on its position on the screen.	
Local-global task (Miyake, Friedman et al., 2000)	In a Navon figure (Navon, 1977) made up of small, “local” shapes disposed in a bigger, “global” shape, participants are instructed to either characterise the local or the global shape based on the colour of the figure. In all three tasks, the switch cost is determined by the time difference between switch and non-switch trials.	
Colour-shape task (Miyake, Emerson, Padilla, & Ahn, 2004*)*	Participants are instructed to indicate the colour or shape of the figure presented depending on the letter displayed above it.	
Category-switch task (adapted from Mayr and Kliegl, 2000). *In Friedman et al. (2008), the last 2 tasks replace the plus-minus and local-global tasks.*	Participants are asked to categorise a word according two one of two distinct rules (living or non-living, or size in comparison to a soccer ball) depending on a symbol displayed above it.	
Wisconsin Card Sorting Test (WCST) (Grant & Berg, 1948).	Series of stimulus cards are presented to the participant. The participant is told to match the cards, but not the rule to follow; They are told whether a particular match is right or wrong. The sorting rule changes after a while. The tasks were developped to involve strategic planning, organised searching, utilising environmental feedback to shift cognitive sets, directing behavior toward achieving a goal, and modulating impulsive responding.	set-shifting
Trail-making task (Spreen & Strauss, 1991).	In part A, participants connect numbers in alphabetical order. In part B, they connect ascending numbers and letters alternatively. Errors are brought to the attention of the participant for correction. The difference between the time in the simple and alternative condition is measured.	alternating attention
Tower-of-London (Shallice, 1982. The task is based on the tower-of-Hanoi puzzle, which uses a set of rings to	participants are instructed to reproduce a model configuration of balls on a set of pegs, starting from a provided configuration. They are allowed to manipulate only one ring at a time, are allowed a given number of rings on each peg, and are given a	**planning**

order by diameter.)	set number of moves to match the target configuration.	

Note. The tasks outlined on a grey background were used by Miyake, Friedman and colleagues (2004, 2008) to isolate executive functions. Descriptions are summed up from Miyake et al. (2000), Friedman & Miyake (2004), Friedman et al., (2008), or reprised from Friedman & al., (2008). Tasks in a white background are other frequent tasks, whose description is summed up from the literature.

B. Historical overview of interpreting modalities

Interpreting has probably existed in some form since speakers of different languages met (Roland, 1999). The practice is mentioned in inscriptions dating as early as between 2300 and 2000 BC in Egypt and Mesopotamia (Kurz, 1986; Possehl, 2006). A hieroglyph with the meaning "interpreter" is even found circa 3000 BC (Delisle & Woodsworth, 1995/2012). The common denominator of all forms of interpreting is the oral translation of a source message. In most cases, the source is a spoken utterance, but in the ancient times of polyglot messengers and dragomans – and nowadays still, though comparatively rarely – it could be a written document, making "sight-translation" a form of interpreting rather than translation, usually carried out by interpreters (for an extensive review on the history of interpreters as messengers and diplomats, see Roland, 1999). The term "translation", by contrast, is now used to refer to the written rendition of a written source message (see Christoffels & De Groot, 2005); And similarly, the written transcription of an oral utterance in another language is considered a form of translation (i.e., written) rather than interpreting, and usually carried out by translators. Thus, the main difference between interpreting and translating resides in its improvised, moment-to-moment, oral nature.

Simultaneous interpreting is a recent phenomenon – and depending on future developments, human simultaneous interpreting might be remembered as a short blip in interpretation history. Throughout the ages, direct interpersonal interpretation is likely to have happened in a sequential way, with the original message first provided to the interpreter and then rendered by the interpreter to the interlocutor. For instance, the 1679 Mercure hollandais, a political review of the year 1677, describes the following scene: "The first Vizir (…) ordered Mr Alexandre Marrocordati, first Truchman of the Kingdom, to let the Ambassador know of his wrongdoing and to tell him to desist from that extravagant act."[60] (Mercure hollandais, 1679). To this day, *dialogue interpreting* takes on a similar form, the message is tranferred sentence-to-sentence or in longer chunks, and notes may or may not be used to refresh the interpreter's memory, depending on the density and length of the source statement. It is probable that forms of whispered interpretation – overlapping with the incoming speech – were also used through the ages. At least one such instance is recorded, when a theatre piece was translated

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[60] « Le premier Visir (…) ordonna à M. Alexandre Marrocordati, premier Truchement du Royaume, de faire connaître à l'Ambassadeur le tort qu'il avait, et de lui dire de désister de cette action extravagante ». (p. 155; translation by NL). The same interpreter, "Dragoman of the Porte, Dr. Mavrocordato" is also mentioned several times in Abbot, 1920, where the activity of Dragomans is also described in detail (pp. 46-51).

in this way for King Frederick of Prussia in 1747 (Barthel, 1982, as cited in Delisle & Woodsworth, 2012).

Conference interpreting was born with multilateral congresses and institutions, though international conferences did not always use interpreters: Diplomats rather resorted to a diplomatic *lingua franca* in many settings for a long period of time – and for a long time that language was French. However, events like the Hague Conference of 1907, where some U.S. delegates needed interpretation into English (see Delisle & Woodsworth, 2012), and notably the Paris Peace Conference in 1919 (see Macmillan, 2009), with both French and English as official languages, marked the start of multilingual conferences. In such settings, *consecutive interpreting* (CI), a somewhat more formalised form of sequential interpreting, was used to translate or summarise speeches of various durations in the plenary assembly, while forms of interpreting closer to dialogue interpreting could still be used in more restricted committees. When interpreting in consecutive the interpreter, today still, listens to the original speech, memorises its content, usually jotting down notes as triggers for retrieval when the time comes, then gives the speech in the target language with the help of their notes. The League of Nations, established in 1920, would pursue this tradition. Salvatore de Madariaga, a member of the Secretariat who went on to head the Spanish delegation in the 1930s, wrote about the various abilities required of interpreters depending on the setting: Interpreting at the Assembly meant memorising an entire speech to render it in the other languages (without taking notes, for some); In committees, those more adept at handling shorter speeches and "swift repartee" shone; And the Council demanded "tact and political acumen" (Madariaga, 1974, p. 58, as cited in Delisle & Woodsworth, 2012, p. 251).

Simultaneous interpreting (SI) made its first appearances between the two World Wars, first in the shape of *whispering* (or *chuchotage*), where interpreters would provide a continuous rendition of the ongoing speech for the benefit of a few individuals, sitting near them and speaking softly so as to hear the speaker. The International Labour Organisation, founded in 1919 at the Paris Peace Conference, first used a device for simultaneous interpreting at its 1925 and 1926[61] Conferences (ILC) on a few specific occasions. That first device, the Filene-Finlay Speech Translator, was a handheld microphone also dubbed *hushaphone* (after the telephone accessory used, invented some years prior: see Flerov, 2013) and nicknamed by interpreters *Bidule* (meaning the "thing", in French) or *Spitoon* (Roland, 1999). Nowadays,

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[61] There seems to be some confusion regarding the various technical trials during the 1925, 1926 and 1927 Conferences, hence the varying dates of birth of the modality recorded in institutional and corporate archives, and diverse interpreting history books and articles.

Bidule still refers to the interpreting modality and technical material used when simultaneous interpreting is performed in the absence of interpreting booths, in the form of half-whispered interpretation into a microphone. The first SI trials involved the interpreters sight-translating in real time a verbatim transcript produced by a typist, which was in effect feasible only between syntactically close languages (Baigorri-Jalón, 2004). That first application of the Filene-Finlay Speech Translator was found wanting; it was somewhat improved in 1927 (IBM, n.d.), and reused for direct interpretation of speeches at the subsequent Conferences (Baigorri-Jalón, 2004; Roland, 1999) with headsets for delegates. The system was then adopted by the League of Nations in 1931 (IBM, n.d.) to save time, as consecutive interpreting, by definition, multiplied the length of Assembly speeches. Gaiba (1998), however, reports that the system adopted was more a form of *simultaneous successive* interpretation, with interpreters working from their notes into the various target languages at the same time (or some interpreting simultaneously from their colleague). Other forms of SI equipment are also reported to have been used in the Soviet Union for the first time in 1928, and in Berlin in 1930 (for a review see Flerov, 2013). The new simultaneous process was a great source of stress for interpreters, who were not trained in the technique on those first occasions (some training was put in place in 1927-28; see Baigorri-Jalón, 2004, for a detailed account), and the final product was less than optimal (Roland, 1999). Numerous guidelines, regarding inter alia advance access to speeches, had to be put in place in order to allow interpreters to compensate for the lack of time to reconstruct the incoming reasoning. Finlay, working as a technician on his machine, wrote in a report after the 1927 ILC, retrieved by Baigorri-Jalón (2011): “Experience has shown this work to be of a difficult and exacting nature, demanding special qualities on the part of the interpreters and particularly fatiguing owing to the degree of concentration involved” (slide 13).[62] The system was further enhanced for and after the Nuremberg Trials in 1945-46, and booth technology, including soundproofing, improved with time, as SI was adopted by the UN and its use generalised.

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[62] The report, as cited by Baigorri-Jalón, also notes that practice showed that thirty minutes was as long as interpreters could interpret at a satisfactory level before fatigue set in and performance started deteriorating. Thirty minutes is now still the prevalent duration after which interpreters alternate at the microphone, and these individual shifts are commonly referred to as “half-hours” regardless of their actual duration (e.g., 20 minutes).

C. Detailed preliminary t-test tables

Table C1

Comparison of outcome variables between the 2-back and beep count baselines and DT1

DV	Baseline		DT1		CI (95%)	*t*	*(df)*	*W*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*						
2-back Accuracy	95.87	3.63	76.32	12.05	16.46 – 22.52	12.87	(58)	1653	<0.001	1.99
2-back RT (ms)	695.09	238.14	970.96	289.33	-360.15 – -194.52	6.70	(58)	161	<0.001	-1.04
Beep count	98.51	4.96	86.45	10.46	09.40 – 15.06	8.66	(59)	1606	<0.001	1.47

Note. Results of two-tailed tests. Test statistics are indicated for both paired-samples t-tests and dependent 2-group Wilcoxon signed-rank tests as the mean differences were normally distributed only for the comparison of the 2-back RT.

Table C2

Comparison of outcome variables between the 2-back and beep count baselines and DT2

DV	Baseline		DT2		CI	*t*	*(df)*	*W*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*						
2-back Accuracy	95.9	3.6	79.48	09.98	13.85 – 18.82	13.15	(62)	1997	<0.001	2.03
2-back RT (ms)	695.09	238.14	911.13	253.64	-281.20 – -153.53	-6.81	(62)	134	<0.001	-0.87
Beep count	98.51	4.96	91.19	07.61	5.29 – 9.30	7.25	(65)	1764	<0.001	1.12

Note. Results of two-tailed tests. Test statistics are indicated for both paired-samples t-tests and dependent 2-group Wilcoxon signed-rank tests as the mean differences were normally distributed only for the comparison of 2-back accuracy for these tasks.

Table C3

Comparison of outcome variables between the last single 2-back iteration and DT2

DV	2-back rep5		DT2		CI	*t*	*(df)*	*W*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*						
2-back Accuracy	96.34	4.20	79.48	09.98	14.24 – 19.41	13.01	(64)	2067	<0.001	2.14
2-back RT (ms)	666.88	221.33	911.13	253.64	-304.01– -185.50	-8.25	(64)	102	<0.001	-1.02

Note. Results of two-tailed tests. Test statistics are indicated for both paired-samples t-tests and dependent 2-group Wilcoxon signed-rank tests as the mean differences were normally distributed only for the comparison of 2-back accuracy.

Table C4

Comparison of outcome variables between DT1 and DT2

DV	DT1		DT2		CI	*T*	*(df)*	*W*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*						
2-back Accuracy	76.32	12.05	79.48	09.98	-06.85 – -01.27	-2.91	(58)	327.5	0.005	-0.36
2-back RT (ms)	970.96	289.33	911.13	253.64	-3.09 – 122.04	1.90	(58)	1131	0.062	0.22
Beep count	86.45	10.46	91.19	07.61	-07.25 – -02.01	-3.54	(58)	419.5	0.001	-0.51

Note. Results of two-tailed tests. Test statistics are indicated for both paired-samples t-tests and dependent 2-group Wilcoxon signed-rank tests. The mean differences were normally distributed only for the comparison of 2-back and RT accuracy for these tasks.

Table C5.

Comparison of the beep count between the baseline and key press conditions

DV	Baseline		Beeps_key		CI	*t*	*(df)*	*W*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*						
Beep count	98.51	4.96	97.25	07.43	-0.09 – 0.34	1.17	(58)	156	n.s.	0.20

Note. Results of two-tailed tests. Test statistics are indicated for both the paired-samples t-test and dependent 2-group Wilcoxon signed-rank test as the data was not normally distributed.

Table C6.

Comparisons of the beep count in the baseline and key press condition between the participants who performed the baseline beep count task first and those who did not.

	Bas. before		Bas. after		CI	*t*	*(df)*	*U*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*						
Baseline Beep count	97.66	6.77	99.29	2.14	-4.16 – 0.91	-1.20	(36)	516	n.s.	-0.33
Key-press Beep count	98.68	3.36	95.97	9.59	-7.84 – 6.2	1.56	(43)	612.5	n.s.	0.37

Note. Results of two-tailed tests. Test statistics are indicated for both Welsh and Mann-Whitney tests as the data was not normally distributed.

D. Overview of the fitted models

Below is an overview of the models that were fitted on the data for the present study. Models were fitted iteratively in order to account for the "tipping point" when adding effects no longer explains variance in the data and bears the risk of mistaking noise for information.

RI: random intercept; RS: random slope. Ctrl: Controls; Cond: Conductors; Int: Interpreters.
DT1: dual task 1; DT2: dual task 2; bs: baseline. BK : beep + key press task.

A RI by subject is entered for all (G)LMMs.

Dependent variable	Model description	Effects
2-back accuracy (7.2.3.1)	**Iterations: Baseline-DT1-DT2** ***(RS not supported)***	
	ACC0: null model glmer(ACCx ~1 + (1|Subject), data = 2b_bsd1d2, family = binomial(link = "logit"))	
	ACC1: iteration only ACC2: group only ACC3: group + iteration ("reduced model")	ACC3: best fit, likely sufficient Effects: DT1-, DT2-. (iteration only)
	ACC4: group * iteration (developed in text)	ACC4: second best fit, same effects: DT1-, DT2-. (iteration only)
	Iterations: All 2-back (DT1, DT2, baseline, reps1-5) ***(RS not supported)***	
	ACC0i null model glmer(ACCx ~ 1 + (1 | Subject), data = 2b_all, family = binomial(link = "logit"))	
	ACC3i: group + iteration (developed in text).	ACC3i: Effect of iteration only.
	ACC4i -> group *iteration	ACC4i: singular, probably overparametrised)
	All 2-back, IV condition ***(RI Subject + RI Iteration)***	
	ACC3c: group + condition	ACC3c Best fit. Effect: condition.
	ACC4c: group*condition	ACC4c: Effects: condition, cond +, cond:dual - (but removing outlying residuals removes effect)

	All 2-back, IV condition *(RI Subject only)*	
	ACC3c’: group + condition	ACC3c’: best fit Effect: condition only
2-back RT (7.2.3.2) DV: logRT	**Iterations : bs, DT1, DT2** ***RS Condition***	
	RT0 null model lmer(logRT ~ 1 + (1+Condition|Subject), data = 2b_bsd1d2, REML = FALSE)	
	RT1: iteration	RT1: best fit. Effects: DT1+, DT2+
	RT2: group	
	RT3: group + iteration	
	RT4: group * iteration	RT4: Effects: DT1+, DT2 +
	Iterations : bs, DT1, DT2 ***RI Subject only*** (assuming constant effect of condition) for comparison of model fit	
	RT 4’: group * iteration	RT4’: best fit of the RI models. Effects: Iteration + DT1/cond. and DT1/int, but RS better fit (group effect possibly Type 1 error, with a lot of individual variation)
	Iterations: all 2-back, *RS Condition*	
	RT0i null model lmer(logRT ~ 1 + (1+Condition|Subject), data = 2b_all, REML = FALSE)	
	RT1i: iteration	
	RT2i: group	
	RT3i: group + iteration	
	RT4i: group * iteration	RT4i: best fit Effects: DT1, DT2, Int rep2, 4, 5
	Iterations: all 2-back, *RI Subject only* (assuming constant effect of condition) for comparison of model fit	
	RT4i’: group * iteration	RT4i’: still bet fit: Effects DT1, DT2, Int rep2,4,5 + DT1 int & cond (faster) BUT not as good a fit as RT4i (Effects possibly too weak)
	Iterations: All 2-back, IV Condition, ***RI subject + RI Iteration***	

	RT4c: group * condition	RT4c: Effects: dual +, cond*dual -
	INT baseline to test H2c.	
	Iterations : bs, DT1, DT2 ***RS Iteration*** better fit than condition.	
	RT4_I: group * iteration	RT4_I: cond, DT1, DT2, ctr DT1 (slower)
	(comparison RT4_C for estimate diff.)	cond: - multitasking cost (estimate diff only, n.s. effects)
	Iterations : DT1, DT2, baseline **DT1 as baseline** (fit- : useful to see differences in DT performance)	
	RT4dual	RT4dual: DT1 no adv cond, int faster. Ctrl faster DT2 vs DT1 and vs other groups
	Iterations: All 2-back, *RS Condition*	
	RT4i_I: group * iteration	RT4i_I: Int faster than 2b_baseline in rep2,3,4,5; faster than other groups in rep2, rep 5 and ctrl in rep4. Effect DT1, DT2 general only. (cond tendentially faster DT1).
Post-error slowing (7.2.4) (RT in ms)	Pre/post error data only. Models use RT in ms (same pattern as logRT. However, in more complex models more effects appear with logRT)	
	Incremental addition of effects and interactions to RT models.	
	Iterations : bs, DT1, DT2 ***No RS supported***	
	PES1: Position only PES2: Position + Iteration	no effect of Position, only DT1 and DT2 on RT generally
	Iterations: All 2-back (more obs.) ***RI Subject + Iteration***	
	PES1i: + Position only, PES2i Position + Iteration	PES1i: Effect "post" PES2i: Effect "post", rep4, dt1, dt2
	PES3i Position * Iteration	PES3i: No effect "post", only dt1 dt2 overall.
	Iterations: All 2-back Error Type added: random effects beyond ***RI by Subject*** not supported.	

	PES4i_o = PES2i + error type (baseline error type = omission)	PES4i-o: effect rep4, dt1, dt2 overall; “Post” faster against very high RT baseline (rt pre-o), Error: pre (items pre error faster) than pre-o) Error: post (slowing vs post-o)
	Baseline error type set to “error” to check pre-error RT	
	PES5i = PES1i + error type	PES51: Effect position (PES), omissions (slower RT pre-o), + post-o (faster)
	PES4i = PES2i + error type: iteration + position*error type only	PES4i: Best fit Effects: position (slower post-error), omissions (slower pre-o), + post-o (faster), + slower pre-error RT in rep4, DT1, DT2
	PES6i (full): Position*errtype*iteration	PES6i: Only sig. effects DT1 DT2 against baseline (little PES DT1, neg in DT2)
	Group added: only ***RI subject*** supported	
	PES7i: iteration + group + position	PES7: DT1, DT2 only (post” almost)
	PES8i: iteration + group* position	PES8: Sig. effects idem
	PES9i: iteration * group * position	PES9: sig. effects idem
	PES10: iteration * group * position * error type	PES10: - good fit -> dt1 dt2 only + control:rep4 (slow, they responsible for slower rep4))
	Iterations: All 2-back, IV Condition Fixed effect condition (+ ***RI Subject***, no RS supported)	
	PES3c: position * condition only	PES3c: Post ++ across the board Pre dual ++, post – (n.s.)
	PES6c: position * condition * errtype	PES6c: best fit Eff post (errors, against single) + Pre-o + (post-o -, ns) Dual: + (pre-error). No dual:post, (-) pre-o +, post-o -
	PES7c: condition + group + position. PES8c: condition + group * position)	PES7c, 8c, 9c: “dual” only
	INT baseline	
	PES9c: condition * group * position baseline INT	PES9c: Effects: “dual”, “post” (against pre-err RT int). No effects group, no effects condition*position (=PES in dual) (neg.

		in INT, + in other groups)
	PES10c condition * group * position * error type	PES10c: good fit Effects: “post” +, “dual” +, dual:omission + (RT pre-omission). No effects post:dual (-), post:dual:omission (-). Position sig. only with interpreters as baseline
	Same models refitted with DT1(i) or dual(c) as baseline to account for perf during dual tasks	Effects : PES + generally (ctrl as baseline)
	PES6_d Iteration * position * errtype	PES6_d: Effects: Post: +. Pre-o: +. Post-o: -. Pre-o dt2: -; post-o DT2 n.s. (- but high SD). Single: -
	PES6c_d condition * position * errtype	PES6c_d: Effects: Post +, pre-o +, single -, post-o -, post:single (+, n.s.), pre-o single -, post-o single +
	PES10_d iteration * position* errtype * group	PES10_d: Effects: Bs + Rep1,2,3,5. “Post” only vs baseline (DT1) (smaller in DT2). All else n.s.
	(group baseline comparisons) Interpreters: _I Conductors:_C	PES10_d_I : same but rep4 too and no effect position (vs baseline dt1). PES10_d_C: diff only 2b_bs, rep2, rep5; pre-o + in DT2; no other effect
	PES10c_d c condition * position * errtype * group	PES10c_d: Post: +, RT pre-o: +, RT post-o: -. Single: -, single pre-o: -.
	(group baseline comparisons)	PES10c_d_I: same except “post” (no PES in dual) PES10c_d_C same except “post” and single pre-o.
Beep count (7.3.2)	**Iterations: bs, DT1, DT2** ***RI Subject and Iteration – no RS supported***	
	B0: null model lmer(BACCx ~ 1 + (1|Subject), data = data1obsBeeps, REML = FALSE)	
	B1: + iteration only	B1: Effects: DT1, DT2
	B2: + group only	Singular
	B3: group + iteration	B3: Effects: DT1, DT2
	B4: group*iteration	B4: Effects: DT1, DT2
	Cond baseline to test H3b	Better fit.

	B4_C: group*iteration **IV Condition** ***RI Subject and Iteration – RS Iteration*** B4c_C: group*condition	B4_C: Same effects, DT1 and DT2 only. Best fit among full models, but no improvement over B1 (B1_C). Effects: Condition only
Beep count: Beeps and key presses (7.3.3)	**Iterations: bs, BK *(no RS supported)*** Bkey1: group*interaction Bkey2: + task order **Iterations: All beep tasks (bs, BK, DT1, DT2) *(no RS)*** (Bkey1_all): group* iteration	Bkey 1: Best fit. Effects: Iteration (bk -), BK cond +, BK int + Bkey2: Same effects, BK cond n.s. Bkey1_all: Effects: DT1 & 2 only
RT: Global processing speed (RT 2-back / beep + key press task) (7.3.3)	**Iterations: bs(2-back), DT1, DT2 + BK** 1: Group*iteration ***(no RS)*** 2: Group*iteration with ***RS Iteration***	Effects: DT1, DT2, but also BK vs 2-back tasks Int faster DT1, DT2 (no group effect with RS by iteration)
RT: Control variables (CV)	Control variables added incrementally to the RT models.	(Effects unchanged overall and in other iterations with or without BK)
RT (logRT) CV: Age (7.4.1.1)	**Iterations: bs, DT1, DT2** RT3_age: group +iteration +age RT4_age: group*iteration*age (table in text) ***RS Condition*** RT4_age_rs: group*iteration*age **Iterations: bs, DT1, DT2 + BK** (RT1_Bkey_age) iteration * age (RT3_Bkey_age): group +iteration +age (RT3_Bkey_age’): group +iteration *age RT4_Bkey_age: group*iteration*age	Age worsens the fit. RT3_age: Effects: DT1, DT2 only. RT4_age: Effects: DT1, DT2, Age (+: slower), Cond:DT2 (-), Cond:DT2:age (+). RT4_age_rs: no effects at all. RT1_Bkey_age: Effects: DT1, DT2 only RT3_Bkey_age, RT3_Bkey_age’: Effects: DT1, DT2 only RT4_Bkey_age: Effects: DT1 DT2 (not with age); Age (against baseline) and age*bkey (faster). Cond (faster) in dt2 (trend dt1). Cond*age slower dt2.

	Iterations: All 2-back +BK ***(No RS sup.)*** RT4i_age: group*iteration*age	RT4i_age: Improves the fit (non-RS) Effects: age (small); Age + dt2 (faster) Age + bk (faster); Cond + dt1, dt2 faster (slowing with age dt2), faster with age in rep2, slower in rep4 interpreters faster in rep3, rep4 and rep5 (with age slower).
RT (logRT) CV: Gender (7.4.1.2)	RT4i_gender: group*iteration*gender	Cond dt1,2 bk slower f (but few obs and poor fit)
RT (logRT) CV: Bilingualism (7.4.1.3)	**Iterations: bs, DT1, DT2 (+BK)** RT4i_bil: group*iteration*bilingualism **Iterations: all 2-back + BK**	bil models: poor fit overall RT4i_bil: Effects: with bil: int, cond faster and ctrl slower in DT1, DT2. Int, cond slower by comparison to ctrl in DT2 once bil controlled for. No effect of bilingualism
RT (logRT) CV: Musicianship (7.4.1.4)	**Iterations: bs, DT1, DT2 (+BK)** ***RS Iteration*** RT3_mus: (group+iteration+musicianship **Iterations: all 2-back + BK** RT4i_mus: group*iteration*musicianship	best fit among models bs-DT1-DT2 Effects: Cond (slower), DT1, DT2, Musicianship (faster overall) RT4i_mus: improves the fit of RT4i Effects: Mus (faster) in bs, rep3, 4, 5, BK; int slower in BK with mus; cond + int faster in DT1 overall
RT (logRT) CV: Non-verbal IQ (7.4.1.5)	**Iterations: bs, DT1, DT2 (+BK)** **Iterations: all 2-back + BK** RT4i_NVIQ: group*iteration*NVIQ	Bs-DT1-DT2: NVIQ worsens the fit Best fit among full models with all iterations (RT4i) Effects: DT1, DT2, Rep3, BK (slower); Cond slower in bs, faster DT1, DT2, BK; int faster DT1, DT2, rep3; NVIQ slowing overall in bs but faster DT1, DT2, BK (in ctrl), i.e. ctrl slow but faster with NVIQ Int faster in bs, slower in DT1, DT2, rep3 with NVIQ Cond slower in DT1, DT2, BK with NVIQ.

RT (logRT) All control variables (7.4.1.6)	**Iterations: all 2-back (+ or - BK)** **Iterations: bs, DT1, DT2 (+ or - BK)** Simple model: ***(RI Subject, RS Iteration)*** group + iteration + age + gender + bil + mus + NVIQ Full model with interactions (***no RS***): Iterative fitting for best additional variable respectively: Iteration -> group -> IQ (over Age as 2nd best fit) -> Mus (best fit) -> Age. Max. model: iteration * group * iq *mus, * age	all effects not supported together Best explanatory power: Age + NVIQ Better fit over model with interactions and over model with only group + iteration. Effects: mus (against baseline); Cond slower (= mus explains faster ones); Iteration (slower dt2 dt2 bk, faster reps 2, 3, 4, 5) Int faster DT1. Age faster DT1 (int -) Mus faster DT1 (int -) int faster with mus sauf DT1 (-) int slower with NVIQ esp. DT1 NVIQ faster overall (= in controls) Int faster with NVIQ + mus + age
Multitasking: 2-back + beep-count accuracy (7.4.2)	Multiple multivariate models (interactions between all terms and Group only, max. structure supported) 1. Including Proc speed ("Fast" true/false) 2. Adding PES true/false by iteration 3. Adding beep count split: beep+ ("bestgm") true/false 4. 2-back acc split: 2b+ ("best2b") yes/no 5. Complete model 1'-5'. Same models centered	1. Fast -> 2b+ in all groups in DT1, int and cond in DT2; Fast -> Beep+ for int in DT2. 2. PES -> 2b+ int and cond, 2b- ctrl; PES -> beep+ ctrl, (ns int), beep- cond DT1; beep- ctrl, beep+ int and cond in DT2 3. DT1, DT2 Ctrl beep+ -> 2b+; Cond DT1 only; DT1, DT2 Int beep+ -> 2b- 4. Ctrl DT1 2b+ -> beep-, DT2 2b+ -> beep+. Cond, int DT2 2b+ -> beep-. (DT1 cond +, int-, n.s.). (table included in results for complete picture) 1'-5': most effects disappear

E. Multiple multivariate regression analyses: Univariate effects

Table D1. Full model: Response 2-back accuracy

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
(Intercept)	0.641	0.027	23.534	<0.001***
TestGroupConductor	-0.275	0.043	-6.470	<0.001***
TestGroupInterpreter	0.059	0.034	1.724	0.084.
Iteration2b_dual2	-0.008	0.005	-1.519	0.129
Age	0.004	0.000	19.648	<0.001***
GenderM	0.002	0.004	0.516	0.605757
BilCoef	-0.001	0.000	-8.597	<0.001***
Musicianship	0.000	0.000	-3.592	<0.001***
Standardised	-0.001	0.000	-2.940	<0.001***
FastTRUE	0.027	0.005	5.526	<0.001***
mPES_I	0.000	0.000	-15.485	<0.001***
GMbestTRUE	-0.001	0.005	-0.191	0.848
Best2bTRUE	0.136	0.005	30.184	<0.001***
TestGroupConductor:Iteration2b_dual2	0.086	0.007	12.454	<0.001***
TestGroupInterpreter:Iteration2b_dual2	0.007	0.008	0.899	0.368
TestGroupConductor:Age	-0.003	0.000	-15.435	<0.001***
TestGroupInterpreter:Age	-0.004	0.000	-17.198	<0.001***
TestGroupConductor:GenderM	-0.031	0.006	-5.190	<0.001***
TestGroupInterpreter:GenderM	0.005	0.006	0.940	0.347
TestGroupConductor:BilCoef	0.001	0.000	12.836	<0.001***
TestGroupInterpreter:BilCoef	0.001	0.000	17.003	<0.001***
TestGroupConductor:Musicianship	0.001	0.000	9.293	<0.001***
TestGroupInterpreter:Musicianship	0.000	0.000	2.539	0.011*
TestGroupConductor:Standardised	0.002	0.000	6.488	<0.001***
TestGroupInterpreter:Standardised	0.000	0.000	0.147	0.883
TestGroupConductor:FastTRUE	0.045	0.006	7.129	<0.001***
TestGroupInterpreter:FastTRUE	-0.003	0.006	-0.547	0.584
Iteration2b_dual2:FastTRUE	0.029	0.006	4.695	<0.001***
TestGroupConductor:mPES_I	0.000	0.000	-0.399	0.690
TestGroupInterpreter:mPES_I	0.000	0.000	0.667	0.505
Iteration2b_dual2:mPES_I	0.000	0.000	6.801	<0.001***
TestGroupConductor:GMbestTRUE	0.038	0.006	5.831	<0.001***
TestGroupInterpreter:GMbestTRUE	-0.003	0.006	-0.547	0.584
Iteration2b_dual2:GMbestTRUE	0.067	0.007	10.199	<0.001***
TestGroupConductor:Best2bTRUE	0.003	0.007	0.418	0.676
TestGroupInterpreter:Best2bTRUE	0.020	0.006	3.198	0.001**
Iteration2b_dual2:Best2bTRUE	-0.047	0.007	-6.848	<0.001***
TGroupConductor:It2b_dual2:FastTRUE	-0.151	0.009	-17.292	<0.001***
TGroupInterpreter:I2b_dual2:FastTRUE	0.027	0.008	3.240	0.001*
TGroupConductor:It2b_dual2:mPES_I	0.000	0.000	0.893	0.372
TGroupInterpreter:It2b_dual2:mPES_I	0.000	0.000	6.050	<0.001***
TGroupConductor:Itb_dual2:GMbestTRUE	-0.053	0.009	-5.948	<0.001***
TGroupInterpreter:It2b_dual2:GMbestTRU	-0.072	0.009	-8.324	<0.001***
TGroupConductor:It2b_dual2:Best2bTRUE	0.066	0.010	6.925	<0.001***
TGroupInterpreter:It2b_dual2:Best2bTRUE	0.016	0.009	1.839	0.066.

Residual se: 0.05557 on 5907 df (21199 observations deleted due to missingness). Multiple R-squared: 0.74, Adjusted R-squared: 0.738. F-statistic: 382 on 44 and 5907 df, p < 0.001

Table D2. Ful model: Response Beep count

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
(Intercept)	1.040	0.034	30.871	<0.001***
TestGroupConductor	-0.752	0.053	-14.307	<0.001***
TestGroupInterpreter	-0.281	0.042	-6.686	<0.001***
Iteration2b_dual2	0.027	0.006	4.249	<0.001***
Age	0.000	0.000	-1.522	0.128
GenderM	0.021	0.005	3.793	<0.001***
BilCoef	0.000	0.000	-4.208	<0.001***
Musicianship	0.000	0.000	3.281	0.001**
Standardised	-0.002	0.000	-5.184	<0.001***
FastTRUE	-0.029	0.006	-4.843	<0.001***
mPES_I	0.000	0.000	-5.586	<0.001***
GMbestTRUE	0.126	0.006	22.080	<0.001***
Best2bTRUE	-0.022	0.006	-3.911	<0.001***
TestGroupConductor:Iteration2b_dual2	0.040	0.009	4.717	<0.001***
TestGroupInterpreter:Iteration2b_dual2	0.065	0.009	7.029	<0.001***
TestGroupConductor:Age	0.001	0.000	1.921	0.055.
TestGroupInterpreter:Age	0.000	0.000	-1.769	0.077.
TestGroupConductor:GenderM	-0.011	0.007	-1.473	0.141
TestGroupInterpreter:GenderM	-0.011	0.007	-1.628	0.104
TestGroupConductor:BilCoef	0.000	0.000	1.511	0.131
TestGroupInterpreter:BilCoef	0.001	0.000	5.671	<0.001***
TestGroupConductor:Musicianship	0.002	0.000	9.092	<0.001***
TestGroupInterpreter:Musicianship	-0.001	0.000	-9.576	<0.001***
TestGroupConductor:Standardised	0.005	0.000	11.707	<0.001***
TestGroupInterpreter:Standardised	0.002	0.000	4.834	<0.001***
TestGroupConductor:FastTRUE	0.025	0.008	3.173	0.002**
TestGroupInterpreter:FastTRUE	0.097	0.008	12.403	<0.001***
Iteration2b_dual2:FastTRUE	-0.007	0.008	-0.888	0.375
TestGroupConductor:mPES_I	0.000	0.000	4.469	<0.001***
TestGroupInterpreter:mPES_I	0.000	0.000	0.492	0.623
Iteration2b_dual2:mPES_I	0.000	0.000	5.875	<0.001***
TestGroupConductor:GMbestTRUE	0.018	0.008	2.281	0.023*
TestGroupInterpreter:GMbestTRUE	0.057	0.008	7.223	<0.001***
Iteration2b_dual2:GMbestTRUE	-0.075	0.008	-9.311	<0.001***
TestGroupConductor:Best2bTRUE	0.007	0.008	0.860	0.390
TestGroupInterpreter:Best2bTRUE	-0.012	0.008	-1.512	0.131
Iteration2b_dual2:Best2bTRUE	0.083	0.008	9.828	<0.001***
TGroupConductor:It2b_dual2:FastTRUE	-0.018	0.011	-1.638	0.101
TGroupInterpreter:It2b_dual2:FastTRUE	-0.051	0.010	-5.007	<0.001***
TGroupConductor:It2b_dual2:mPES_I	0.000	0.000	-4.133	<0.001***
TGroupInterpreter:It2b_dual2:mPES_I	0.000	0.000	0.637	0.524
TGroupConductor:It2b_dual2:GMbestTRU	0.029	0.011	2.673	0.008**
TGroupInterpreter:It2b_dual2:GMbestTRU	0.019	0.011	1.809	0.070.
TGroupConductor:It2b_dual2:Best2bTRUE	-0.052	0.012	-4.427	<0.001***
TGroupInterpreter:It2b_dual2:Best2bTRUE	-0.031	0.011	-2.835	0.005**

Residual se: 0.06867 on 5907 df (21199 observations deleted due to missingness). Multiple R-squared: 0.56, Adjusted R-squared: 0.5567. F-statistic: 170.8 on 44 and 5907 DF, p < 0.001.

Formula, full model:
(mAccx, BaccClean) ~ TestGroup * Iteration + TestGroup * Age + TestGroup * Gender +
TestGroup * BilCoef + TestGroup * Musicianship + TestGroup * Standardised +
TestGroup * Fast * Iteration + TestGroup * mPES_I * Iteration +
TestGroup * GMbest * Iteration + TestGroup * Best2b * Iteration

Centered full model:

Formula:
(z_Acc, zBeep) ~ TestGroup * Iteration + TestGroup * z_Age + TestGroup * Gender +
TestGroup * z_Bil + TestGroup * z_Mus + TestGroup * z_NVIQ +
TestGroup * Fast * Iteration + TestGroup * z_PES * Iteration +
TestGroup * GMbest * Iteration + TestGroup * Best2b * Iteration

Table D3. Complete multivariate regression analysis: multivariate effects.

Variable(s)	Pillai's Trace	F	df	Error df	p-value
TestGroup	0.035	0.713	4	158	0.584
Iteration	0.006	0.245	2	78	0.783
z_Age	0.011	0.436	2	78	0.648
Gender	0.008	0.300	2	78	0.742
z_Bil	0.023	0.937	2	78	0.396
z_Mus	0.006	0.237	2	78	0.790
z_NVIQ	0.015	0.610	2	78	0.546
Fast	0.055	2.263	2	78	0.111
z_PES	0.015	0.598	2	78	0.553
GMbest	0.541	46.007	2	78	<0.001***
Best2b	0.475	35.355	2	78	<0.001***
TestGroup:Iteration	0.014	0.277	4	158	0.893
TestGroup:z_Age	0.053	1.076	4	158	0.371
TestGroup:Gender	0.011	0.216	4	158	0.929
TestGroup:z_Bil	0.052	1.051	4	158	0.383
TestGroup:z_Mus	0.078	1.605	4	158	0.176
TestGroup:z_NVIQ	0.054	1.096	4	158	0.360
TestGroup:Fast	0.083	1.721	4	158	0.148
Iteration:Fast	0.025	1.008	2	78	0.370
TestGroup:z_PES	0.010	0.208	4	158	0.934
Iteration:z_PES	0.007	0.278	2	78	0.758
TestGroup:GMbest	0.070	1.436	4	158	0.224
Iteration:GMbest	0.006	0.220	2	78	0.803
TestGroup:Best2b	0.013	0.254	4	158	0.907
Iteration:Best2b	0.065	2.699	2	78	0.074.
TestGroup:Iteration:Fast	0.078	1.595	4	158	0.178
TestGroup:Iteration:z_PES	0.033	0.667	4	158	0.616
TestGroup:Iteration:GMbest	0.027	0.546	4	158	0.702
TestGroup:Iteration:Best2b	0.015	0.293	4	158	0.882

Table D4. Response z_Acc

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*	
(Intercept)	-0.806	0.356	-2.262	0.026	*
TestGroupConductor	-0.436	0.687	-0.635	0.527	
TestGroupInterpreter	-0.028	0.496	-0.057	0.955	
Iteration2b_dual2	-0.260	0.430	-0.605	0.547	
z_Age	0.377	0.191	1.972	0.052	.
GenderM	0.062	0.365	0.170	0.865	
z_Bil	-0.162	0.178	-0.911	0.365	
z_Mus	-0.063	0.145	-0.437	0.663	
z_NVIQ	-0.027	0.214	-0.128	0.898	
FastTRUE	0.186	0.392	0.475	0.636	
z_PES	-0.007	0.158	-0.044	0.965	
GMbestTRUE	0.058	0.381	0.152	0.880	
Best2bTRUE	1.273	0.378	3.368	0.001	**
TestGroupConductor:Iteration2b_dual2	0.489	0.554	0.882	0.380	
TestGroupInterpreter:Iteration2b_dual2	-0.167	0.615	-0.272	0.786	
TestGroupConductor:z_Age	-0.331	0.223	-1.482	0.142	
TestGroupInterpreter:z_Age	-0.399	0.219	-1.821	0.072	.
TestGroupConductor:GenderM	-0.246	0.496	-0.496	0.621	
TestGroupInterpreter:GenderM	0.132	0.466	0.282	0.778	
TestGroupConductor:z_Bil	0.302	0.220	1.372	0.174	
TestGroupInterpreter:z_Bil	0.444	0.235	1.891	0.062	.
TestGroupConductor:z_Mus	0.557	0.513	1.085	0.281	
TestGroupInterpreter:z_Mus	0.111	0.221	0.500	0.618	
TestGroupConductor:z_NVIQ	0.152	0.265	0.572	0.569	
TestGroupInterpreter:z_NVIQ	-0.033	0.247	-0.135	0.893	
TestGroupConductor:FastTRUE	0.359	0.512	0.702	0.485	
TestGroupInterpreter:FastTRUE	0.011	0.514	0.021	0.983	
Iteration2b_dual2:FastTRUE	0.233	0.511	0.456	0.650	
TestGroupConductor:z_PES	-0.252	0.268	-0.939	0.351	
TestGroupInterpreter:z_PES	-0.158	0.234	-0.673	0.503	
Iteration2b_dual2:z_PES	-0.144	0.221	-0.652	0.516	
TestGroupConductor:GMbestTRUE	0.110	0.522	0.211	0.833	
TestGroupInterpreter:GMbestTRUE	0.057	0.503	0.113	0.911	
Iteration2b_dual2:GMbestTRUE	0.458	0.527	0.869	0.387	
TestGroupConductor:Best2bTRUE	-0.167	0.568	-0.295	0.769	
TestGroupInterpreter:Best2bTRUE	-0.026	0.511	-0.051	0.959	
Iteration2b_dual2:Best2bTRUE	-0.238	0.558	-0.426	0.671	
TestGroupConductor:Iteration2b_dual2:FastTRUE	-1.288	0.724	-1.780	0.079	.
TestGroupInterpreter:Iteration2b_dual2:FastTRUE	0.418	0.693	0.604	0.548	
TestGroupConductor:Iteration2b_dual2:z_PES	0.377	0.331	1.139	0.258	
TestGroupInterpreter:Iteration2b_dual2:z_PES	0.478	0.352	1.357	0.179	
TestGroupConductor:Iteration2b_dual2:GMbestTRUE	-0.173	0.709	-0.243	0.808	
TestGroupInterpreter:Iteration2b_dual2:GMbestTRUE	-0.696	0.684	-1.017	0.312	
TestGroupConductor:Iteration2b_dual2:Best2bTRUE	0.694	0.779	0.892	0.375	
TestGroupInterpreter:Iteration2b_dual2:Best2bTRUE	0.255	0.717	0.356	0.723	

Residual standard error: 0.6489 on 79 degrees of freedom (10 observations deleted due to missingness)

Multiple R-squared: 0.7172, Adjusted R-squared: 0.5597. F-statistic: 4.553 on 44 and 79 DF, $p < 0.001$.

Table D5. Response z_Beep

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*	
(Intercept)	-0.300	0.366	-0.819	0.415	
TestGroupConductor	-1.015	0.705	-1.439	0.154	
TestGroupInterpreter	-1.273	0.509	-2.501	0.014	*
Iteration2b_dual2	-0.208	0.441	-0.472	0.638	
z_Age	-0.113	0.196	-0.575	0.567	
GenderM	0.050	0.374	0.134	0.894	
z_Bil	-0.105	0.182	-0.577	0.566	
z_Mus	0.059	0.148	0.395	0.694	
z_NVIQ	-0.138	0.219	-0.628	0.532	
FastTRUE	-0.262	0.402	-0.652	0.516	
z_PES	0.012	0.162	0.076	0.940	
GMbestTRUE	1.192	0.391	3.048	0.003	**
Best2bTRUE	-0.110	0.388	-0.283	0.778	
TestGroupConductor:Iteration2b_dual2	0.110	0.569	0.194	0.846	
TestGroupInterpreter:Iteration2b_dual2	0.179	0.631	0.283	0.778	
TestGroupConductor:z_Age	0.175	0.229	0.765	0.447	
TestGroupInterpreter:z_Age	0.044	0.225	0.194	0.847	
TestGroupConductor:GenderM	0.062	0.509	0.123	0.903	
TestGroupInterpreter:GenderM	0.185	0.478	0.386	0.701	
TestGroupConductor:z_Bil	0.033	0.226	0.146	0.884	
TestGroupInterpreter:z_Bil	0.191	0.241	0.791	0.431	
TestGroupConductor:z_Mus	0.608	0.527	1.154	0.252	
TestGroupInterpreter:z_Mus	-0.396	0.227	-1.748	0.084	.
TestGroupConductor:z_NVIQ	0.482	0.272	1.775	0.080	.
TestGroupInterpreter:z_NVIQ	0.166	0.254	0.655	0.514	
TestGroupConductor:FastTRUE	0.264	0.525	0.504	0.616	
TestGroupInterpreter:FastTRUE	0.987	0.528	1.871	0.065	.
Iteration2b_dual2:FastTRUE	-0.276	0.524	-0.526	0.600	
TestGroupConductor:z_PES	-0.014	0.275	-0.051	0.960	
TestGroupInterpreter:z_PES	0.005	0.241	0.021	0.983	
Iteration2b_dual2:z_PES	-0.127	0.227	-0.559	0.577	
TestGroupConductor:GMbestTRUE	0.268	0.536	0.500	0.619	
TestGroupInterpreter:GMbestTRUE	0.658	0.516	1.275	0.206	
Iteration2b_dual2:GMbestTRUE	-0.554	0.541	-1.024	0.309	
TestGroupConductor:Best2bTRUE	-0.189	0.582	-0.325	0.746	
TestGroupInterpreter:Best2bTRUE	-0.161	0.524	-0.307	0.760	
Iteration2b_dual2:Best2bTRUE	0.970	0.573	1.693	0.094	.
TestGroupConductor:Iteration2b_dual2:FastTRUE	-0.120	0.743	-0.162	0.872	
TestGroupInterpreter:Iteration2b_dual2:FastTRUE	-0.283	0.711	-0.398	0.692	
TestGroupConductor:Iteration2b_dual2:z_PES	0.239	0.339	0.704	0.484	
TestGroupInterpreter:Iteration2b_dual2:z_PES	0.221	0.361	0.611	0.543	
TestGroupConductor:Iteration2b_dual2:GMbestTRUE	0.528	0.727	0.726	0.470	
TestGroupInterpreter:Iteration2b_dual2:GMbestTRUE	0.634	0.702	0.903	0.369	
TestGroupConductor:Iteration2b_dual2:Best2bTRUE	-0.327	0.799	-0.409	0.684	
TestGroupInterpreter:Iteration2b_dual2:Best2bTRUE	-0.394	0.736	-0.535	0.594	

Residual standard error: 0.6659 on 79 degrees of freedom (10 observations deleted due to missingness) Multiple R-squared: 0.7047, Adjusted R-squared: 0.540. F-statistic: 4.285 on 44 and 79 DF, $p < 0.001$.

F. Principal Component Analysis for DT1

The analysis was performed on 67 individuals, described by 10 variables. The variables were scaled prior to the analysis. All variables were scaled and dummy variables were created to account for conducting and simultaneous interpreting experience.

39.07% of the variances contained in the data are retained by the first two principal components.

Figure F1

Proportion of variances retained by the principal components

	Eigenvalue	*Variance (%)*	*Cumulative variance (%)*
Dim.1	2,27	22,71	22,71
Dim.2	1,64	16,35	39,07
Dim.3	1,35	13,55	52,61
Dim.4	1,20	12,05	64,66
Dim.5	1,01	10,07	74,73
Dim.6	0,71	7,07	81,80
Dim.7	0,67	6,71	88,51
Dim.8	0,52	5,21	93,72
Dim.9	0,40	4,05	97,77
Dim.10	0,22	2,23	100,00

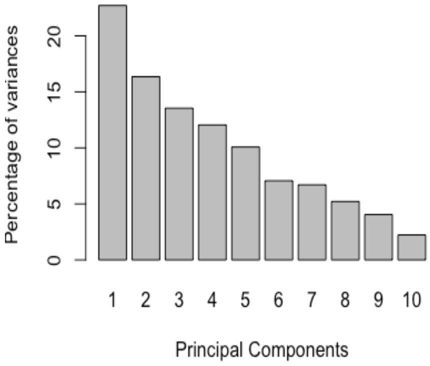


Table F1

Contribution of the variables to the respective components

	Dim.1	*Dim.2*	*Dim,3*	*Dim,4*	*Dim,5*	*Dim,6*	*Dim,7*	*Dim,8*	*Dim,9*	*Dim,10*
z_Beep	3,54	16,65	14,68	0,73	13,82	7,28	17,16	25,12	0,42	0,61
zlog_RT	1,01	0,08	0,91	66,76	0,00	0,00	8,40	8,73	14,10	0,00
z_Acc	2,22	19,91	13,01	9,17	2,66	1,23	23,82	26,59	0,06	1,32
z_Age	0,20	29,69	3,93	2,88	7,11	34,42	1,21	14,70	5,07	0,79
z_Mus	27,74	1,04	6,81	2,35	6,58	0,17	0,79	0,00	20,97	33,56
z_Bil	9,07	0,44	4,07	1,58	59,21	2,30	2,76	1,96	16,41	2,21
z_PES	1,33	24,86	6,13	4,75	3,21	43,12	0,11	15,72	0,76	0,00
z_NVIQ	0,05	0,31	46,75	4,10	0,31	8,65	33,88	1,88	0,57	3,52
z_SI	23,60	6,86	0,08	5,87	4,21	1,61	1,76	4,62	41,64	9,76
z_CONDUCTING	31,24	0,17	3,64	1,81	2,89	1,21	10,10	0,69	0,00	48,24

Note: the components used to plot the data are highlighted.

Figure F2

Contribution of the variables to the first (left) and the second dimension (right)

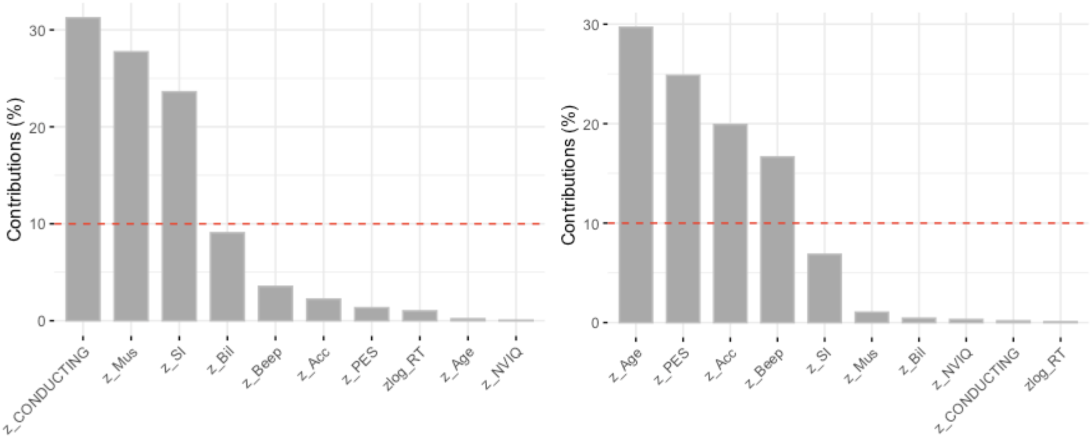


Table F2

Quality of representation (cos2) of the variables in the first two dimensions

	Dim.1	*Dim.2*
z_Beep	0,08	0,27
zlog_RT	0,02	0,00
z_Acc	0,05	0,33
z_Age	0,00	0,49
z_Mus	0,63	0,02
z_Bil	0,21	0,01
z_PES	0,03	0,41
z_NVIQ	0,00	0,00
z_SI	0,54	0,11
z_CONDUCTING	0,71	0,00

Note: the total for each variable across the 10 dimensions equals 1.

G. Recruitment procedure

Flyers targeting conductors were posted at various institutes of higher education in musical studies across New York City (e.g., Queens College, Mannes New School of Music, Juilliard, etc.) and sent by e-mail by the principal investigator to personal contacts among music professionals and conductors, some of which had volunteered to spread the word among the profession. These persons received an e-mail with the flyer and were free to forward it as they saw fit. An e-mail was also sent to the relevant contact address of conductors' associations, asking the person in charge to kindly broadcast the flyer among the members as they saw fit. A flyer targeting interpreters was e-mailed to the Chief of the Interpreting Service at the United Nations Headquarters in New York City and forwarded to staff interpreters. The flyer was also posted in the interpreters' meeting point at the United Nations in Geneva during the 2016 ILC. An e-mail was also sent to personal contacts among the profession and AIIC members with a public profile in various regions, and forwarded by a third party to teaching staff at the FTI Interpreting Department in the University of Geneva whose contact details were not known directly of the investigator. The control group was recruited at a later stage following a similar protocol. Once persons interested in participating contacted the investigator by phone or e-mail, the investigator asked them a few questions using the person's preferred means of communication to confirm that they did meet the inclusion criteria and the testing location and time was mutually agreed. Potential participants reporting inability to sit, walk or carry out prolonged cognitive tasks without discomfort were not included in the experiment. The exact purpose of the experiment was indicated in broad terms on the flyers and in communications to avoid creating an expectancy bias. The term "multitasking" was therefore not mentioned before the experiment, but replaced by the less precise formulation "attentional processes".

A consent form (see Appendix H) in a language understood by the participant (English or French) was presented prior to administering the questionnaire and the experiment, for the participant to read and sign, and time and space provided for reading, asking questions, or signalling any change of mind. Whenever possible, the consent form was sent prior to the scheduled session for information. The experiment title as indicated in the consent form was formulated in similarly broad terms as in other communication materials in order to avoid expectancy bias. Participants were informed about the exact research purpose after completing the experiment. Withdrawal from the study was possible at any time.

In the case of in-person contact, participants were only contacted through any means that they themselves had provided to that effect to the investigator or a mutually known third-party. In all cases, participant information, personal contacts, and their participation in the study remained confidential. Precautions were taken to limit necessary interactions with persons unrelated to the experiment.

Each participant's name and all identifying information collected during the testing session are confidential and locked in a file cabinet in the Cognition and Language Laboratory at the CUNY Graduate Center. The questionnaire, computerised tasks, results and data do not contain any direct identifier; instead a random numeric code comprised of 3 digits and a letter was randomly generated for each participant and only the code was reported on all forms and results. Anonymised data collected during the experiment is stored in an offline, password-protected computer, to be accessed only by the investigator.

H. Consent form

CONSENT FORM

Project Title: Attentional processes: task performance in various adult populations

Principal Investigator: Nathalie Loiseau, nloiseau@gmail.com
Advisor: Dr. Klara Marton, kmarton@gc.cuny.edu
Department of Speech-Language-Hearing Sciences, the Graduate Center of the City University of New York (CUNY).
Address: 365 Fifth Avenue, Rm. 7307, New York, NY 10016-4309
Phone: (212) 817-2712

Site where study is to be conducted: CUNY Graduate Center / Private domicile as convenient

General information: You are invited to participate in a research project. The purpose of this study is to examine the attentional processes involved in various tasks in various adult populations. The results of this study may help us to better understand the nature of individual differences in the involvement of attentional processes and the various processes which come into play.
Further specifications regarding the object of study will be provided at the end of the session and any questions you may still have at that time will be answered.

Procedure: 80 to 120 adults are expected to participate in this study. You will participate in 1 session of a duration of ca. 90 minutes. You will be seated in a quiet room, and consent will be obtained from you. First, you will answer a few simple questions about your occupation, education and previous training. Then you will perform a short non-verbal test and a computerised series of tasks.

Possible Discomforts and Risks: There are no known or expected risks or hazards in participating in this study, other than possible minor fatigue. Breaks are planned every 15 minutes, for a duration of 5 to 10 minutes.

Benefits: There are no direct benefits to you from volunteering. However, the results may help us to better understand the nature of multiple task performance in adults.

Voluntary Participation: Participation in this project is voluntary. You will be free to stop any activity or refuse to respond to any questions. You are free to withdraw at any time without penalty.

If you are a CUNY employee, your willingness to participate in this research study, or your request to withdraw from the research study, will not affect your employment with CUNY in any way.

If you are a CUNY student, your willingness to participate in this research study, or your request to withdraw from the research study, will have no effect whatsoever on your grades or academic standing with CUNY.

Compensation: For your participation in this project you will receive a token of appreciation.

Confidentiality: Your name and all identifying information will remain strictly confidential and locked in a file cabinet in the Cognition and Language Laboratory at the CUNY Graduate Center. All the data collected, will be anonymised and will be accessible only to the Principal Investigator of this project, Nathalie Loiseau, and her advisor, Dr. Klara Marton. Information collected during this project may be presented or published, but no data that could identify you will be included.

A short part of the experiment will entail audio recording. You have the right to review the recording taken as part of this research to determine whether they should be erased, in which case all the data pertaining to your participation in the study will be deleted. Audio files will not be used for any other purposes than data analysis; they will be anonymised and transformed to prevent recognition.

Contact Questions/Persons: If you have any questions about this project now or in the future, you should contact the Principal Investigator, Nathalie Loiseau, natloiseau@gmail.com, or her advisor Dr. Klara Marton, kmarton@gc.cuny.edu, phone: 212-817-2712. If you have any questions concerning your rights as a participant in this study, you may contact the CUNY Research Compliance Administrator at 646-664-8918.

Statement of Consent

"I have read the above description of this research and I understand it. I have been informed of the risks and benefits involved, and all my questions have been answered to my satisfaction. Furthermore, I have been assured that any future questions that I may have will also be answered by the principal investigator of the study. I voluntary agree to participate in this study.

By signing this form I have not waived any of my legal rights to which I would otherwise be entitled.

I will be given a copy of this statement."

______________________	____________________________	___________
Name of Participant (print)	Signature of Participant	Date Signed
______________________	____________________________	___________
Name of Investigator (print)	Signature of Investigator	Date Signed

Future Participation

With your permission, we may contact you for our future studies. If you are interested in future participation, please provide your contact information below.

Address: ____

E-mail Address: ____

Telephone Number: ____

I. Questionnaire

Thank you for taking a little time to answer the following questions:

1) Age

2) Gender

3) Current occupation

4) Number of years of experience in your current occupation or as interpreter / conductor (if applicable)

5) Frequency of occupation as interpreter / conductor over the past 5 years (if applicable), of which orchestra conducting (if applicable)

- less than once a year
- 1 to 5 times a year
- 5 to 10 times a year
- more than once a month
- more than once a week

6) Have you had formal musical training (in your life)?

No Yes: >3y >5y >10y

7) Have you been able to play an instrument or sing in an ensemble ? Y / N

7b) if so: what instrument(s) ?

8) Have you been able to sight-read music, i.e. play or sing by sight ? Y / N

9) Have you had any formal musical training / sung in a formal musical setting / played an instrument over the past: (please circle everything that applies)

5 years /4years / 3 years / 2 years /1 year

10) Frequency of musical activity as understood in Q.9 over the past 5 years

- less than once a year
- 1 to 5 times a year
- 5 to 10 times a year
- more than once a month
- more than once a week

Remarks:

11) How many years have you studied after completing high school ?

12) What is the highest degree you have obtained ?

13) Please list the disciplines you have studied at post high-school level:

14) Please list any previous formal occupation you may have had:

15) Have you played sports at advanced / professional level ? No / Yes: which ?

16) Can you drive? No / Yes: What kind of vehicle can you drive / pilot ?

Remarks:

18) In how many languages are you fluent (including your mother tongue)?

18b) What is/are your native language(s) ?

19) Have you had to translate, sight-translate or swich languages in your daily life over the past: (please circle everything that applies)

5 years /4years / 3 years / 2 years /1 year

20) Have you ever had to translate, sight-translate or swich languages in your daily life for more than

1 2 3 4 5 6 7 8 9 10 consecutive year(s)

Remarks:

20) How many children have you got?

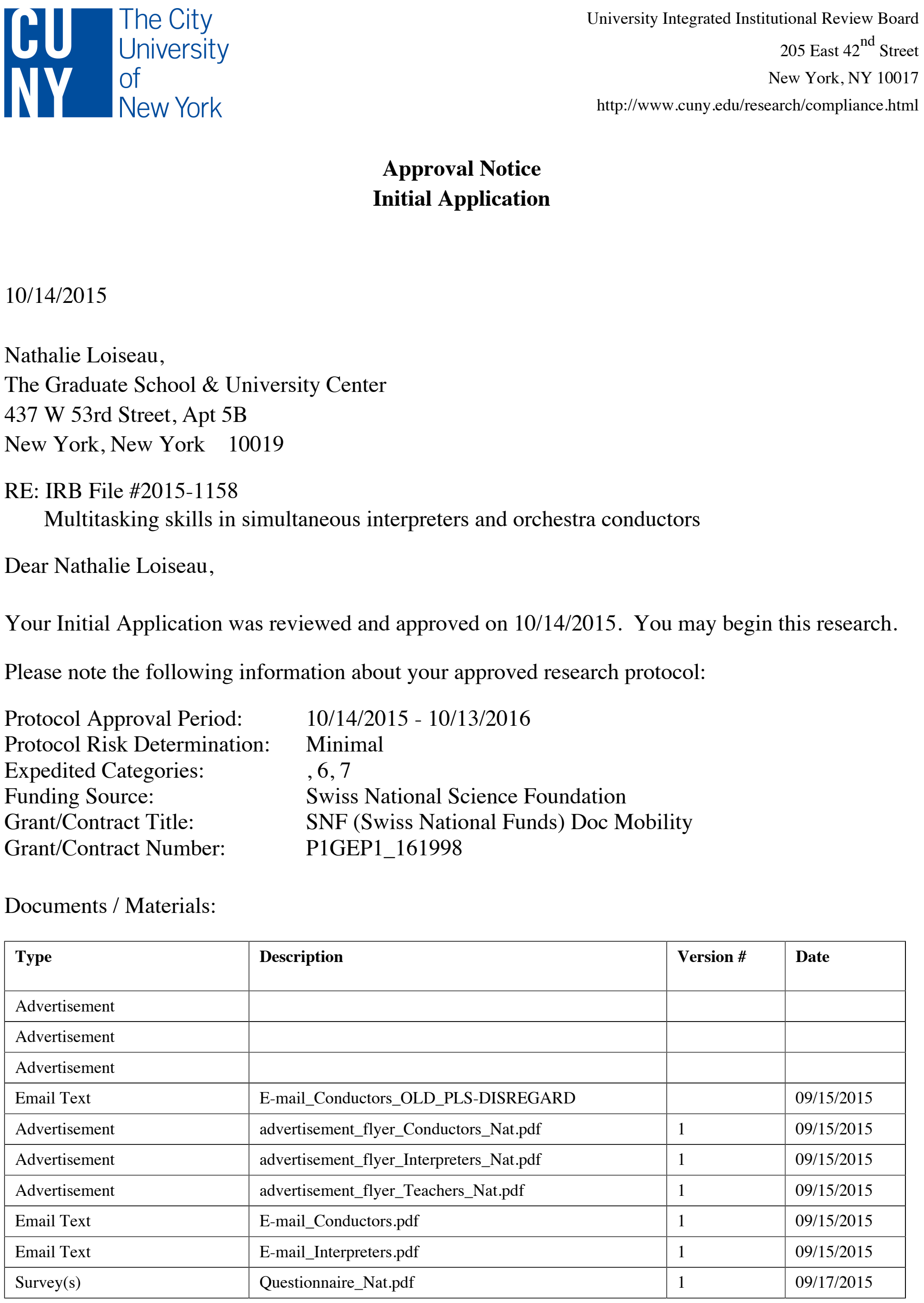
21) Please indicate the age difference(s) between your children:

- less than a year - less than 2 years - less than 3 years
- less than 4 years - less than 5 years - more than 5 years

Remarks:

THANK YOU !

J. IRB approval



The City University of New York

University Integrated Institutional Review Board
205 East 42nd Street
New York, NY 10017
http://www.cuny.edu/research/compliance.html

Approval Notice
Initial Application

10/14/2015

Nathalie Loiseau,
The Graduate School & University Center
437 W 53rd Street, Apt 5B
New York, New York 10019

RE: IRB File #2015-1158
Multitasking skills in simultaneous interpreters and orchestra conductors

Dear Nathalie Loiseau,

Your Initial Application was reviewed and approved on 10/14/2015. You may begin this research.

Please note the following information about your approved research protocol:

Protocol Approval Period:	10/14/2015 - 10/13/2016
Protocol Risk Determination:	Minimal
Expedited Categories:	, 6, 7
Funding Source:	Swiss National Science Foundation
Grant/Contract Title:	SNF (Swiss National Funds) Doc Mobility
Grant/Contract Number:	P1GEP1_161998

Documents / Materials:

Type	**Description**	**Version #**	**Date**
Advertisement			
Advertisement			
Advertisement			
Email Text	E-mail_Conductors_OLD_PLS-DISREGARD		09/15/2015
Advertisement	advertisement_flyer_Conductors_Nat.pdf	1	09/15/2015
Advertisement	advertisement_flyer_Interpreters_Nat.pdf	1	09/15/2015
Advertisement	advertisement_flyer_Teachers_Nat.pdf	1	09/15/2015
Email Text	E-mail_Conductors.pdf	1	09/15/2015
Email Text	E-mail_Interpreters.pdf	1	09/15/2015
Survey(s)	Questionnaire_Nat.pdf	1	09/17/2015

Informed Consent Document	Multitasking_consent_form_final_Nathalie.pdf	1	09/24/2015
	CITI course completion report - PI	1	10/01/2015
	CITI course completion report - Advisor	1	10/06/2015
Funding proposal/Grant application/Contract	Grant_application_Swiss-national-science-foundation	1	10/07/2015
Funding proposal/Grant application/Contract	Grant_release_Approved	1	10/07/2015
Funding proposal/Grant application/Contract	grant_application_processing_information	1	10/07/2015

Please remember to:

- Use **the IRB file number** 2015-1158 on all documents or correspondence with the IRB concerning your research protocol.

- Review and comply with CUNY Human Research Protection Program policies and procedures.

The IRB has the authority to ask additional questions, request further information, require additional revisions, and monitor the conduct of your research and the consent process.

If you have any questions, please contact:
Natalie Wright
718-951-5000 ext3829/5519
nwright@brooklyn.cuny.edu

K. Plagiarism declaration

UNIVERSITÉ DE GENÈVE

FACULTÉ DE TRADUCTION ET D'INTERPRÉTATION

Déclaration attestant le caractère original du travail effectué

J'affirme avoir pris connaissance des documents d'information et de prévention du plagiat émis par l'Université de Genève et la Faculté de traduction et d'interprétation (notamment la *Directive en matière de plagiat des étudiant-e-s,* le *Règlement d'études de la Faculté de traduction et d'interprétation* ainsi que l'*Aide-mémoire à l'intention des étudiants préparant un mémoire de Ma en traduction*).

J'atteste que ce travail est le fruit d'un travail personnel et a été rédigé de manière autonome.

Je déclare que toutes les sources d'information utilisées sont citées de manière complète et précise, y compris les sources sur Internet.

Je suis conscient-e que le fait de ne pas citer une source ou de ne pas la citer correctement est constitutif de plagiat et que le plagiat est considéré comme une faute grave au sein de l'Université, passible de sanctions.

Au vu de ce qui précède, je déclare sur l'honneur que le présent travail est original.

Nom et prénom : Loiseau, Nathalie

Lieu / date / signature : Vienne, le 15 août 2022

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Ce formulaire doit être dûment rempli par tout étudiant ou toute étudiante rédigeant un travail substantiel et remis à l'enseignant ou l'enseignante.