Luís Miguel da Silva Pires

PROCESSING UNDERPINNINGS OF EXECUTIVE FUNCTIONS ACROSS ADULTHOOD: THE INTERPLAY OF COGNITIVE CONTROL AND INHIBITION

Tese de Doutoramento em Psicologia, na especialidade de Neuropsicologia, sob orientação do Professor Doutor José Augusto Simões Gonçalves Leitão, da Professora Doutora Chiara Guerrini e do Professor Doutor Mário Manuel Rodrigues Simões, apresentada à Faculdade de Psicologia e de Ciências da Educação da Universidade de Coimbra

Julho 2017

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UNIVERSIDADE DE COIMBRA

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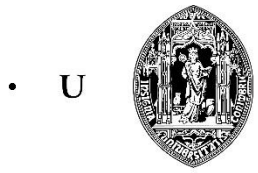

UNIVERSIDADE DE COIMBRA

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À filha Maria,

… por me darem vida!

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RESUMO

Introdução

As Funções Executivas (FE) são um conjunto de "funções cognitivas superiores" responsáveis pelo controlo de outras funções. Este controlo permite uma rápida adaptação às mudanças constantes que ocorrem no nosso dia-a-dia. Existem diferentes FE e subprocessos distintos em cada função executiva. Este sistema de FE possibilita o planeamento, a coordenação, a sequenciação e a monitorização do comportamento humano. Défices nestas funções são geralmente identificados em adultos idosos. Estes défices são importantes mediadores do efeito do envelhecimento em funções não executivas (FnE), como a memória e a linguagem. Contudo, com o envelhecimento, o défice nas FE não é, aparentemente, generalizado: FE em que os níveis de controlo cognitivo são maiores são mais suscetíveis aos efeitos do envelhecimento do que FE que dependem sobretudo de processamento automático. Para investigar a natureza das FE e o efeito do envelhecimento nestas funções, uma série de estudos foram realizados a dois níveis de análise: estrutural e processamento. A nível estrutural, examinámos a hipótese de existir uma unidade nas FE ─ uma função executiva que regula todas as FE ─ ou se, pelo contrário, existem diferentes FE que embora relacionadas são independentes. A nível do processamento, analisámos de que forma é que o recrutamento e a implementação de controlo cognitivo são processados.

Métodos

Estrutura das FE e efeitos do envelhecimento: Foi utilizada uma bateria de avaliação neuropsicológica constituída por testes que, com base em pressupostos teóricos, avaliam FE, FnE relacionadas com habilidades verbais (HV), e velocidade de processamento (VP). Foram recolhidos dados numa amostra de noventa adultos jovens e utilizada a análise fatorial confirmatória para identificar a estrutura interna da bateria de testes neuropsicológicos. Também foi investigada a relação entre as FE, as HV e a VP. Para avaliar os efeitos do envelhecimento nestas funções, comparámos o desempenho nos testes neuropsicológicos de vinte adultos jovens e vinte adultos idosos. Uma revisão da literatura sobre o envelhecimento das funções executivas, com enfâse em estudos de avaliação neuropsicológica, contribuiu para a seleção dos testes a incluir no estudo.

Processamento das FE e efeitos do envelhecimento: Quatro experiências foram desenvolvidas com uma tarefa de Stroop espacial. (i) três delas permitiram examinar a natureza dos processos de controlo implementados para resolver conflito entre várias respostas possíveis, e uma outra experiência (ii) permitiu avaliar os efeitos do envelhecimento nestes processos, comparando um grupo de adultos jovens e um grupo de adultos idosos. A tarefa de Stroop espacial usada em todos os estudos foi desenvolvida após a revisão de muitos paradigmas e métodos utilizados em estudos sobre controlo inibitório. Nesta revisão, focámo-nos em estudos que identificaram o curso temporal dos processos que implementam o controlo inibitório através da análise de potenciais evocados cognitivos. A revisão destes diversos paradigmas evidenciou que existem paradigmas mais apropriados para o estudo do controlo cognitivo, como o paradigma de Stroop, do que outros (e.g., Go/No-go). Ainda assim, mesmo nestes paradigmas, processos controlados e automáticos coexistem e interagem. Para analisar esta interação, o controlo cognitivo foi estudado numa tarefa de Stroop espacial em duas manifestações distintas, mas fortemente relacionadas: o efeito de interferência e os efeitos de sequência decorrentes do impacto do tipo de congruência do ensaio *n*-1 no processamento do ensaio *n*. Na nossa tarefa, os participantes deveriam responder esquerda/direita de acordo com a orientação de uma seta e ignorar a sua localização à esquerda ou à direita no monitor que as apresentava. A orientação e a posição das setas poderia ser congruente (C) ou incongruente (IC). (i) No sentido de investigar os processos implicados no controlo cognitivo, realizámos três experiências, construídas de forma a confrontar duas teorias sobre a natureza e implementação destes processos: a "Prediction of Response-Outcome (PRO) theory" e a "Conflict Monitoring Theory (CMT)". Na primeira experiência participaram trinta e sete adultos jovens, tendo sido analisado o efeito do tipo de congruência do ensaio *n*-1 num ensaio *n* C. Na segunda experiência participaram trinta e dois adultos jovens, tendo sido analisado o efeito do tipo de congruência do ensaio *n*-1 num ensaio *n* PO (ensaios em que o participante deveria responder esquerda/direita de acordo com a posição de um círculo). Na terceira experiência participaram trinta e seis adultos jovens, tendo sido analisado o efeito do tipo de congruência do ensaio *n*-1 num ensaio *n* IC. (ii) Para investigar possíveis alterações decorrentes do envelhecimento na interação entre processos controlados e automáticos que contribuem para o processamento do controlo cognitivo, foi comparado o desempenho de adultos jovens e adultos idosos na tarefa de Stroop espacial. Foi analisado o efeito da interferência e o efeito do tipo de congruência do ensaio *n*-1 num

ensaio *n* C. Os adultos jovens e os adultos idosos que participaram no estudo descrito na secção *Estrutura das FE e efeitos do envelhecimento* foram também participantes neste estudo.

Resultados

Estrutura das FE e efeitos do envelhecimento: Dos modelos testados, o modelo tripartido com os três fatores (FE, HV e VP) relacionados foi o que melhor ajustamento demonstrou. As FE e a VP apresentaram uma forte relação mas mantiveram-se como fatores independentes, enquanto as FE e as HV não se apresentaram relacionadas entre si. No que aos efeitos de envelhecimento diz respeito, os adultos idosos tiveram um desempenho inferior aos adultos jovens em apenas dez das vinte e seis medidas neuropsicológicas analisadas. Estas diferenças parecem refletir que as mudanças na capacidade cognitiva com o envelhecimento estão sobretudo relacionados com a diminuição da VP e ineficiência da inibição. Nas restantes medidas, que incluíam a avaliação de domínios das FE e das FnE, não foram identificadas diferenças e em duas medidas o desempenho dos adultos idosos foi mesmo superior ao desempenho dos adultos jovens.

Processamento das FE e efeitos do envelhecimento: A PRO explica melhor do que a CMT os resultados encontrados. De acordo com a PRO, o controlo cognitivo é recrutado quando existe conflito, existindo duas ou mais respostas previstas que têm de ser diferenciadas. Os planos de ação em que as respostas previstas têm um custo demasiado elevado (e.g., grande possibilidade de cometer um erro) são suprimidos. Apenas o plano de ação mais apropriado se mantém disponível, permitindo a seleção da resposta apropriada e a consequente resolução do conflito. No que aos efeitos do envelhecimento diz respeito, os resultados encontrados sugerem que com o envelhecimento existe uma lentificação geral que interage com a resolução do conflito, gerando um maior efeito de interferência em adultos idosos. Apesar desta lentificação, os adultos idosos apresentam percentagens de acertos semelhantes aos adultos jovens, sugerindo que com o envelhecimento, a implementação do controlo cognitivo na resolução de conflitos se torna mais lenta, mas mantém-se igualmente eficaz. Nos efeitos de sequência não se encontram diferenças entre os adultos jovens e adultos idosos para lá da lentificação verificada em todas as condições para os adultos idosos.

Conclusões

De uma forma geral, os nossos resultados sugerem a existência de diferentes FE e não a existência de uma capacidade executiva geral subjacente a todas as FE: A nível

estrutural, algumas FE demonstraram uma maior relação com FnE e com a VP do que outras. É também possível constatar que para um desempenho adequado em tarefas de FE desenvolvidas para avaliar uma função executiva em particular, várias FE têm de ser implementadas. As tarefas de FE menos dependentes da VP ou da eficiência dos processos inibitórios aparentam ser mais resistentes aos efeitos do envelhecimento. A nível do processamento, quando existe conflito são recrutados processos "top-down" responsáveis por gerar e estimar as consequências esperadas dos vários planos de ação possíveis. Processos automáticos subsequentes, incluindo processos inibitórios e processos de reforço da ativação, parecem desempenhar um papel fundamental na implementação do controlo cognitivo. Estes processos automáticos, tal como é sugerido pelo estudo dos efeitos de sequência, são mais resistentes aos efeitos do envelhecimento. No que respeita aos processos controlados, os resultados encontrados sugerem que o efeito do envelhecimento sobre estes processos pode envolver apenas uma redução geral da VP. Esta hipótese deverá ser testada em estudos futuros.

Palavras-chave: Funções executivas; Controlo cognitivo; Inibição; Avaliação neuropsicológica; Potenciais evocados; Envelhecimento

ABSTRACT

Introduction

Executive Functions (EF) are a set of "higher-level" cognitive functions that allow quick shifts of mindset, necessary to adapt our behaviour to a wide range of life situations. There are several EF, each often comprising several subsidiary processes. This EF system supports planning, coordinating, sequencing, and monitoring of other cognitive operations. Deficits in EF are usually found in the elderly population, playing a key role as mediators of age-related changes in non-executive functions (nEF), such as memory and language. These deficits in EF are apparently selective rather than generalized: EF relying on the recruitment of automatic processes are less affected by ageing than processes relying on higher levels of cognitive control. In order to examine the nature of EF and the ageing impact upon these functions, we conducted a series of studies at two levels of analysis: the structural level and the processing level. At the structural level, we addressed the problem of the existence of a unitary EF, and the alternative to this view, that different EF do interact systematically, but without relying on a central EF "regulator" of some sort. At the processing level, we analysed the processing steps involved in the recruitment and implementation of cognitive control in a conflict task.

Methods

EF structure and age-related changes: We used a neuropsychological assessment battery comprising nine tests that theoretically assess EF, nEF pertaining to verbal abilities (VA), and processing speed (PS). We collected data from ninety young adults and used confirmatory factor analysis to examine the internal structure of the battery. We also studied the relation between EF, VA and PS. To study possible age-related changes in EF and nEF, we administered a neuropsychological battery to twenty young adults and twenty older adults. A review of the current literature on EF and ageing, with an emphasis on neuropsychological assessment, guided the selection of the nine tests.

EF processing and age-related changes: We conducted four experiments using a spatial Stroop task, (i) three of them scrutinizing the nature of the control processes deployed to resolve response-conflict, and one (ii) contrasting the implementation of the conflict-resolving control setup in young and older adults. The spatial Stroop task employed in all studies was designed after a review of the numerous paradigms and

methods used in inhibitory control studies. In this review, we focused on studies that used the high temporal resolution of the event-related potential (ERP) technique to identify the time-course of different processes involved in the implementation of inhibitory control. We found that some paradigms, like the Stroop paradigm, are more appropriate to study control processes than others (e.g., the Go-Nogo). These cognitive control paradigms could be expected to mostly recruit controlled processes, but in fact the latter co-occur and interact with automatic processes. In order to analyse this interplay, we studied cognitive control in two different, yet closely related, manifestations in a spatial Stroop task: the interference effect and the congruency sequence effects. In our task, participants responded to the left/right direction of an arrow, while ignoring its left/right position in a computer screen. The arrow's direction and position could be congruent (C) or incongruent (IC). (i) To study the processing underpinnings of cognitive control, we conducted a set of three experiments, designed to contrast two theoretical views pertaining to the nature of those processes, the Prediction of Response-Outcome (PRO) theory and the Conflict Monitoring Theory (CMT). In Experiment 1, we collected data from thirty seven young adults to analyse the effect of the trial *n*-1 congruency type on an n^{th} C trial. In Experiment 2, we collected data from thirty two young adults to analyse the effect of the trial *n*-1 congruency type on an n^{th} position-only trial (PO; participants must respond to the left/right position of a circle). In Experiment 3, we collected data from thirty six young adults to analyse the effect of the trial *n*-1 congruency type on an n^{th} IC trial. (ii) To investigate age-related modulations of the interplay between the controlled and automatic processes involved in cognitive control processing, performance in the spatial Stroop task was contrasted in young and older adults. The interference effect in IC trials as well as the effect of trial *n*-1 congruency type on a n^{th} C trial were analysed. The participants in this study were the same that took part in the ageing study, mentioned in the *EF Structure and age-related changes* section.

Results

EF structure and age-related changes: We found that a three-correlated-factor model (EF, VA and PS) was the most suitable for our data. EF and PS were related but separable functions, whereas the EF and VA factors were unrelated. Concerning the cognitive ageing study we found that older adults' performance was inferior to young adults' performance in only ten of the twenty six neuropsychological measures analysed. These age-related deficits are mainly explained by cognitive slowing and/or

by inhibition deficits. There were no age-related deficits in fourteen measures that included both EF and nEF and in two measures, related to EF, the performance of older adults was superior.

EF processing and age-related changes: Our results showed that PRO can better predict our participants' performance than CMT. According to PRO, cognitive control is recruited in the presence of conflict, when multiple responses are available. The action plans yielding responses with an unacceptable cost (e.g., high error probability) are suppressed, leaving only the most appropriate action plan available. This enables the selection of the appropriate response, leading to conflict resolution. Concerning age-related modulations, our results revealed a generalized slowing that interacted with conflict resolution, yielding a larger interference effect for older adults. Despite this generalized slowing, the accuracy rates were similar in young and older adults, suggesting that with ageing, the implementation of cognitive control to resolve conflict becomes slower, but remains effective. Concerning the congruency sequence effects, older adults were slower than young adults in all conditions. However, we did not find any differences between the age groups in respect to the pattern found for the congruency sequence effects.

Conclusions

Taken together, our results support the diverse nature of EF. At the structural level, some EF tasks rely more on nEF and PS than others. Also, for an adequate performance in EF tasks designed to single-out one specific EF, multiple EF are in fact recruited. EF tasks less reliant on PS or on inhibition seem to be less affected by ageing. At the processing level, top-down processes are recruited in the presence of conflict for the computation and valuation of the multiple expected outcomes. Then, automatic processes, including both inhibition and enhancement processes, seem to play a key role in the cognitive control implementation. These automatic processes, as manifest in congruency sequence effects, are minimally affected by ageing. As for the controlled processes that are responsible for the implementation of control, it remains as an open question to what extent their age-related decline does not merely reflect a generalized reduction in PS.

Keywords: Executive functions; Cognitive control; Inhibition; Neuropsychological assessment; Event-related potentials; Ageing

"A journey with a thousand miles begins with a first step."

(Laozi)

INTRODUCTION

Executive functions (EF) and cognitive control are used frequently as interchangeable concepts but they can be differentiated. EF are a more tangible set of processes or functions that are necessary for cognitive control of behaviour such as the ability to plan ahead, inhibit irrelevant or contextually inappropriate information, or monitor any relevant environmental changes (Diamond, 2013; Friedman & Miyake, 2017; Jurado & Rosselli, 2007). Cognitive control refers to a more abstract set of processes as noted by Botvinick, Braver, Barch, Carter, and Cohen (2001): "*A remarkable feature of the human cognitive system is its ability to configure itself for the performance of specific tasks through appropriate adjustments in perceptual selection, response biasing and the on-line maintenance of contextual information. The processes behind such adaptability" are referred "collectively as cognitive control*" (p. 624). In this thesis we present theoretical and empirical work on two levels of analysis, one pertaining to the structure of EF as a set of more operationalized functions and another pertaining to the processing of EF, allowing more detailed understanding of cognitive control. The extent and the detailed instantiation of cognitive control required to achieve our goals in a given situation are regulated by several processes underpinning EF. Specifically, these processes are responsible for the detection of situations in which higher control is needed, for the continuing adjustment of control levels, and for the implementation of control in order to appropriately regulate our behaviour. Inhibition is an EF with a key role in cognitive control by enabling us to reduce the interference of relevant but contextually inappropriate information and to actively supress any irrelevant information (Kok, 1999). In a continuous changing environment in which there is a massive amount of information available at a given time, these inhibition processes are vital. In this introduction, we consider the theoretical definitions and neuroanatomical correlates of cognitive control, EF and inhibition. We also consider different models pertaining to cognitive ageing with a specific focus on EF. A deficit in cognitive control, and specifically in EF such as inhibition, is considered a hallmark of cognitive ageing (Collette, Schmidt, Scherrer, Adam, & Salmon, 2009; Turner & Spreng, 2012; West & Alain, 2000). However, there is still an ongoing debate about how these processes are modulated by ageing and which cognitive processes are more

resistant to ageing effects. Ageing studies have also contributed to a better understanding of EF and cognitive control processing.

1. Cognitive Control

1.1. Definition

Cognitive control has been widely studied in the past twenty years (Alexander & Brown, 2010; Botvinick et al., 2001; Braver & Barch, 2002; Brown & Braver, 2005; Carter, Botvinick, & Cohen, 1999; Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Egner, 2007; Egner & Hirsch, 2005; Friedman & Miyake, 2017; Hommel, 2009; Kerns et al., 2004; Miller & Cohen, 2001; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuiss, 2004; van Veen & Carter, 2006; Verguts & Notebaert, 2009; Yeung, 2013). There are meaningful advances in the clarification of the processes involved in cognitive control but there are still many open questions and inconsistencies in the literature pertaining to its recruitment and implementation.

Since Botvinick et al. (2001)' defined cognitive control as the ability of our cognitive system to "*configure itself for the performance of specific tasks*" through several adjustment functions. There have been some developments in the definition of cognitive control. Koechlin, Ody, and Kouneiher (2003) described cognitive control as "*the ability to coordinate thoughts and actions in relation with internal goals*" and specify that cognitive control "*is often required in our everyday life and subserves higher cognition processes such as planning and reasoning.*" (p. 1181). This definition highlights that cognitive control acts upon thoughts and responses and that its action is dependent on our current goals. Braver (2012) also recognizes that cognitive control coordinates and directs our thoughts and actions/responses in relation to internal goals and defines cognitive control as "*the ability to regulate, coordinate, and sequence thoughts and actions in accordance with internally maintained behavioral goals*" (p. 1). This definition is a step forward since it highlights that cognitive control not only coordinates but also regulates and delineates the sequence by which our perceptual, cognitive and motor processes occur. The online maintenance of our current goals during task's performance is vital for cognitive control implementation. Cognitive control is also responsible for the shift from a goal to another in a coordinated manner.

The prefrontal cortex (PFC) has been associated with cognitive control. According to Miller and Cohen (2001), that proposed the Guided Activation model to portray PFC function, this brain region is responsible for the online maintenance of goals over time while resisting to distractions. Despite being able to resist to the interference of irrelevant or inappropriate information, the PFC is also capable of continuously updating context data. This function is vital since previously ignored information can become relevant with a context change. Other important characteristic of PFC regarding its role in cognitive control is its connection to many brain areas. The cognitive control system must coordinate and regulate both internal information (e.g., relevant information from previous similar situations) and external information (e.g., world information captured by our senses) to optimize our behaviour. The maintenance and updating of current goals is modulated by visual, auditory and somatosensory information incoming from the occipital, temporal and parietal areas of the brain. Also, the PFC directs information to posterior and premotor regions and biases processing in order to guide responses in accordance to current goals. An important function of PFC is the regulation of the degree of control needed in a given task. For example, while driving, we pay closer attention to novel routes than to usual routes. According to some studies the allocation of control may be related to the anterior cingulate cortex (ACC) activation in the presence of conflict (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns, 2006; Larson, Kaufman, & Perlstein, 2009; Liotti, Woldorff, Perez, & Mayberg, 2000; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). The Conflict Monitoring Theory (CMT; Botvinick et al., 2001) was proposed to account for these human neuroimaging findings. According to this theory, the ACC is mainly a conflict monitoring system. After the detection of conflict (i.e., the competition between two or more possible responses), ACC signals the need for increased cognitive control, relaying this request to the dorsolateral PFC (DLPFC), directly responsible for cognitive control implementation. Conflict is resolved by biasing attentional focus towards the task's relevant stimulus information. An alternative approach, the Prediction of Response-Outcome (PRO) theory (Alexander & Brown, 2010, 2011), suggests that inhibition has a more noticeable role in conflict resolution. According to PRO, the ACC is engaged in computing the expectable outcomes of a response before its occurrence, including both beneficial and unfavourable outcomes. The prediction of multiple responses (i.e., correct and incorrect action plans) leads to conflict. The incorrect action plans are actively suppressed by an amend/veto function, leaving only the correct action

plan available for selection. These different models of cognitive control offer a potentially explanation of how the human cognitive system configures itself to optimize responses. According to Botvinick, Cohen, and Carter (2004) this ability is particularly important "*in challenging and nonroutine situations*" (p. 539). This highlights an old subject in psychology research that will be addressed in the next topic: the existence of automatic processing, related to less demanding or routine situations, and the existence of controlled processing, associated to challenging or novel situations.

1.2. Automatic and Controlled Processing

One of the first descriptions of automatic and controlled processing dates back to the nineteen century when William James (1890; Chapter 26) wrote: "*...wherever movement follows unhesitatingly and immediately the notion of it in the mind, we have ideo-motor action. We are then aware of nothing between the conception and the execution. All sorts of neuro-muscular processes come between, of course, but we know absolutely nothing of them. We think the act, and it is done; (...)".* In contrast, some acts require will: *"(...) sometimes an additional conscious element, in the shape of a fiat, mandate, or express consent, has to intervene and precede the movement."* (p. 497). Differences on the level of cognitive control needed in a cognitive process have been conceptualized in the distinction between automatic and controlled processing (Andres, Guerrini, Phillips, & Perfect, 2008; Collette et al., 2009; Friedman & Miyake, 2004; Nigg, 2000). Richard Shiffrin and Walter Schneider (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) proposed a general framework for human information processing emphasizing the role of automatic and controlled processing. Automatic processing is fast and occurs without conscious control. It is usually more appropriate in routine situations allowing responses to be executed quickly. However, this automatic/bottom-up processing is determined essentially by the nature of the sensory stimuli, resulting in inflexible responses that are not appropriate in novel situations. Controlled processing is slow, requires a considerable amount of control and has limited capacity, reducing the possibility to simultaneously perform multiple operations. However, as highlighted by Shiffrin and Schneider (1977) "*the cost of capacity limitations is balanced by the benefits deriving from the ease with which such processes may be set up, altered, and applied in novel situations*" (p. 156). According to Shiffrin and Schneider's model, automatic and controlled processing are interrelated. In our

daily lives, tasks or situations reliant only on automatic processing or merely on controlled processing do not exist. So, in a task theoretically more related to control processing as the Stroop task (Stroop, 1935) both controlled and automatic processes contribute to optimize performance. In this thesis, we present empirical data that reveals and details some features of this co-existence.

2. Executive Functions

2.1. Definition

EF are easily considered vital to a better adaptation in our challenging world. Despite the general agreement on its key role, the scientific community has not been able, until recently, to reach a consensus about the nature of these functions. Almost twenty years ago Miyake et al. (2000) defined EF as a set of "*general purpose control mechanisms that modulate the operation of various cognitive subprocesses and thereby regulate the dynamics of human cognition.*" (p. 50). This definition highlights the cybernetic nature of EF as control functions acting upon nEF such as memory or language. Royall et al. (2002) described EF as "*a set of cognitive skills that are responsible for the planning, initiation, sequencing, and monitoring of complex goal directed behavior.*" (p. 378). Therefore, there are different indicators of the control functions pertaining to EF that began even before the start of task execution (i.e., planning) and remained during task' performance (i.e., initiation, sequencing and monitoring). Diamond (2013) simply defined EF as "*a collection of top-down control processes used when going on automatic or relying on instinct or intuition would be ill-advised, insufficient, or impossible*" (p. 136), highlighting their vital role in novel situations. For Alvarez and Emory (2006) «*Executive functions generally refer to "higher-level" cognitive functions involved in the control and regulation of "lower-level" cognitive processes and goal-directed, future-oriented behavior.*» (p. 17). This definition supports the cybernetic view of EF and their role in controlling other functions towards the current goal. It is also important to note that Alvarez and Emory (2006) present the notion of higher-level and lower-level between brackets, highlighting that EF can operate as higher-level and lower-level processing functions. For example, Stuss and Benson (1986) proposed a hierarchical model of EF with the existence of

higher order EF (e.g., goal selection) and second-order EF (e.g., inhibition). The higher order EF interact with the second-order EF that are in turn responsible for controlling nEF (e.g., memory). All these definitions seem to support the existence of different EFs ("*control mechanisms*", "*cognitive skills*", "*a collection of top-down control functions*"; «*"high-level" cognitive processes*») but it is not clear whether or not these processes are independent functions (Stuss & Alexander, 2007; Stuss, Shallice, Alexander, & Picton, 1995), if they rely on a general control function (Duncan & Owen, 2000), or even if they have a diverse and unitary nature, as a set of different processes that are interrelated (Friedman & Miyake, 2017; Miyake et al., 2000).

2.2. Neuroanatomical correlates

EF were linked for the first time to the frontal lobes and specifically to the PFC more than a century ago, from the time when Bianchi (1895) investigated the behavioural consequences of injuries in these structures. Since then, PFC association with EF has been repeatedly encountered (see for a review, Cabeza & Nyberg, 2000). Posterior brain regions, such as the parietal cortex have also been linked to EF (Collette, Hogge, Salmon, & Van der Linden, 2006), but PFC seems to play a more important role in executive function by controlling the level of activation of other brain structures (Miller & Cohen, 2001). Developments in functional neuroimaging and the proposal of new theoretical models concerning EF generated a very complex picture of this link between PFC and EF (Chan, Shum, Toulopoulou, & Chen, 2008; Fassbender et al., 2004). One of the challenges is the fact that there are different EF and even different subprocesses within each EF (Burgess, 1997; Friedman & Miyake, 2004; Miyake et al., 2000) and also the fact that specific EF have been associated to different PFC regions. For example, the dorsolateral PFC (DLPFC) has been implicated in working memory (Alvarez & Emory, 2006). This differentiation is also found between subprocesses of a specific EF (e.g., neural correlates of response inhibition subprocesses; Sebastian et al., 2013). Despite this apparent differentiation, the activation of the same PFC region has been found for different EF (Collette et al., 2006). For example the DLPFC is related to working memory but also to other EF such as planning, sequencing or shifting (Royall et al., 2002). Elliott (2003) proposed that even if some commonality exists, with different EF functions being related to the same brain region, the extent of the region

activation will be different for different EF. Accordingly, there is some degree of specialization in the different PFC regions.

3. Inhibition

Inhibition has been a long-lasting concept in Psychology that was present in early theories (e.g., Wundt proposed that inhibition of unattended information is vital for selective attention) and it is still extensively studied (Anguera & Gazzaley, 2012; Aron, Robbins, & Poldrack, 2004; Friedman & Miyake, 2017; Kok, 1999; Logan, Cowan, & Davis, 1984; MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003; Miyake et al., 2000; Naber, Vedder, Brown, & Nieuwenhuis, 2016; Nigg, 2000; Tipper, 2001; Yi & Friedman, 2014). It is considered a core EF (Miyake et al., 2000) and some authors consider that all other EF involve some kind of inhibition processes (Friedman & Miyake, 2017; Hasher & Zacks, 1988). Different cognitive control theories highlight the role of inhibition but there is not yet an agreement about the way how inhibition contributes to cognitive control implementation (Alexander & Brown, 2010; Yeung, 2013). Several types of inhibition have been studied (e.g., motor inhibition; semantic inhibition; lateral inhibition) (Collette et al., 2009; Kok, 1999). In this thesis we focus on cognitive inhibition (Bjorklund & Harnishfeger, 1995; Koch, Gade, Schuch, & Philipp, 2010). Even within inhibition, several subprocesses can be differentiated. For example, Friedman and Miyake (2004) found that resistance to proactive interference was clearly dissociated from prepotent response inhibition and resistance to distractor interference.

4. Relationship between executive function and cognitive ageing studies

Several studies have been conducted to identify age-related changes in EF (Allain et al., 2005; De Beni & Palladino, 2004; Fournier, Herbert, & Farris, 2004; Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). In general some EF are impaired (e.g., suppression of irrelevant information) while other EF are more resistant to ageing effects (e.g., resistance to interference from irrelevant information). Some explanations have been put forward to justify why some EF are more resistant to

cognitive ageing than others. Some authors conclude that different EF entail different degrees of cognitive control, that is, some EF domains are more automatic and others are heavily dependent on control. The EF domains less reliant on control would be less affected by ageing (Andres et al., 2008; Nigg, 2000). Other authors explain these differences with the discrepancy in the study methodologies (experimental paradigms versus neuropsychological tests, etc.). Some methods bring more benefit for older adults' performance by allowing the use of nEF and multiple EF to optimize performance. Other methods can easily identify an age-related EF deficit but most of the decline can still be accounted by mediator factors such as processing speed (Salthouse, Atkinson, & Berish, 2003).

5. Doctoral thesis structure

The present thesis is organized in two parts. In Part I entitled "*Structure* of *executive functions and age-related changes*" there is a broader level of EF analysis, examining neuropsychological assessment data to understand the nature of EF (as a unitary function or a set of diverse functions) and to scrutinize age-related modulations in cognition, and particularly in EF. In Part II entitled "*Processing of executive functions and age-related changes*" there is a narrow level of EF analysis, examining processing of cognitive control during a spatial Stroop task. Age-related changes in cognitive control are also investigated.

Part I is organized in three sections. Section 1, entitled "*Executive functions and ageing*" (Pires, Simões, Leitão, & Guerrini, 2016), presents a brief review of cognitive and neuroanatomical EF models and examines issues related to EF neuropsychological assessment. It also describes models of cognitive ageing and examines age-related modulations in EF. This section sets the background for the research described in the next sections. Section 2, entitled "*Confirmatory factor analysis of neurocognitive measures in healthy young adults: The relation of executive functions with other neurocognitive functions.*" (Pires, Moura, Guerrini, Buekenhout, Simões, & Leitão, submitted), presents the use of confirmatory factor analysis to test different models of neurocognitive functional dependencies involving EF, nEF and processing speed (PS). This study allowed us to decide on the more appropriate neurocognitive model to explain the factor structure of a neuropsychological assessment battery. This deeper

understanding of the functions being assessed by the different neuropsychological tests is key to understand age-related modulations of performance in these tests. In section 3, entitled "*Ageing and Executive Functions: the specific role of inhibition*" (Pires, Leitão, Simões, & Guerrini, 2014), age-related changes in cognition are examined by comparing young and older adults performance in several neuropsychological tests. These tests assess multiple cognitive domains such as EF, attention, memory or language.

Part II is also organized in three sections. In section 1, entitled "*Event-related brain potentials in the study of inhibition: Cognitive control, source localization and age-related modulations*" (Pires, Leitão, Guerrini, & Simões, 2014), a review of event-related potentials (ERP) studies of inhibition is presented. Many of the paradigms designed to probe inhibitory control are analysed and different types of inhibitory processes are identified. Some inhibition processes are more automatic while others heavily depend on cognitive control. As a result these processes are differently affected by ageing. The brain regions associated with ERP components reflecting inhibitory processing are also discussed by examining source analysis studies. This review allowed the selection of the Stroop paradigm as particularly appropriate to study cognitive control, and specifically inhibitory control. It also allowed us to identify the need to study different degrees of cognitive control within the same task for a better identification of age-related modulations in cognitive control. Therefore, the topics presented in this first section contributed for the empirical research described in the next sections. Section 2, entitled "*Cognitive control during a spatial Stroop task: comparing conflict monitoring and prediction of response-outcome theories*" (Pires, Leitão, Guerrini, & Simões, 2017), compares two theoretical accounts of cognitive control activation and implementation by analysing congruency sequence effects in a spatial Stroop task. The studies included in this section also allowed for a better understanding of the top-down and bottom-up processes that interact in order to resolve conflict in our spatial Stroop task. In section 3, entitled "*Age-related changes in cognitive control: conflict resolution and sequence effects*" (Pires, Leitão, Guerrini, & Simões, submitted), we compare the performance of young and older adults in a spatial Stroop task. Two measures of cognitive control are considered, the Stroop interference effect and congruency sequence effects.

After Part II, a Discussion is presented highlighting empirical results and theoretical conclusions from the six studies included in this thesis. The two levels of

analysis of EF are integrated and strengths and limitations of this research are outlined. Future directions for research examining the processing underpinnings of EF are also discussed.

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"You are never too old to set another goal or to dream a new dream."

(C.S. Lewis)

PART I: STRUCTURE OF EXECUTIVE FUNCTIONS AND AGE-RELATED CHANGES

1. EXECUTIVE FUNCTIONS AND AGEING

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1.1. Introduction

Executive functions (EF) are the "director" that drives other cognitive functions in order to evaluate and perform an action (Goldberg, 2001). These functions allow us to be constantly updated in order to organize relevant information. They also help us to inhibit irrelevant information. Finally, they allow us to make decisions to facilitate our adaptation to new situations or to contexts of greater complexity (Collette, Hogge, Salmon, & Van der Linden, 2006; Jurado & Rosselli, 2007).

An important feature of EF, that makes them especially relevant to mental health, is the emotional and social regulation of behaviour (Bechara, Damasio, Tranel, & Damasio, 1997; Dunn, Dalgleish, & Lawrence, 2006). EF are often referred as a set of functions in the literature. However, there is a controversy about the existence of different independent functions or the existence of unity among EF. Some researchers suggest that there is a single executive system that is not subdivided into different components (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kimberg, D'Esposito, & Farah, 1997). Other researchers advocate the existence of different EF (see Table 1), and even of distinct subprocesses in each EF (Burgess & Shallice, 1994; Friedman et al., 2006; Royall et al., 2002). Organizing, sequencing, monitoring, inhibiting and updating are some examples of cognitive functions that can perform executive functions (Elias & Treland, 2000; Royall et al., 2002; Stuss, Pogue, Buckle, & Bondar, 1994).

Table 1. Examples of cognitive functions that have been studied for the understanding of the executive system.

Planning (Sorel & Pennequin, 2008)
Prospective Memory (McDaniel & Einstein, 2011)
Inhibition (Andres, Guerrini, Phillips, & Perfect, 2008)
Cognitive Flexibility or Shifting (Kiesel et al., 2010)
Divided Attention (Verhaeghen & Cerella, 2002)
Selective Attention (Haring et al., 2013)
Working Memory (Toepper et al., 2014)
Abstraction (Goh, Beason-Held, An, Kraut, & Resnick, 2013)
Decision Making (Peters, Dieckmann, & Weller, 2011)

In this chapter, especially dedicated to the effects of ageing on EF, we will follow an intermediate approach advocated by Miyake et al. (2000) according to which the executive system is composed of distinct but interrelated functions.

EF have traditionally been associated with the functioning of frontal lobes and their disruption to specific behaviours such as impulsivity, disinhibition, inability to detect errors, greater cognitive slowing and forgetfulness related to attention deficits (Jurado & Rosselli, 2007). Initially, the EF were studied as higher-level cognitive functions that like memory or language, could be directly and independently assessed (Tranel, Anderson, & Benton, 1994). Later, EF were interpreted according to a cybernetic perspective (Royall et al., 2002), following which EF interact with non-executive functions (nEF) in order to control the execution of complex activities. In this context, EF assume a role that is metacognitive and its implementation requires the effective activity of other cognitive functions such as attention, memory and language.

Among age-related cognitive changes, executive deficits are predominant (West, 2000) and are an important mediator of the effects of ageing on other cognitive functions (Salthouse, Atkinson, & Berish, 2003). However, some EF are more susceptible than others to the effects of ageing (Crawford, Bryan, Luszcz, Obonsawin, & Stewart, 2000; Lin, Chan, Zheng, Yang, & Wang, 2007).

In this chapter, we will first address the different cognitive and neuroanatomical models that contributed to a better understanding of EF. Next, we will focus on EF neuropsychological assessment, highlighting the different evaluative tools that have been used to test these functions. Finally, we will consider the different explanatory models of cognitive ageing, with a special focus on the models that value the role of EF, systematizing the changes that occur in different EF with ageing.

1.2. Cognitive and neuroanatomical models of executive functions

Frontal lobes have unique characteristics that associate them with EF (Royall et al., 2002). They play a metamodal role, working on information that has already been processed at a lower level. The frontal region of the brain is also the system that receives more information from the cortical-basal ganglia-thalamic circuits and has more connections with other cerebral regions than any other cortical region. Frontal lobes are the main receptors of limbic system information, integrating cognitive and sensory-motor information with emotional valence and internal motivation. Even before this understanding of the structure and function of the frontal lobes, Luria, Karpov, and Yarbuss (1966) published a case study of a 54-year-old patient with a tumour in the right frontal lobe. The patient was oriented in time and space but euphoric, emotionally unstable, with concentration deficiencies and error *perseveration* even after correction by the examiner. Luria et al. (1966) associated the functioning of the frontal lobes, and in particular the prefrontal cortex, to the EF, responsible for the programming, regulation and monitoring of human behaviour. Later, Norman and Shallice (1986) modified the model proposed by Luria et al. (1966) by dividing the frontal system into two main systems, the contention scheduler, responsible for evaluating the relative importance of different behaviours, selecting the most appropriate behaviour and defining the order in which they should be executed when facing a routine situation, and the Supervisory Attentional System (SAS), responsible for the regulation and sequencing of new behaviours. This model is particularly important because it allows us to understand that even if the executive system is preserved in the person's daily life, it may be impaired in adapting to new situations. Another model considered relevant is the hierarchical model of EF proposed by Stuss and Benson (1986) that emphasizes the interaction of distinct EF and nEF at different levels. According to this model there are four higher-order EF: anticipation, goal selection, pre-planning and monitoring. These higher hierarchical functions would control other EF such as initiative and sequencing (which would involve working memory, prospective memory, and inhibition). And it would be these second-order EF that would direct nEF such as attention, memory, and language. Thus, this model implies the impossibility of evaluating the functioning of the executive system without the evaluation of the cognitive systems coordinated by it. Another important point in Stuss and Benson's (1986) model is the reference to self-awareness. Self-awareness would be the awareness of ourselves, of the goals we intend

to achieve, but also of the awareness of our successes and failures in pursuit of those goals, necessary for us to be able to readjust our behaviours in order to better achieve the goals. For Stuss and Benson (1986) self-awareness would be at the top of the hierarchy, directing the higher order EF.

Subsequently, Stuss, Shallice, Alexander and Picton (1995) identified different neuronal substrates for different EF. For example, inhibition would be related to the dorsolateral prefrontal cortex while planning would involve not only areas of the prefrontal cortex but also areas of the parietal cortex. Thus, the results found by Stuss et al. (1995) suggest that different EF have different anatomical substrates. Further studies using brain imaging techniques have shown that there is indeed a specificity of EF but, at the same time, there is a commonality that is observed at both cognitive and brain levels. Table 2 shows different studies that aimed to evaluate the anatomical substrates of EF. These studies are divided into two types: cognitive subtraction studies and cognitive conjunction studies. Cognitive subtraction studies involve the subtraction between the brain areas activated during the performance of a task involving a particular cognitive component under investigation and the brain areas activated during a control task that shares all the characteristics of the experimental task except the cognitive component under investigation. Conjunction studies can be seen as an extension of previous ones because they involve a series of subtractions, seeking to make two or more comparisons in order to isolate the brain areas responsible for processing the cognitive component of interest (Price & Friston, 1997). The set of studies presented in Table 2 suggest that although different EF anatomic substrates have been found, EF seems mainly associated with prefrontal and parietal brain regions.

Table 2. Neuroanatomical substrates associated with different Executive Functions identified with cognitive subtraction studies and with a cognitive study of conjunction.

COGNITIVE SUBTRACTION STUDIES			
Authors	Task (EF)	Method	Brain Areas
Phelps, Hyder, Blamire, & Shulman (1997)	Phonemic Verbal Fluency task (Initiation, Cognitive Flexibility)	FMRI[a]	Lower Left Frontal Turn, Anterior Cingulate, Dorsolateral Prefrontal Cortex, Lower Parietal Turn
Van der Linden et al. (1999)	*Continuous Performance Task (Update Working Memory)*	PET[b]	Anterior Prefrontal Cortex and Dorsolateral Prefrontal Cortex
Jahanshahi, Dirnberger, Fuller, & Frith (2000)	*Random Number Generation task (Cognitive Flexibility)*	PET	Left Dorsolateral Prefrontal Cortex, Anterior Cingulate, Upper Bilateral Parietal Cortex
Aron, Fletcher, Bullmore, Sahakian, & Robbins, (2003) Collette et al. (2001)	*Stop-signal task and Hayling task (Inhibition)*	FMRI	Prefrontal Cortex, Cingulate Circuit, Parietal Cortex, Temporal Cortex
Newman, Carpenter, Varma, & Just (2003)	*Tower of London (Planning)*	FMRI	Prefrontal Cortex - Right Part (Elaboration of the Plan) Left side (Plan execution), Bilateral Upper Parietal Cortex, Bilateral Occipital Cortex
Perianez et al. (2004)	*Wisconsin Card Sorting Test - WCST (Cognitive Flexibility)*	MEG[c]	Anterior frontal rotation, Anterior Cingulate Cortex and Supra Marginal Gyrus (Parietal Cortex)
Hagen et al. (2014)	*Trail Making Test - TMT (Cognitive Flexibility)*	FNIRS[d]	Dorsolateral Prefrontal Cortex, Frontopolar Cortex and Broca Area.
COGNITIVE CONJUNCTION STUDY			
Authors	Task (EF)	Method	Brain Areas
Collette et al. (2005)	*Different Continuous Performance tasks (Update Working Memory)*	PET	Anterior Prefrontal Cortex and Dorsolateral Prefrontal Cortex, Pre-Motor Cortex and Cortex Supplemental Motor, Lower Left Frontal Turn
	Switching Tasks (Cognitive Flexibility))		Supra-marginal gyrus, left pre cuneus and left part of the parietal cortex (parietal lobe)
	Stroop task and Antisaccade task (Inhibition)		Lower Right Frontal Cortex
	Work Memory Update Tasks + Cognitive Flexibility Tasks + Inhibition Tasks	PET	Upper Left Parietal Groove, Right Intra-Parietal Groove, Right Middle and Bottom Front Turn

[A] FUNCTIONAL MAGNETIC RESONANCE IMAGING OR FUNCTIONAL MRI; [B] POSITRON EMISSION TOMOGRAPHY;

[C] MAGNETOENCEPHALOGRAPHY; [D] FUNCTIONAL NEAR-INFRARED SPECTROSCOPY.

Another aspect particularly relevant to the understanding of EF in mental health is the role of the frontal lobes and, in particular, the prefrontal cortex, on emotions, social behaviour, and decision making. This role is emphasized in Damasio's "*somatic marker hypothesis*" (1996). In Damasio's model (1996) emotions would be mediated by the connections of the prefrontal cortex to other cortical regions such as the ventromedial

cortex and subcortical regions such as the thalamus, amygdala and hypothalamus. Patients with lesions in the prefrontal cortex and, specifically, lesions in the ventromedial region, present a deficit in decision making but maintain other cognitive abilities totally preserved. This model thus identifies a component of EF that is primarily responsible for emotional regulation rather than cognitive control.

1.3. Executive functions assessment in older adults

The frontal lobes occupy a large area of our brain and most of the EF also involve the functioning of other cerebral regions, such as the parietal lobes, and for this reason it is difficult to devise a single instrument for the assessment of EF. In order to achieve this aim, multiple tests and even different assessment test batteries have been developed (Salthouse, 2005). Table 3 identifies examples of different evaluation tools and the executive components they are intended to examine.

Table 3. Examples of Executive Functions assessment tests.

Tests	Function
Tower of London test (Shallice, 1982); *Tower test* (*Delis-Kaplan Executive Function System* - DKEFS; Delis, Kaplan, & Kramer, 2001); *Zoo Map test* (*Behavioural Assessment of the Dysexecutive Syndrome* - BADS; Wilson, Alderman, Burgess, Emslie, & Evans, 1996).	Planning - organize behaviour in order to achieve a particular goal.
Stroop (Stroop, 1935; Castro, Martins & Cunha, 2003; Fernandes, 2009); *Hayling Sentence Completion test* (Burgess & Shallice, 1996).	Inhibition - removing information that is not relevant or has become irrelevant and restricting to the interference of inappropriate information.
Controlled Oral Word Association Test – Phonemic Fluency Test (COWAT*;* Benton & Hamsher, 1989*;* Cavaco et al., 2013a).	Initiation - initiate a task or activity and independently generate ideas, responses, or problem-solving strategies.
Trail Making Test - Part A minus Part B (TMT; Retain, 1958; Cavaco et al. 2013b); *Wisconsin Card Sorting Test* (WCST; Grant & Berg, 1948).	Cognitive flexibility - switching between two tasks or between two ways of performing the same task.
Semantic Fluency Test - *Animals* (Cavaco et al., 2013a).	Categorization - ability to organize into categories objects, people or events, recognizing the similarities between them and the differences that separate one category from another.
Corsi (Corsi, 1972; Constâncio, 2009); Letter-Number Sequencing (*Wechsler Adult Intelligence Scale – third edition* - WAIS-III; Wechsler, 1997a, 2008a); Digit Span – Backward (*Wechsler Memory Scale– third edition* - WMS-III; Wechsler, 1997b, 2008b)	Working Memory - information manipulation and temporary storage of information.
Cambridge Prospective Memory Test (CAMPROMPT; Wilson et al., 2005); Rivermead Behavioural Memory Test (RBMT; Wilson, Cockburn, & Baddeley, 1986);	Prospective Memory - remember a planned task that will have to be developed in the future.
Similarities (WAIS-III; Wechsler, 1997a, 2008a)	Abstraction - conceptual process by which general rules or concepts are derived from specific, concrete objects.
Iowa Gambling task (Bechara, Damasio, Damasio & Anderson, 1994)	Decision Making - Select an action or thought among several alternatives.
d2 Test of Attention (Brickenkamp & Zilmer, 1998; Ferreira & Rocha, 2006; Canelas, 2014)	Selective attention - Selective focus on one aspect of the information while ignoring the remaining information
Difference between time per target in two tasks: *Telephone Search* and *Dual task Telephone Search* (*Test of Everyday Attention*; Robertson, Ward, Ridgeway & Nimmo-Smith, 1996)	Divided Attention - concentration on two or more aspects of information at the same time.

Although each instrument presented in Table 3 aims to evaluate a specific EF (e.g., the Wisconsin Card Sorting Test - WCST - intends to assess cognitive flexibility), the fact is that, regardless of its simplicity, in each instrument or task, other EF will always be involved (e.g. WCST in addition to cognitive flexibility is also involved inhibition or planning) and even nEF (e.g., WCST involves memory and language processes). Thus, it is vital, in the neuropsychological evaluation of the EF, to assess

nEF in order to identify whether there is a deficit in the executive domain, in non-executive domain or both.

In addition to the tests developed for the assessment of specific domains of EF, there are also neuropsychological assessment batteries whose objective is the comprehensive evaluation of EF. Among the neuropsychological assessment batteries of EF that have been most used are the Delis-Kaplan Executive Function System (D-KEFS, Delis, Haplan, & Kramer, 2001) and the Behavioural Assessment of the Dysexecutive Syndrome (BADS; Wilson, Alderman, Burgess, Emslie, & Evans, 1996). D-KEFS is composed of 9 tests that allow the evaluation of the EF components whose neuronal substrate is related to the frontal lobe, such as cognitive flexibility, inhibition or planning. BADS is also sensitive to abilities dependent on the functioning of the frontal lobes but was specially constructed in order to evaluate the EF in a way close to the person's daily life. In addition to the six tests that comprise it and which aim to evaluate EF such as cognitive flexibility, planning and monitoring, BADS also includes a questionnaire of 20 items, the Dysexecutive Questionnaire (DEX; Wilson, Alderman, Burgess, Emslie, & Evans, 1996), which aims to evaluate the impact of a possible executive dysfunction on day-to-day tasks, particularly it aims to identify behavioural, personality, motivational, emotional or cognitive changes.

Despite the existence of different EF tests and EF test batteries, there is still no consensus regarding the test or group of tests ideal for the evaluation of these functions. For example, in a review by Royall et al. (2002), the authors present 46 studies conducted between 1983 and 2001 in which 34 different tests are used for EF assessment. There are, however, some criteria that can be used to select the most appropriate test or test battery in a given situation. First, it is necessary to contextualize the assessment that will be carried out. What is the main objective of the assessment? The assessment of a particular EF, with a specific instrument, or the comprehensive assessment of executive functioning, with a battery of tests? What is the target population? It is important to select tests that have been used in previous studies with the type of population being assessed. Related to this last question is the representativeness of the test in previous studies.

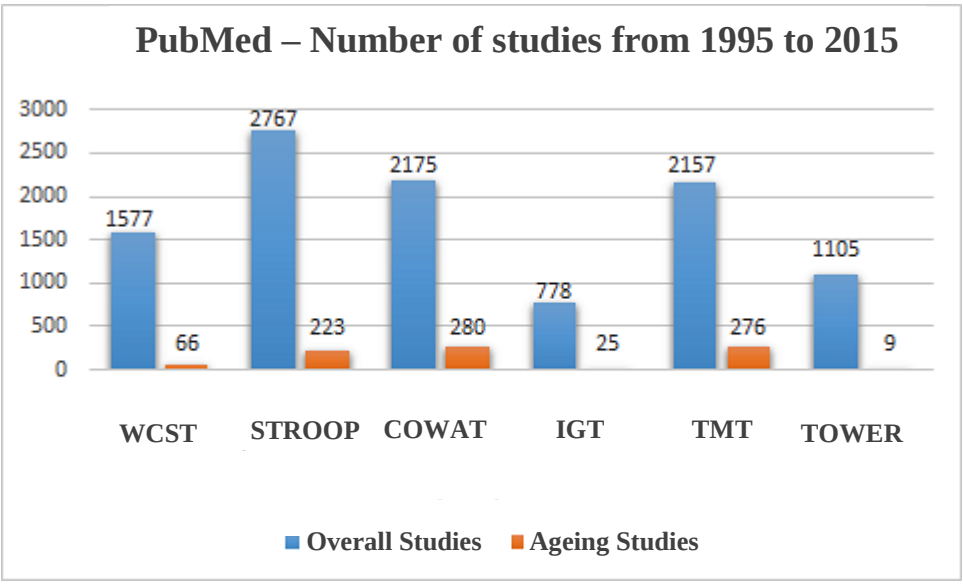

Figure 1. Number of studies that were published between April 1st 1995 and April 1st 2015, in the PubMed Central archive, which mentioned the Tower of London (TOWER), the Stroop Colour-Word test (STROOP), the Wisconsin Card Sorting Test (WCST), the Trail Making Test (TMT), the Controlled Oral Word Association Test (COWAT), and the Iowa Gambling Task (IGT). Among these studies, the number of the ageing studies was identified.

Figure 1 presents the results of a literature search that intended to identify the number of studies that were published between April 1, 1995 and April 1, 2015, in the PubMed Central archive, which mentioned the following tests: Tower of London, Stroop Colour-Word test, the Wisconsin Card Sorting test (WCST), Trail Making Test (TMT), Controlled Oral Word Association Test (COWAT) and the Iowa Gambling Task (IGT). This literature search comprised two distinct phases. In the first phase the tests were selected and a search was conducted for the number of studies that mentioned them during the 20 years period mentioned above (1995-2015). Only tests that have been used as specific EF measures were considered. The EF tests included in this literature search were selected also by its use in clinical settings, with the inclusion of the most often used tests. In the search for the number of studies that mentioned those tests, only the studies published in the form of complete scientific articles were considered. The keywords used were the full names of the assessment tests in English. In a second phase, the full test names were crossed with the term "ageing" or “aging”. In Figure 1, we can see that among the tests most frequently mentioned in the literature in the last 20 years are the Stroop Test, the COWAT and the TMT, whereas the IGT is the least mentioned. The same pattern was found for ageing studies although there are considerably less ageing studies. So, if the representativeness of the test in previous studies is used as a criteria the Stroop test, the TMT and the Verbal Fluency tests would

be the best choices. Other criteria for the tests selection is the selection of the EF tests with the best psychometric properties. In a simple way, we can reduce the psychometric properties of an instrument to its reliability and validity. An instrument is reliable when it produces consistent test-retest results. Examples of measures of an instrument's reliability are internal consistency, time stability, interrater reliability and error of measurement. An instrument is valid when evaluates the variable you want to measure. Examples of validity are content, concurrent, predictive, construct, convergent and discriminant validity. Chan, Shum, Toulopoulou, and Chen (2008) made some considerations on EF assessment tests and highlighted some psychometric aspects especially relevant for the evaluation of EF: reliability and ecological validity. EF allow us, as already mentioned in the introduction to this chapter, to better adaptation to complex environments and novel tasks. However, when the task is not new it may be more difficult to detect EF deficits because the level of EF involvement is reduced by task repetition. Thus, the test-retest reliability scores of EF tests are generally low. In relation to the validity of the EF tests, ecological validity is of particular relevance (Goldstein, 1996; Chaytora, Schmitter-Edgecombea, & Burr, 2006; Lamberts, Evans, & Spikman, 2010). It is generally assumed that brain changes that result in poor performance in a neuropsychological assessment test also imply a lower ability to perform related daily activities outside the assessment context. However, this relationship between performance in the test and functional capacity is not always found in the literature. Some studies have found robust relationships (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Dimitrov, Grafman, & Hollnagel, 1996; Mitchell & Miller, 2008) while others have not identified any significant relationship (Amieva, Phillips, & Della Sala, 2003; Bogod, Mateer, & MacDonald, 2003; Chan, 2001). Despite this inconsistency, longitudinal studies have shown that EF alone can indeed predict the decline in the ability to perform daily activities (Cahn-Weiner, Malloy, Boyle, Marran, & Salloway, 2000; Royall, Palmer, Chiodo, & Polk, 2004). Table 4 presents examples of activities in our daily lives for which the contribution of EF is decisive.

Table 4. Daily activities in which Executive Functions are involved.

- Read a book for several days, remembering what has already been read and anticipating what is going to be read;
- Remember where we put something;
- Remember to take a medicine;
- Organize important personal documents such as bills (e.g., water, electricity, health expenses), VAT, insurances, etc.;
- Dealing with a problem for the first time;
- Make mental calculations while shopping;
- Count the amount of money needed to make a payment;
- Planning and carrying out weekly activities;
- Control the time needed to complete a task;
- Learn new tasks or assimilate new instructions;
- Talk in a noisy environment;
- Dial a phone number to make a call;
-Use a map to locate an office or store to which we are addressing for the first time;
- Understand sequential steps necessary for build something;
- Write a short letter or message to someone.

1.4. Cognitive ageing and executive functions

One of the explanatory hypotheses for age-related cognitive changes is the frontal ageing hypothesis (West, 1996). According to this hypothesis, there is a greater reduction in general volume, white matter density and synaptic density with ageing in the prefrontal cortex, compared to other brain regions (Hedden & Gabrieli, 2004). Neuroimaging studies have shown that with ageing the first changes in brain structure and function occur in the frontal lobes (Raz, Williamson, Gunning-Dixon, Head, & Acker, 2000). Consequently, cognitive functions whose anatomic substrate are related to the frontal lobes and more specifically to the prefrontal cortex are more (early) sensitive to the effects of ageing than functions related to other brain areas (Phillips & Henry, 2008). Particularly relevant in this relationship between executive functioning and ageing is the role of inhibition (Andres & Van der Linden, 2000). With ageing there is a weakening of inhibitory mechanisms (Hasher & Zacks, 1988), which are responsible for the suppression of irrelevant information and the reduction of susceptibility to information interference that although relevant, is contextually inappropriate. These inhibitory deficits have been used to explain other age-related cognitive deficits such as an increased distractibility (Wascher, Schneider, Hoffmann, Beste, & Sänger, 2012), the need for more time to provide an adequate response (Anguera & Gazzaley, 2012), greater forgetfulness due to coding inefficiency or competition between related ideas (Raaijmakers & Jakab, 2013), greater difficulty to understand a conversation when other conversations occur at the same time (Tun, O'Kane, And Wingfield, 2002), or greater inability to ignore visually distracting

information in a reading task (Li, Hasher, Jonas, Rahhal, & May, 1998). Despite this negative impact of the inhibitory deficit, Biss, Ngo, Hasher, Campbell and Rowe (2013) suggest that this age-related inhibition deficit may be beneficial in the daily life of older adults. Biss et al. (2013) found that the repeated presentation of previously memorized items as irrelevant information only benefited elderly and not young adults in the subsequent recall of the memorized items. Older adults, that did not ignored the distracting information due to inhibition deficits, implicitly used this information to minimize or eliminate forgetting associated with ageing. Thus, Biss et al. (2013) suggest that older adults may, in some situations, produce more informed, and even more accurate, decisions because they include more elements that would initially be irrelevant to the decision.

Another relevant model for understanding the cognitive ageing process is the automatic and controlled processing model proposed by Shiffrin and Schneider (1977). According to this model, automatic processes can occur without conscious control. Thus, these processes are fast and can occur in parallel with other operations without losing efficiency. On the other hand, controlled processes require substantial control by the subject, are slow, and rely on limited capacity resources, which reduce the possibility of mobilizing another process at the same time (Posner & Snyder, 1975). However, this limited capacity is, according to Shiffrin and Schneider (1977, p. 156), "*balanced by the benefits deriving from the ease with which such processes may be set up, altered, and applied in novel situations for which automatic sequences have never been learned*.". Examples of controlled and automatic processes can be found in our daily lives. Driving is arguably the best example for understanding the nature of automatic and controlled processing. An experienced driver while driving in known, traffic-free roads uses the mechanisms that control the steering, acceleration and braking of the vehicle automatically. Other tasks like looking through mirrors and following more complex road rules require controlled processes. As demonstrated in this example, daily activities require both controlled and automatic processes. It is also important to note that controlled and automatic processes are not totally distinct processes and that a controlled process may over time become automatic (e.g., if the vehicle is equipped with manual transmission, the driver can initially use the gear in a controlled way, but with experience, it begins to use it automatically, without conscious control). With ageing, controlled processing undergoes a greater decline than automatic processing (Andres et al., 2008).

Cross-sectional and longitudinal investigations have demonstrated the existence of an earlier and more pronounced decline with ageing in EF compared to other cognitive functions (Adkins et al., 2000, Andres & Van der Linden 2000, Crawford et al., 2004). In particular, there is a lower performance of older adults compared to young adults in EF tests such as WCST, Stroop Test or TMT. However, the executive deficit found is not generalized, and the performance of older adults may be similar to that of young adults, even in complex EF tests such as the Tower tests (Collette & Salmon, 2014; Collette, Schmidt, Scherrer, Adam, & Salmon, 2009; Raz et al., 2000). In the following section we will illustrate some examples of the repercussions of ageing on different EF, highlighting the effects of ageing on cognitive flexibility, divided attention, working memory, inhibition and planning.

A central notion of many theories of executive control is the need for specialized mechanisms to allow flexibility and shifts between different tasks to be completed. It is well-known that with ageing there is a loss of the ability to coordinate multiple tasks. Classically, processes underlying task coordination have been studied in ageing research using shifting paradigms, divided attention and dual-task paradigms. Older adults have demonstrated a lower cognitive flexibility capacity than young adults when this ability is assessed by TMT (Salthouse, 2000) and WCST (Crawford et al., 2000). However, there are two levels of cognitive flexibility that are differently affected by ageing. The overall cognitive flexibility, the ability to select and maintain two mental plans, is reduced with ageing; the specific cognitive flexibility, the ability to alternate between two mental plans, is preserved with ageing (Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). Other ability related to our multiple tasks coordination is the ability of divided attention. There is a general agreement that there is a decrease in divided attention abilities with ageing (Bopp & Verhaeghen, 2005). However divided attention can be seen at three different modalities that seem to be differentially affected by ageing: maintaining and manipulating visuospatial information; maintaining and manipulating verbal information; and the ability to coordinate different types of information. The ability to maintain and manipulate multiple verbal information simultaneously and to coordinate different types of information, which requires storage in working memory, are diminished with ageing. However, the ability to maintain and manipulate visuospatial information is even more compromised with ageing (Fournier, Herbert, & Farris, 2004). On the contrary, there is greater capacity for divided attention if the divided attention tasks involve different modalities (Hein & Schubert, 2004).

Working memory (WM) is diminished with ageing (Rajah & D'Esposito, 2005). However, various WM functions or systems seem to be differently affected by ageing. There is a decrease in the capacity of updating WM (i.e., central executive) but not in storage capacity (i.e., phonological cycle, episodic buffer and visuospatial storage area) (De Leon & Palladino, Rettenbach, Nase, & Sireteanu, 2002). Another important point to understand age-related changes in WM is the type of information to be maintained and modified. A greater decline in the performance of older adults in spatial WM tasks than in verbal WM tasks has been identified (Myerson, Hale, Rhee, & Jenkins, 1999). WM for spatial information is then especially weakened with ageing.

Despite the decline in the efficiency of the inhibitory processes with ageing already discussed throughout this chapter, not all inhibitory processes decline with ageing. In a recent review, Pires, Leitão, Guerrini, and Simões (2014) suggested that the activation of inhibitory processes for the suppression of irrelevant information is diminished with ageing but only with respect to controlled inhibition processes such as motor inhibition or inhibition that is activated to resolve the interference in a Stroop task. Other inhibition processes are related to automatic processes and are more resistant to ageing effects. The inhibition involved in interference resolution in an Eriksen Flanker task (in which the irrelevant and relevant information are spatially segregate), semantic inhibition and sensory inhibition are a few examples of these inhibition processes less affected by ageing.

Older adults have a reduced planning ability while compared with young adults (Godbout, Doucet, & Fiola, 2000). However, planning can be described at two levels differently affected by ageing. The formulation of the plan, which involves the ability to develop a logical mental strategy to achieve a goal, would be more diminished with ageing than the execution of the plan, which involves the ability to monitor and guide the successful execution of plan (Allain et al., 2005). Table 5 summarizes EF that are preserved and EF that are impaired in older adults compared to young adults.

Table 5. Ageing of Executive Functions (EF): preserved functions vs age-related deficit functions.

Preserved EF	EF with age-related deficit
Specific Cognitive Flexibility (e.g., alternation between two semantic categories) (Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011)	Global Cognitive Flexibility (Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011)
	Divided Attention between verbal (Hein & Schubert, 2004) or visuospatial tasks (Fournier, Herbert, & Farris, 2004) Although it is less compromised when the two tasks do not share the same sensory modality (Hein & Schubert, 2004)
Storage capacity in working memory (De Beni & Palladino, 2004; Leonards et al. 2002; Myerson et al., 1999)	Update capacity in working memory (De Beni & Palladino, 2004; Leonards et al. 2002; Myerson et al., 1999)
Semantic inhibition, sensory inhibition and resistance to interference from inappropriate information (Pires et al., 2014)	Motor Inhibition; Inhibition of irrelevant information (Pires et al., 2014)
	Planning (although the ability to formulate a plan is more harmed than the ability to execute the plan) (Allain et al., 2005).

Some of the differences found in executive functioning between older adults and young adults may be explained by a decrease in processing speed in older adults. These age-related slowing is an important mediator of the diminished performance usually found for older adults in EF tests (Albinet, Boucard, & Audiffren, 2012). On the contrary, similar performance of older adults and young adults in the same executive task does not determine that EF processing is unaffected (Burke & Barnes, 2006). In fact, older adults and young adults exhibit different brain activity patterns that seems to reflect the use of different strategies for an efficient task performance (Phillips & Andres, 2010; Turner & Spreng, 2012). Functional brain imaging of executive control processes reported robust differences in brain activity during the same executive task between older adults and young adults (Turner & Spreng, 2012). One of the explanatory hypotheses for these discrepancy is the compensatory hypothesis proposed by Reuter-Lorenz and Cappell (2008). According to this hypothesis there is a compensatory use of extra neuronal circuits in older adults that results in efficient processing even in tasks in which greater executive control is needed. For example, in older adults there is an extra activation of the lateral prefrontal cortex regions that function as a neural scaffold that temporarily supports performance in complex or novel tasks (Park & Reuter-Lorenz, 2009).

In conclusion, ageing is accompanied by a decrease in performance in tasks that mobilize different EF. However, this deterioration in EF is not general. Older adults can

perform similarly to young adults in different EF tasks, especially if variables such as processing speed are controlled. Nevertheless, this similar performance at a behavioural level can be explained by the existence of compensatory mechanisms in older adults such as the recruitment of other executive and non-executive functions.

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2. Confirmatory factor analysis of neurocognitive measures in healthy young adults: The relation of executive functions with other neurocognitive functions

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2.1. Structured Abstract

Objective: The present study aimed to investigate the factor structure of a set of neurocognitive tests that the literature classically consider measures of executive functions (EF), verbal abilities (VA) and processing speed (PS). This study extended previous research by analysing if these tests are explained by the specific factor to which it theoretically belongs or by a general neurocognitive factor; and also by analysing the relations between the neurocognitive factors.

Methods: Using confirmatory factor analysis (CFA) we examined the factor structure of nine neurocognitive tests (that in theory assess inhibition, working memory, planning, verbal fluency, selective and divided attention, episodic memory, confrontation naming and processing speed) in a nonclinical sample (N=90; 18-33 years old, 76 women). We tested five factor models of neurocognitive functioning: a one-factor model; two models with two correlated factors; and two models with three correlated factors.

Results: A three-correlated-factor model, with EF, VA and PS factors, was the most parsimonious for our neuropsychological data. The Verbal Fluency test was better explained in the VA factor rather than on the EF factor. The EF factor was correlated with the PS factor, but not with the VA factor.

Conclusions: Despite the fact that most of the neurocognitive measures used in the present study were derived theoretically, they loaded in the expected factors (the exception was Verbal Fluency that is more related to VA). EF and PS represent related but separable functions. Our results highlight the need for a careful interpretation of test scores since performance in one test usually requires multiple functions.

Keywords: Cognition; Executive Functions; Verbal Abilities; Processing Speed; Neuropsychological Assessment; Confirmatory Factor Analysis.

2.2. Introduction

Many of the tests currently used in clinical neuropsychology were derived from theoretical models of neurocognitive functions (e.g., Chan, Shum, Toulopoulou, & Chen, 2008). For example, Tower tests (Simon, 1975; Shallice, 1982; Delis, Kaplan, & Kramer, 2001) commonly used in neuropsychological assessment are derived from the supervisory attentional system (SAS) model from Norman and Shallice (1986). According to this model, cognition depends on the activation and interaction of two systems: a contention scheduling system, responsible for routine/automatic behaviour; and supervisory attentional system, responsible for non-routine/controlled behaviour. The Tower tests allow the study of these systems since an optimal performance in these tests involves both automatic and control functions such as planning, monitoring and inhibition.

Even though most neuropsychological tests are theory-driven, it is crucial to analyse their psychometric properties (e.g., the reliability and validity of the test) to improve their clinical utility allowing a better interpretation of the results. Performance on neuropsychological tests often rely on the recruitment of multiple functions and it is critical to define the functions being assessed in each test. This dependence on several functions is especially noticeable on neuropsychological tests tapping executive functions' assessment. Executive Functions (EF) comprise different cognitive capacities such as planning, cognitive flexibility, updating, inhibition, abstraction, decision making, among others (Royall et al., 2002). The role of these diverse functions in orchestrating resources such as memory, attention or language is vital to achieve success in everyday activities and interpersonal relationships (Jurado & Rosselli, 2007). An adequate performance in a test that in theory should assess a specific executive function, depends on the involvement of non-executive functions (nEF) and even on the recruitment of other EF (Burgess, 1997; Royall et al., 2002). For example, the Stroop Colour Word test (Stroop, 1935), requires nEF like reading and naming (MacLeod, 2015), whereas the Verbal Fluency test (Benton, 1968; Newcombe, 1969) requires not only EF but also verbal abilities including lexical knowledge and retrieval (Shao, Janse, Visser, & Meyer, 2014). Conversely, many nEF tests also involve EF. For example, in

the Word List test (Wechsler, 1997b) the participant must recruit EF, such as the abilities of updating and inhibiting, in order to correctly retain in long term memory a list of words (Duff, Schoenberg, Scott, & Adams, 2005).

Conversely, EF are also closely related to processing speed (PS). As a basic cognitive function that mediates higher cognitive processes, PS is determinant for EF efficiency. Many EF tests are time-limited and even without a time limit a faster PS can be advantageous since it leads to a more rapid flow of information, enhancing test performance. Regardless of the relationship between PS and EF, PS does not influence all measures of EF in the same way (Salthouse, Atkinson, & Berish, 2003). For example, the Stroop Colour Word test, a measure of inhibition, is heavily dependent on PS since a better score depends on the time taken to complete the task (MacLeod, 2015). However, a good performance on the Wisconsin Card Sorting Test (WCST; Berg, 1948), a measure of cognitive flexibility, is not dependent on the time taken to complete the task and therefore the PS will be less determinant to task performance (Nyhus & Barcelo, 2009). This complex nature of EF, as multiple control functions acting upon several aspects of cognition, contributed to the current uncertainty about the nature of these functions. Currently, EF can be conceptualized as a unitary process (Duncan & Owen, 2000), a set of separable functions (Stuss & Alexander, 2007) or as both unitary and diverse functions (Friedman & Miyake, 2017). In order to clarify the nature of EF, factor analytic studies [exploratory factor analysis (EFA) and confirmatory factor analysis (CFA)] have been conducted to identify constructs underling EF test performance in clinical (Park et al., 2012; Savla et al., 2012; Voss & Bullock, 2004) and healthy populations (Fisk & Sharp, 2004; Miyake et al., 2000; Testa, Bennett, & Ponsford, 2012). EFA studies of EF have been conducted to explore the underlying factor structure of a set of EF tests or a set of items within the same test. This has generally been done without any a priori hypothesis about the possible relationship between the tests/items or about the number and nature of the underlying factors. For example, Testa, Bennett and Ponsford (2012) used EFA to identify the underling factor structure of nineteen EF tests in healthy adults. A principal components analysis with varimax rotation was performed and six independent factors were found: prospective working memory, set shifting and interference management, task analysis, response inhibition, strategy generation and regulation, and self-monitoring or set-maintenance. Their results revealed the diversity of cognitive functions assessed by the EF tests, explored their interrelationship and indicated how each one of these factors

explained performance on the EF tests. CFA are usually conducted to verify an a priori hypothesized factor structure for a set of tests/items based on theoretical assumptions, empirical research (e.g., EFA studies), or both. An example is the study conducted by Miyake et al. (2000) in which three EF were analysed: shifting, updating, and inhibition. Young adults performed 9 computerized tasks, 3 for each EF under study. They compared a three-factor model in which shifting, updating and inhibition were related but separable functions to other possible models (i.e., one-factor model, two-factor model and three-factor models in which the three EF were completely independent). Their results supported a three-correlated factor model showing that the three EF were indeed related but also separable functions. Therefore, CFA seems to be particularly relevant in determining the organization of EF and several CFA studies were conducted for this purpose (see Table 1). Most of these CFA studies were conducted with children (Brydges, 2012; Duan, Wei, Wang, & Shi, 2010; Friedman et al., 2006; Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; Miller, Giesbrecht, Müller, McInerney, & Kerns, 2012; Usai, Viterbori, Traverso, & De Franchis, 2014; van der Sluis, de Jong, & van der Leij, 2007; van der Ven, Kroesbergen, Boom, & Leseman, 2013; Wiebe, Espy, & Charak, 2007) but some CFA studies were also conducted with young adults (Miyake et al., 2000) and older adults (Hull, Martin, Beier, Lane, & Hamilton, 2008).

Table 1. Factor Analytic Studies of Executive Functions.					
Authors/Year	Sample	Number of Tests	Factorial Analysis	Number of Factors	EF Factors
Wiebe, Espy, & Charak (2007)	N=243 (135 girls) 2 to 6 years old	10 EF tests	CFA	1	-Executive Function
Miller, Giesbrecht, Muller, McInerney, & Kerns (2012)	N=129 (51 girls) 3 to 5 years old	8 EF tests	CFA	1	-Executive Function
van der Ven, Kroesbergen, Boom, & Leseman (2013)	N=211 (101 girls), 6 years old	9 EF tests	CFA	2	-Updating -Shifting and Inhibition
Usai, Viterbori, Traverso, & De Franchis (2014)	Time 1: N=175 (76 girls), 5 and 6 years old Time 2: N=145 (57 girls), 6 years old	6 EF tests 1 Fluid Intelligence test	CFA	2	-Inhibition -Working Memory and Shifting
Brydges, Reid, Fox, & Anderson (2012)	N=215 (105 girls) 7 to 9 years old	9 EF tests 1 Fluid Intelligence test 3 Crystalized intelligence test	CFA	1	-Executive Function
Lehto, Juujarvi, Kooistra, & Pulkkinen (2003)	N=108 (48 girls) 8 to 13 years old	9 EF tests	EFA and CFA	3	-Working Memory -Inhibition -Shifting
van der Sluis, de Jong, & van der Leij (2007)	N=172 (88 girls), 9 to 12 years old	11 EF tests 2 Fluid Intelligence test 2 Crystalized intelligence test	CFA	2	-Updating -Shifting
Duan, Wei, Wang, & Shi (2010)	N=61 (27 girls), 11 and 12 years old	7 EF tests 1 Fluid Intelligence test	CFA	3	-Updating -Inhibition -Shifting
Friedman, Miyake, Corley, Young, DeFries & Hewitt (2006)	N=234 twins 16 to 18 years old	8 EF tests 2 Fluid Intelligence test 2 Crystalized intelligence test	CFA	3	-Updating -Inhibition -Shifting
Miyake, Friedman, Emerson, Witzki, and Howerter (2000)	N=137 undergraduates	9 EF tests	CFA	3	-Updating -Inhibition -Shifting
Hull, Martin, Beier, Lane, & Hamilton (2008)	N=100 (80 women), 51 to 74 years old	12 EF tests 1 Fluid Intelligence test 1 Crystalized intelligence test	CFA	2	-Updating -Shifting
EF- Executive Functions; CFA – Confirmatory Factor Analysis; EFA – Exploratory Factor Analysis					

Most of the factor analytic studies conducted so far, focused on defining the underlying factor structure of a set of tests assessing specific cognitive functions like EF. However, in clinical settings comprehensive neuropsychological batteries are often used, assessing distinct cognitive functions that are interrelated (e.g., an EF test encompasses also nEF and at the same time nEF tests rely on EF). Some studies used EFA and/or CFA to study the underlying factor structure of comprehensive neuropsychological batteries that were administered to clinical (Dowling, Hermann, La Rue, & Sager, 2010; Hayden et al., 2011; Leonard et al., 2007; Park et al., 2012; Stinnett, Oehler-Stinnett, Fuqua, & Palmer, 2002) or non-clinical samples (Floyd,

Bergeron, Hamilton, & Parra, 2010; Greenaway, Smith, Tangalos, Geda, & Ivnik, 2009; Moleiro et al., 2013; Mosconi, Nelson, & Hooper, 2008; Moura et al., 2017; Pedraza et al., 2005; Santos et al., 2015; Siedlecki, Honig, & Stern, 2008; Tuokko et al., 2009). For example, Stinnett et al. (2002) examined with EFA the underlying factor structure of the NEPSY, a neuropsychological battery assessing attention/executive functions, language, sensorimotor functions, visuospatial processing, memory and learning in children. They found that a structure with only a single neurocognitive factor was the most suitable, with almost all the tests adequately loading in this single factor. This study highlighted the common variance among tests theoretically assessing different cognitive domains. Santos et al. (2015) investigated the factor structure of neurocognitive measures assessing general cognitive status, short and long term memory, inhibition and verbal fluency in older adults. They found with EFA a two-factor solution with memory and general/executive function. Then, they used CFA in a distinct sample from the same original cohort to confirm that a two-correlated factor model suggested by EFA was indeed the best fit. Recently, Moura et al. (2017) studied the factor structure of the Coimbra Neuropsychological Assessment Battery (BANC; Simões et al., 2016), that comprise the assessment of laterality, motor function, orientation, memory, language and attention/executive functions abilities in children. Only the tests theoretically assessing memory, language and attention/executive functions were studied. Several neurocognitive models with three, four and five factors were compared and a three-correlated factor model (memory, language and attention/executive function) represented the best fit to their data. Overall, mixed results have been found in respect to the factor structure derived from EFA and/or CFA and the proposed theoretical models. The present study aimed to investigate the factor structure of nine neurocognitive tests theoretically assessing EF, verbal abilities (VA) and PS. This study extended previous research by analysing if these tests are explained by the specific factor to which it theoretically belongs or by a more general neurocognitive factor; and analysing the relations between the neurocognitive factors. In order to analyse different aspects of EF, we included measures of inhibition, working memory (WM), planning, verbal fluency and divided attention. Inhibition and WM (particularly the updating function of its content) are considered core EF functions (Miyake et al., 2000). Verbal fluency tasks have also been commonly used as an EF measures and it is clear that a number of EF (e.g., inhibition, updating) contribute to performance in these tasks along with memory and language processes (Henry & Crawford, 2004; Moura, Simoes, &

Pereira, 2015). The ability to execute complex plans (Allain et al., 2005) and divided attention abilities have also been described as relevant EF (Diamond, 2013). We also included two VA measures, one assessing verbal episodic memory and the other one assessing confrontation naming ability. We are not advocating that these VA measures do not comprise any EF abilities but we selected measures in which the level of EF involvement is certainly reduced in comparison to the one needed in the EF tests (Bowles, 1993; Duff et al., 2005). Because PS may be an important mediator of the selected EF and VA measures (Bryan & Luszcz, 1996; Bryan, Luszcz, & Crawford, 1997; Henninger, Madden, & Huettel, 2010; Lee et al., 2012), we also included two PS measures. We tested through CFA five models of neurocognitive functioning:

1. Model 1: A one-factor model suggesting that neuropsychological tests that in theory assess different cognitive domains are better explained by a single neurocognitive factor, as found for example by Stinnett et al. (2002);
2. Model 2: A two-correlated factor model with EF and nEF factors, in which the VA and PS measures are included in the nEF and Verbal Fluency that is theoretically related to both EF and VA was included in the EF factor. The separation between EF and nEF (such as memory, language and PS) has been found in different studies (Floyd et al., 2010; Leonard et al., 2007). The inclusion of the Verbal Fluency measure as EF is supported by previous studies (Moleiro et al., 2013; Moura et al., 2017; Santos et al., 2015);
3. Model 3: Another two-correlated factor model with EF and nEF factors was tested. PS measures were included in the EF factor, considering PS as a basic function underlying performance in EF tests (Park et al., 2012);
4. Model 4: Despite the close relationship between PS and other neurocognitive measures, several studies suggest that PS is separable from EF and nEF (Floyd et al., 2010; Leonard et al., 2007; Moleiro et al., 2013). So we tested a three-correlated factor model with EF, PS and VA factors.
5. Model 5: Another three-correlated factor was tested. It was identical to Model 4, except for the inclusion of Verbal Fluency in the VA factor, as suggested by previous studies (Floyd et al., 2010; Park et al., 2012; Siedlecki et al., 2008).

We hypothesized that a three-correlated-factor model (Model 4 or Model 5) would best represent the underlying structure of our neurocognitive battery. We expect that EF, VA and PS will be separable but related functions.

2.3. Method

2.3.1. Participants

A sample of 115 young adults volunteered to participate. All the participants were first-year Psychology students at the University of Coimbra (Portugal) and received course credit in return for their participation. They provided written informed consent in accordance with institutional guidelines prior to their inclusion in the study. The study was approved by the ethical committee of the Psychology department. Exclusion criteria comprised current or previous diagnosis of psychologic, psychiatric or neurologic disorder, vision or hearing impairment. In addition, during neuropsychological assessment, participants were screened for depressive symptoms with the Beck Depression Inventory II (Beck, Steer, & Brown, 1996) and a cut-off score of 20 points (i.e., moderate depression symptoms) was used to determine exclusion. Due to the presence of moderate depressive symptoms, sixteen participants were excluded from the sample. Nine participants were also excluded due to current psychoactive medication intake (e.g., anxiolytics) and/or the presence of other medical conditions that could interfere with behavioural testing (e.g., Diabetes Mellitus). As a result, data from 90 young adults (76 female; 18-33 years old, *M*=19.77, *SD*=2.85; 12-20 years of formal education, *M*=13.10, *SD*=1.47) were analysed. The mean estimated intelligence, as measured by the TeLPI - Irregular Words Reading Test (Alves, Simoes, & Martins, 2012), a Portuguese test similar to the National Adult Reading Test (Nelson, 1982), was 118.33 (range=108-130), indicating that the sample was well placed within the average range for their age and education levels.

2.3.2. Materials

A comprehensive neuropsychological battery designed to assess EF (i.e., inhibition, planning, WM, divided attention, and verbal fluency), VA (i.e., episodic memory and confrontation naming) and PS was administered to all participants.

Below we present the different measures included in the CFA analysis.

Coding - The Digit Symbol Coding or Coding test (Wechsler Adult Inteligence Scale - Third edition; Wechsler, 1997a) allows the evaluation of psychomotor control,

processing speed, sustained attention and (incidental) memory (Joy, Kaplan, & Fein, 2004). The examinee must copy symbols previously associated with numbers, in a predetermined matrix. Thus, the examinee's capacity to make a fast association between symbols and numbers is evaluated in this task. There is a time limit of 2 mins. The total score is the number of correct items within the time limit, ranging from 0 to 133 points.

Telephone Search – This subtest from the Test of Everyday Attention battery (TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994) involves visual selective attention and processing speed. In this task the participants have to look at stimuli similar to the yellow pages from a telephone directory, in which they can find different services (i.e., restaurants, plumbers…). In these yellow pages there are pairs of symbols (e.g., a square and a circle; two stars…), one pair per service, and the participants must search for the pairs in which the symbols are the same (e.g., two circles) and ignore the mismatched pairs (e.g., one star and one circle). The participant is instructed to complete the task as fast and accurate as possible. There is a time limit of 4 mins. The total score is the time per target, the mean time needed to correctly identify each one of the targets. This time per target measure is used in the analyses.

Divided Attention - This divided attention measure is obtained from the difference between the time per target in the Telephone Search and the time per target when the participant has to perform the same task (a parallel form is used) while trying to execute a second task at the same time. This second task requires the participant to count a series of phone tones played by an audio recorder – the Dual Task Telephone Search subtest from TEA. In this test the instructions emphasize that both tasks are equally important and the participant must complete both tasks as accurately as possible. The time required to complete the task is 4 mins.

Working Memory – This is a composite WM score obtained from two WM tests: a verbal WM test (Digit Suppression Test - DST; Beblo, Macek, Brinkers, Hartje, & Klaver, 2004) and a spatial WM test (Block Suppression Test - BST; Beblo et al., 2004). In the DST the participant must repeat every second digit of a sequence of digits orally presented by the examiner, beginning with the first digit (e.g., 1-7-4 repeats 1-4; 1-5-7-8 repeats 1-7). The trial starts with a sequence of 3 digits and the length of the sequences increases until 16 digits are reached. There is a total of 28 items, two for each level. The task ends when the participant fails to correctly recall the digits of the two items of the same level (i.e., same sequence length). The total score is the number of accurately remembered digits, ranging from 0 to 28 points. In the BST, the spatial

version of the DST, the participants must tap every second block of a sequence of blocks tapped by the examiner, beginning with the first block. The blocks are tapped by the examiner in a 1 sec pace. The task ends when the participant fails to correctly tap the blocks in the two items of the same level. The total score is the number of accurately reported taps. The composite measure obtained from verbal and spatial WM tests is used.

Stroop - In this version of the Stroop test (Castro, Martins, & Cunha, 2003; Trenerry, Crosson, DeBoe, & Leber, 1989) there are four colours (red, blue, pink and grey) used in four tasks: reading coloured words in which the written colour word and the ink colour in which the word is printed are incongruent (e.g., the word red printed in blue reads "red"); the Stroop condition - naming the colour of coloured words (e.g., the word red printed in blue says "blue"); reading colour words printed in black ink (e.g., the word red printed in black reads "red"); naming the colour of coloured bars (e.g., when the bar is filled with red ink says "red"). The task contains 112 items and has a time limit of 2 mins. In the Stroop Test we use the number of correct items in the reading black words task (W) and the number of correct items in the naming coloured bars task (C) to predict the number of correct items in the Stroop condition [WC'= (WxC)/(W+C)]. Then we computed the difference between the number of correct items in the Stroop condition (WC) and the prediction (WC-WC') and used it as a measure of interference.

Tower – This is a subtest from the Delis-Kaplan Executive System (D-KEFS; Delis, Kaplan & Kramer, 2001) in which the participants are asked to construct several towers up to a maximum of nine towers. A photograph with the tower to be constructed is presented to the participant, who has to manipulate wooden disks with different sizes and blue colour tones on a board with three vertical pegs. They must construct each tower using as few movements as possible and follow two rules: (i) move just one disk at a time, using only one hand; (ii) never place a larger disk on a smaller disk. The difficulty level increases from the 1st tower to the 9th tower (e.g., in the 1st tower one movement is necessary to complete the tower; in the 9th tower at least 26 movements must be executed to correctly construct the tower). All the items have a time limit (e.g., the 1st tower has a time limit of 30 sec; the 9th tower has a time limit of 240 sec). The achievement score, combining the number of correct towers and the overall movement accuracy, was used in the analyses.

Verbal Fluency – This is a composite Verbal Fluency score obtained from two tests from D-KEFS: the Phonemic Fluency test and the Semantic Fluency test. In the Phonemic Fluency test the participant is asked to generate as many words as possible beginning with a specific letter within 1 minute. There were three phonemic categories: P, M, and R. These categories represent the Portuguese language equivalent to the F, A and S categories used in English language. In the Semantic Fluency test the participant is asked to generate as many words from a semantic category as possible within 1 minute. There were three semantic categories: animals; food commonly found in a supermarket; things people do (i.e., action verbs). In both phonemic and semantic tasks the sum of the number of words recalled during the three categories was computed. The composite measure obtained from Phonemic and Semantic Fluency tests was used in the analyses.

Confrontation Naming – This is a subtest from the Psycholinguistic Assessment of Language battery (PAL 09; Caplan & Bub, 1990; Portuguese version, PAL-PORT, Festas, Martins, Leitão, 2007). In this task the ability of the participant to access the phonological form of words from the meaning (activated by black and white pictures) is assessed. There are 44 pictures corresponding to 44 words from seven semantic categories (animals, fruits, clothes, artefacts; instruments, vehicles and vegetables), with high and low frequency (22 items each) and with long and short length (22 items each). The total score is given by the number of correct named pictures, ranging from 0 to 44 points.

Word List – This test from Wechsler Memory Scale – third edition (WMS-III; Wechsler, 1997b) assesses verbal episodic memory. It encompasses free immediate recall of 12 words' lists over four trials, followed by a free short-delayed recall (after the recall of an interference 12 words' list) and long-delayed recall (after a 25mins interval). There is also a delayed recognition test (with 24 words, 12 new and 12 presented before). The total score is derived from the number of words recalled or accurately recognised. In this task we only used the percentage of long-delay retention.

2.3.3. Procedure

Participants needed in average 1.5 hours to complete testing. The testing sessions were always conducted in a well-lit room within the Psychology Department. The neuropsychological tests were administered in random order except for the following

order constraints: (i) the long-term interval of the Word List test (25 mins) was always occupied with the same tests applied in the same order: a semi-structured interview; the Beck Depression Inventory; and the Digit Symbol Coding. These tests did not include words as stimuli that could cause interference with the learned word list; (ii) the Telephone Search subtest was always administered prior to the Dual Task Telephone Search subtest, following guidelines from TEA; (iii) the Digit Suppression and the Block Suppression tests were always administered together to facilitate instructions comprehension and were applied in a random order; (iv) the Phonemic Fluency and the Semantic Fluency tests were always administered together to facilitate instructions comprehension and were applied in a random order.

2.3.4. Data Analysis

To control for the influence of age (ranging from 18 to 33 years old) and years of formal education (ranged from 12 to 20 years) on the results of the neurocognitive measures, an adjusted score was created by regressing the raw score of each neurocognitive measure onto age and formal education years, and then saving the standardized residual score. These standardized residual scores were used in the CFA analysis.

To test the factor structure of the neuropsychological battery, a CFA was performed using IBM SPSS Amos 20 (Arbuckle, 2011). The models tested were estimated through covariance matrices using maximum likelihood estimation. Model fit was assessed through various fit statistics. We reported chi-square (χ^2), two absolute fit indices (SRMR and RMSEA), as well as an incremental fit index (CFI) and a parsimonious fit index (AIC). The χ^2 is known to be extremely sensitive to sample size, meaning that with larger samples, even reasonable models are likely to produce statistically significant chi-square *p* values (Bentler, 1990; Bentler & Bonett, 1980; Bryant & Yarnold, 1995; Joreskog & Sorbom, 1986). Therefore, the use of other fit indices besides the chi-square is recommended (Byrne, 2005). Hu and Bentler (1999) recommend a CFI of > .95, a SRMR of < .08 and an RMSEA of < .06 to determine good fit. The AIC was reported to compare different models, with smaller values representing a better fit. As suggested by Marsh, Hau, and Wen (2004) these traditional cut-off values should not be used as rules of thumb. Therefore, more stringent cut-off values are recommended for simple models, and less stringent cut-off values are

recommended for more complex models (Cheung & Rensvold, 2002; Marsh et al., 2004).

2.4. Results

2.4.1. Descriptive Statistics and Correlation Analysis

Descriptive statistics (raw scores) for each neurocognitive test are presented in Table 2. For the Telephone Search test and the Stroop test higher values indicate worse performance. For the Divided attention values closest to 0 indicate better performance. For all the other tests higher values indicate better performance.

Table 2. Mean, standard deviations (SD) and range scores of the neurocognitive measures (N=90).

Test		Dependent Measure	Mean (SD)	Range
Coding (WAIS-III)		Number of correct codifications	89.50 (13.37)	59 – 117
Telephone Search (TEA)		Time per target (sec)	2.96 (.72)	1.8 – 6
Confrontational Naming (PAL)		Number of correct named pictures	33.41 (3.55)	22 – 42
Long-term Recall–Word List (WMS-III)		% of retention after a 25 mins interval.	89.70 (12.77)	50 – 110
Divided Attention		Difference between the Time per target (sec) in Telephone Search and in Dual Task Telephone Search	-1.38 (1.87)	-8.34 – 3.77
Working Memory	Digit Suppression Test	Number of correct items	12.36 (3.49)	3-18
	Block Suppression Test	Number of correct items	11.09 (3.35)	4-19
Stroop		Interference Score	49.09 (10.67)	10 – 56.50
Tower (D-KEFS)		Achievement score	17.80 (3.59)	10 – 27
Verbal Fluency	Phonemic Fluency	Sum of total number of words in three conditions: P; M; R	35.46 (10.23)	16 – 64
	Semantic Fluency	Sum of total number of words in three conditions: Animals; Food commonly found in a supermarket; Verbs	56.97 (10.54)	29 – 82

WAIS-III - Wechsler Adult Intelligence Scale 3rd version; TEA - Test of Everyday Attention; PAL - Psycholinguistic Assessment of Language; WMS-III - Wechsler Memory Scale 3rd version; D-KEFS - Delis–Kaplan Executive Function System.

The correlations among all the measures are presented in Table 3. There are several significant correlations between the neuropsychological measures, mostly of moderate size (Cohen, 1988). There was a strong and positive correlation between WM and Stroop measures [$r(88) = .501$, $p < .01$], a moderate and positive correlation between the WM and Divided Attention measures[$r(88) = .355$, $p < .05$], and a small and positive correlation between WM and Tower measures [$r(88) = .255$, $p < .01$]. Verbal Fluency was not significantly correlated to any EF measure, but a moderate and positive correlation was found with Confrontation Naming [$r(88) = .316$, $p < .01$] and a small and negative

correlation was found with Telephone Search [$r(88) = -.292$, $p<.01$]. A moderate and negative correlation between the Coding and Telephone Search tasks [$r(88) = -.374$, $p<.01$] was found.

Table 3. Pearson product-moment correlations between neurocognitive measures.

	1	2	3	4	5	6	7	8	9
1.Telephone Search	1								
2.Divided Attention	-.009	1							
3.Stroop	-.340**	.181	1						
4.Tower	.003	.189	.181	1					
5.Working Memory	-.108	.355**	.501**	.255**	1				
6.Verbal Fluency	-.292**	-.077	.120	-.029	-.017	1			
7.Confrontation Naming	-.129	-.083	-.016	.027	.025	.316**	.1		
8. Word List	-.123	-.0.90	.070	-.051	.080	.193	.347**	1	
9. Coding	-.374**	.135	.398**	.169	.195	.111	.110	.175	1
*$p<.05$ **$p<.01$									

2.4.2. Confirmatory Factor Analysis

CFA enabled us to evaluate several *a priori* models (i.e., based on theoretical considerations and on the results of previous factor analysis studies) in terms of their fit with the observed data. Five theoretical models of neurocognitive functioning were tested through CFA (see Table 4).

Table 4. Factor models estimated through CFA

Models	Factors	Variables
Model 1 (one-factor model)	Single neurocognitive factor	Working Memory; Tower; Divided Attention; Stroop; Verbal Fluency; Word List; Confrontation Naming; Coding; Telephone Search
Model 2 (two-correlated-factor model)	EF	Working Memory; Tower; Divided Attention; Stroop; Verbal Fluency
	nEF	Word List; Confrontation Naming; Coding; Telephone Search
Model 3 (two-correlated-factor model)	EF	Working Memory; Tower; Divided Attention; Stroop; Verbal Fluency; Coding; Telephone Search
	nEF	Word List; Confrontation Naming
Model 4 (three-correlated-factor model)	EF	Working Memory; Tower; Divided Attention; Stroop; Verbal Fluency
	VA	Word List; Confrontation Naming
	PS	Coding; Telephone Search
Model 5 (three-correlated-factor model)	EF	Working Memory; Tower; Divided Attention; Stroop
	VA	Word List; Confrontation Naming; Verbal Fluency
	PS	Coding; Telephone Search
EF - Executive Functions; nEF - Non-Executive Functions; VA - Verbal Abilities; PS - Processing Speed		

In Model 1 (one-factor model) we tested how the nine neurocognitive measures are explained by a single (general) neurocognitive factor (see Table 4). As shown in Table 5, Model 1 did not provide a good fit to the data, with CFI = .674; RMSEA (90% CI) = .106 (.064 - .147); and SRMR =.109. So, a single neurocognitive factor is not sufficient to explain the variance in most the tests.

Table 5. Goodness-of-fit indices for the five factor models estimated through CFA

CFA models	χ^2	*Df*	χ^2/df	CFI	RMSEA (90% CI)	SRMR	AIC
Model 1	53.964, p = .002	27	2.00	.674	.106 (.064 - .147)	.109	89.964
Model 2	45.397, p = .011	26	1.75	.765	.092 (.044 - .135)	.101	83.397
Model 3	42.853, p = .020	26	1.65	.796	.085 (.034 - .130)	.098	80.853
Model 4	34.887, p = .070	24	1.45	.868	.071 (.000 - .120)	.089	76.887
Model 5	24.661, p = .424	24	1.03	.992	.018 (.000 - .088)	.065	66.661

χ^2 = Chi-square; χ^2/df = Relative/Normed Chi-square; CFI= Comparative Fit Index; RMSEA (90% CI) = Root Mean Square Error of Approximation (90% confidence interval); SRMR = Standardised Root Mean Square Residual; AIC = Akaike Information Criterion.

A two-correlated-factor model, Model 2, was then tested. This model predicts that the neurocognitive measures included in our battery can be explained by two factors: an EF factor, and a nEF factor, including VA and PS measures (see Table 4). Model 2 did not provide a good fit to the data, with CFI = .765; RMSEA (90% CI) = .092 (.044 - .135); and SRMR = .101. Another two-correlated factor model (EF and nEF factors) was tested, with PS measures included in the EF factor (Model 3). This model also did not provide a good fit to the data, with CFI = .796; RMSEA (90% CI) = .085 (.034 - .130); and SRMR = .098. So, the two-factor models (i.e., Model 2 and Model 3) were unable to adequately explain the data. Subsequently, we tested two different three-factor models, with EF, VA and PS factors. In Model 4, Coding and Telephone Search were included in the PS factor, whereas Verbal Fluency remained in the EF factor. Despite these changes, Model 4 did not provide a good fit to the data, with CFI = .868; RMSEA (90% CI) = .071 (.000 - .120); and SRMR = .089. Finally, another three-correlated factor model was tested with one adjustment relative to Model 4: the inclusion of Verbal Fluency in the VA factor. In Model 4, Verbal Fluency was poorly explained by the EF (λ = .12).Thus, the inclusion of Verbal Fluency on the VA factor makes empirical and statistical sense. Model 5 showed a good model fit, with CFI = .992;

RMSEA (90% CI) = .018 (.000 - .088); and SRMR = .065. Taken together, the results from the CFA showed that Model 5 provided the best fit to the data. The factor loadings and correlations among factors of Model 5 are presented in Figure 1. EF and VA are not related to each other (r=.06), and PS is more related to EF (r=.64) than to VA (r=.41).

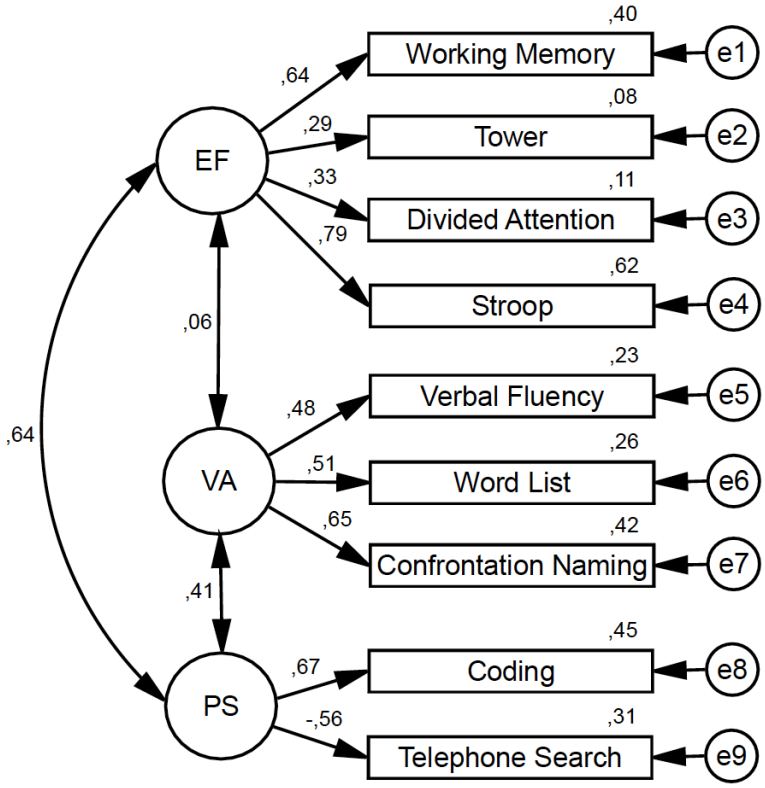

Fig. 1. Model 5 - three-correlated-factor model (standardized solution) with Executive Functions (EF), Verbal Abilities (VA) and Processing Speed (PS). Circles represent the latent variables and boxes represent each observed variable. Values in the middle of two arrow heads lines represent correlation between factors. Values in the arrows pointing from the factors to the observed values represent loadings of each one of the observed values in the corresponding factor. The values above each observed variable represent the variance explained by the factor (e.g., in the Stroop test a loading of .79 indicates that the EF factor explain 62% [(.79^2)=.62] of the variance in the Stroop test' performance).

2.5. Discussion

A large number of factor analytic studies of neurocognitive tests were conducted to analyse the psychometric properties of neuropsychological batteries assessing specific neurocognitive domains such as the ones assessing EF (e.g., D-KEFS; Delis, Kaplan, & Kramer, 2001), attention (e.g., TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994), memory (e.g., WMS; Wechsler, 1997b) or language (e.g., PAL; Caplan & Bub, 1990). However, in a comprehensive clinical evaluation, several

neurocognitive tests tapping multiple domains (usually from different batteries/scales) are commonly administered. In the present study, the factor structure of neurocognitive tests assessing different cognitive domains and widely used in a clinical neuropsychology was analysed. We used CFA to determine if the tests included in our test battery, that in theory should assess EF, VA and PS, are better explained by a single neurocognitive factor or by a underlying factor structure with two or three related neurocognitive factors. Consistent with the theoretical conceptualization of our test battery, a three-correlated factors model (EF, VA and PS; Model 5), revealed the best fit to the data. When we examined local fit, the factor loadings showed in general adequate factor loadings, the exceptions were the Tower test and the Divided Attention test. The EF factor only explained 11% of the variance in the Divided Attention test and 8% of the variance in the Tower test. Higher factor loadings for these two tests were expected, as they are usually associated with EF. The Divided Attention test assesses dual task coordination and has been linked also to sustained attention (Robertson, Ward, Ridgeway, & Nimmo-Smith, 1996). One possible explanation for the low factor loading of Divided Attention test in the EF factor, could be its reduced adequacy to assess dual task coordination in our sample. Indeed, there was little variation in the young adults' performance and a small dual task cost. This could indicate that the task was not challenging enough to activate control processes associated with dual task coordination. Previous studies also did not find a relation between dual tasks and other EF tests (McDowell, Whyte, & D'Esposito, 1997; Miyake et al., 2000; Fournier-Vicente, Larigauderie, & Gaonac'h, 2008), thus suggesting that these tasks due to their complexity may be relying in wide range of EF and nEF functions. Concerning the Tower test, we also expected a higher factor loading in the EF factor. The Tower test assesses planning, but inhibition and working memory are also relevant to test performance (Welsh, Satterlee-Cartmell, & Stine, 1999; Miyake et al., 2000; Letho et al., 2003). Other studies also did find a smaller loading of the Tower test (Fasfous et al., 2015; Moura et al., 2017) and a small correlation between the Tower test and other EF tests (Savla et al. 2012; Floyd, Bergeron, Hamilton, & Parra, 2010). One possible justification for the lower factor loading could be the high complexity of the Tower test that relies on a wide range of cognitive functions. The EF factor seems to better explain variance in the Stroop test and WM test performance. This highlights the key role of inhibition (assessed in the Stroop test) and of the activation of the relevant information in WM to EF. These two functions have been considered core EF (Diamond, 2013;

Friedman & Miyake, 2017) and previous CFA studies conducted with EF tests regularly identified factors representing inhibition and WM (Duan et al., 2010; Lehto et al., 2003; Miyake et al., 2000; van der Ven et al., 2013).

Contrary to our initial prediction, variance in the Verbal Fluency tests performance was explained by the VA factor and not by the EF factor. Also, no significant correlations were found between Verbal Fluency and the other EF tests. Multiple cognitive functions have been pointed to be recruited during performance in verbal fluency tests, including EF (e.g., cognitive flexibility, WM and inhibition), verbal intelligence, semantic retrieval and PS (Boone, Ponton, Gorsuch, Gonzalez, & Miller, 1998; Bryan et al., 1997; Henry & Crawford, 2004; Ross et al., 2007; Ruff, Light, Parker, & Levin, 1997; Stolwyk, Bannirchelvam, Kraan, & Simpson, 2015). Some studies attempted to isolate the core functions in these tests (Kraan, Stolwyk, & Testa, 2013; Ross et al., 2007; Shao et al., 2014; Whiteside et al., 2016). For example, Whiteside et al. (2016) used EFA to examine the underlying cognitive structure of Verbal Fluency tests (including both phonemic and semantic fluency) and found that the language processing is the critical component for these tasks. However, the authors assessed a mixed clinical sample and their study was retrospective, making the generalization of the results difficult. Their version of Verbal Fluency included three categories of phonemic fluency (i.e. words starting with F, A and S) and only one category of semantic fluency (animals). Also, they included just two EF measures in the study (WSCT and Trail Making Test). Our study addressed some of these limitations by assessing healthy young adults, additional EF measures and more semantic categories in the Verbal Fluency test. Our results supported their findings and suggest that Verbal Fluency is more related to VA than EF. Recently, van den Berg, Jiskoot, Grosveld, van Swieten, and Papma (2017) examined Verbal Fluency in a clinical sample and found a close relationship between these tests and language/verbal memory tests similar to the ones included in the present study. In agreement to these findings, our results indicated that Verbal Fluency was significantly correlated to the Confrontation Naming test. In both tests the participants use their lexical access ability in order to retrieve words from the mental lexicon. As expected, variance in the performance on the Confrontation Naming test and on the Word List test was adequately explained by the VA factor. Previous studies found a close relationship between language and memory abilities similar to the ones included in our battery (Mosconi et al., 2008; Moura et al., 2017). In relation to the PS factor, we found adequate loadings from the two PS measures, the

Telephone Search and the Coding tests. Performance in the Telephone Search heavily rely on processing speed despite being considered a selective attention measure (Robertson et al., 1996; Chan, Lai, & Robertson, 2006). The Coding test is often used as measure of PS (Sattler & Ryan, 2009).

Concerning the correlations among the three factors, we found that PS was indeed related to both EF and VA but surprisingly EF and VA were unrelated. PS and EF were separable but related domains. The role of PS in the Stroop test was recently highlighted by Naber, Vedder, Brown, and Nieuwenhuis (2016). In their study, the performance in the Stroop task was not only explained by EF. Specifically, both stimulus PS and lateral inhibition explained 40% of the variance in a Stroop task. The strong relation that we found between PS and EF was also expected due to the general nature of the tests that intended to measure PS and EF abilities. Three of the four EF tests are time-constrained: the Stroop, the Divided Attention and the Tower tests. Regarding WM, even if participants were not performing the WM tests under time constraints they still benefited from higher PS. A slower rate of processing reduces the amount of information that can be processed, impairing encoding and retrieval (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002). Indeed, PS is important to performance in EF tests and vice versa. In our study, we used two measures of PS in which there is an involvement of EF, the Coding test from WAIS-III and the Telephone Search from TEA. In the Coding test visual-motor coordination and WM are relevant to task performance (Baudouin, Clarys, Vanneste, & Isingrini, 2009; Bryan & Luszcz, 1996). In the Telephone Search, visual selective attention abilities along with processing speed allow successful task performance (Chan et al., 2006). We also found a moderate correlation between PS and VA. This is consistent with the view that PS is an important neurocognitive function that mediates the performance of other neurocognitive functions like EF, language and memory (Floyd et al., 2010; Henninger et al., 2010; Lee et al., 2012; Moleiro et al., 2013; Naber et al., 2016; Salthouse, 1996; Salthouse et al., 2003). In our study, EF was not significantly correlated to VA. However, the current conceptualization of EF (Royall et al., 2002; Jurado & Rosselli, 2007) suggests that these functions interact with nEF in order to control the execution of complex activities. Other studies did find EF to be related to performance in Verbal Fluency tests (Kraan et al., 2013; Shao et al., 2014), Confrontation Naming tests (Abrahams et al., 2003) and in verbal memory tests like the Word List test (Duff et al., 2005). One explanation for this discrepancy could be that the EF recruited in these tests are in some manner distinct

from the EF assessed in our study. Abrahams et al. (2003) suggest that verbal fluency and confrontation naming may recruit a semantic executive system, which is responsible for accessing, maintaining and manipulating semantic representations. None of the EF measures included in our study are closely related to semantic processing. DeDe, Caplan, Kemtes, and Waters (2004) found that online syntactic processing was not related to traditional working memory measures and proposed that this language comprehension mechanism could rely on a different working memory resource linked to language processing. Overall, these studies suggest the existence of different EF operating in verbal tasks that are not linked to traditional EF measures.

We acknowledge that our results have some limitations. In particular, some other EF tests commonly used in clinical neuropsychology (e.g., WCST and TMT) could have been also included in our battery. The reduced size of our sample and its homogeneity reduces the generalization of the results. It would be also particularly interesting to measure invariance of the factor structure of Model 5 across age groups (e.g., middle-aged adults vs. older adults) and clinical populations.

In sum, we confirmed our a priori assumptions about the general cognitive domains assessed in our neurocognitive test battery. A three-correlated factor model with EF, VA and PS factors presented the best fit to the data. Despite the fact that most of the neurocognitive measures used in the present study were derived theoretically, they loaded in the expected factors (the exception was Verbal Fluency). EF and PS were strongly related suggesting that PS is relevant to the performance of EF tasks and vice versa. These findings are relevant for the valid use of these measures in a clinical neuropsychology and for a more accurate interpretation of test scores.

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Conflict of Interest

None declared.

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3. AGEING AND EXECUTIVE FUNCTIONS: THE SPECIFIC ROLE OF INHIBITION

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3.1. Abstract

One of the most widely studied hypotheses for cognitive ageing assumes that age-related effects can be explained by a less efficient operation of the executive functions and particularly inhibition. According to this hypothesis executive functions are more susceptible to ageing or are the first to be deteriorated with ageing. The present study examined the neuropsychological profile of young adults and older adults in order to understand whether there is a general deficit in executive functions or any changes in cognition (attention, memory and language abilities) that could contribute to a better understanding of the ageing process. Older adults (N=20; *M*=63.45, *SD*=6.21 years old) and young adults (N=20; *M*=18.95, *SD*=1.79 years old) participated in the present study. These age groups were matched by gender and estimated intelligence quotient. Participants were assessed with a comprehensive neuropsychological test battery (including attention, memory, language and executive function measures). Our results indicated that older adults, comparatively to young adults, present: (i) cognitive slowing; (ii) preserved retention and recognition abilities; (iii) preserved naming and comprehension abilities; (iv) preserved selective and divided attention (iv) preserved abstraction and planning; (v) inhibition deficits. Older adults have a greater number of inaccurate responses and require more time to respond accurately than young adults. However, in some cases, they have a similar or even increased performance than young adults in the neuropsychology tests included in our battery (e.g., the Tower test). This suggest that even some executive functions can be resistant to ageing effects.

Keywords: Cognitive Ageing; Executive Functions; Inhibition; Neuropsychology Assessment.

3.2. Introduction

Among cognitive changes that occur with ageing, executive deficits are predominant (West, 2000) and are an important mediator of the effects of ageing on other cognitive functions (Salthouse, 2003). One of the most influential hypotheses to explain cognitive ageing is the *frontal hypothesis of cognitive ageing* (West, 1996), which proposes that ageing affects more the prefrontal cortex (e.g., reduction of its general volume and synaptic density) than other brain regions (Hedden & Gabrieli, 2004). So, cognitive functions whose anatomic substrate is related to the frontal lobes, and specifically to the prefrontal cortex, are more susceptible to ageing effects than functions related to other brain areas (Andres, Guerrini, Phillips, & Perfect, 2008; Hull, Martin, Beier, Lane, & Hamilton, 2008). In accordance to this hypothesis, cross-sectional and longitudinal studies have found an early and more pronounced decline with normal ageing in executive functions (Albert, Lopez-Martin, Hinojosa, & Carretie, 2013; Linden, 2000, Belleville, Rouleau, & Van der Linden, 2006; Crawford, Bryan, Luszcz, Obonsawin, & Stewart, 2000; Royall, Palmer, Chiodo, & Polk, 2004). In the study of ageing effects on executive functions, it has been emphasized that there is a decline on inhibition processes. Hasher and Zacks' (1988) inhibitory deficit theory not only recognizes the existence of these deficits in inhibition but also suggests that these deficits are key mechanisms to several age-related changes (e.g., greater distractibility, greater forgetfulness due to a poor codification of the information to be memorized). Although some studies have found an inhibition deficit (Falkenstein, Hoormann, & Hohnsbein, 2002; Fisk & Sharp, 2004; West & Alain, 2000) and a deficit in other executive functions (Allain et al., 2005; Baudouin, Clarys, Vanneste, & Isingrini, 2009; Lee et al., 2012; Salthouse, Atkinson, & Berish, 2003), the executive deficits are not general and the pattern and course of these age-related changes is still not well defined (Raz, Williamson, Gunning-Dixon, Head, & Acker, 2000; & Isingrini, 2004). The present study aimed to compare the neuropsychological profile of young adults and older adults to examine age-related changes not only in executive functions but also in non-executive cognitive domains comprising attention, language, memory and processing speed. We hypothesized for a specific rather than a general cognitive decline. Specifically, we expect older adults will performance as good as young adults in several cognitive measures, including the ones pertaining to executive functions (Collette & Salmon, 2014). We also expect that inhibition deficits and a reduced

processing speed can account for the majority of the age-related differences that we expect to find.

3.3. Methods

3.3.1. Sample

Forty volunteers aged 18-74 participated in this study. A group of young adults (N=20, *M*=18.95, *SD*=1.75 years old) and a group of older adults (N=20, *M*=63.45, *SD*=6.11 years old). An initial interview was administered to all participants to exclude participants with a prior history of neurological or psychiatric illness or/and that were currently taking medications that could interfere with the normal functioning of the central nervous system (e.g., anxiolytics). The Addenbrooke Cognitive Examination - Revised (ACE-R; Hodge & Mioshi, 2005; Firmino, Simões, Pinho, Cerejeira, & Martins, 2008) was administered to exclude participants with general cognitive decline, based on adjusted norms for age and years of education. To estimate the intelligence quotient (IQ), an Irregular Words Reading Test (TELPI; Alves, Simões & Martins, 2012) was used, a Portuguese test similar to the National Adult Reading Test (NART; Nelson 1982). Finally, the presence and severity of depressive symptomatology was assessed with two different tests according to participants' age group: the 30-item Geriatric Depression Scale (Yesavage et al., 1982; Barreto, Leuschner, Santos, & Sobral, 2003) was administered to older adults and the Beck Depression Inventory II (BDI-II; Beck, Steer, & Brown, 1996) was administered to young adults. Participants who had a moderate or severe significant depressive symptomatology were excluded. Young adults and older adults were matched for gender (16 women and 4 men in each group) and estimated IQ [$F(1, 38) < 1$, ns] (see Table 1). The two age groups presented a similar general cognitive capacity [$F(1, 38)=3.875$, $p=.056$], without cognitive decline, and did not present significant depressive symptoms. Regarding functional capacity, although statistically significant differences were observed in the percentage of functional incapacity in the two age groups [$F(1, 38)=20.172$, $p < .01$] (with older adults presenting more functional incapacity than young adults), the analysis of functional incapacity results allowed to conclude that older adults did not present a significant percentage of functional incapacity (<1%).

Table 1. Sample characterization, including gender, estimated intelligence quotient, general cognitive state and the presence and severity of depressive symptomatology. Significant differences are highlighted in bold

Variables	*Young Adults (N=20; 4 male)*		*Older Adults (N=20; 4 male)*		*Differences*	
	M	*SD*	*M*	*SD*	*F*	*p*
TeLPI	118.43	1.909	117.45	3.419	.432	.515
ACE-R	95.85	2.455	94.10	3.127	3.875	.056
IAFAI (% Incapacity)	**.000**	**.000**	**.814**	**.811**	**20.172**	**.000**
BDI-II/GDS-30	5.40	6.581	5.55	3.886		

Note: TelPI=Irregular Words Reading Test; ACE-R=Addenbrooke's Cognitive Examination Revised; IAFAI= Adults and Older Adults Functional Assessment Inventory; BDI-II=Beck Depression Inventory II; GDS-30=Geriatric Depression Scale-30 items.

3.3.2. Materials and Procedure

The neuropsychological tests used in this study were selected in order to assess different functions, such as memory, attention, language or executive functions (see Table 2). For a brief description of each neuropsychological test please see Table A in the Appendix section.

Table 2. Neuropsychological measures and their corresponding assessment domains

Neuropsychological Measures	*Assessment Domains*
Addenbroke's Cognitive Examination Revised (ACE-R; Hodge & Mioshi, 2005; Firmino, Simões, Pinho, Cerejeira, & Martins, 2008).	Cognitive screening
Geriatric Depression Scale 30-items (GDS-30; Yesavage et al., 1982; Barreto, Leuschner, Santos, & Sobral, 2003) / Beck Depression Inventory II (BDI-II; Beck, Steer, & Brown, 1996)	Measurement of the level of depressive symptomatology
Irregular Words Reading Test (TELPI; Alves, Simões & Martins, 2012)	IQ estimation
Adults and Older Adults Functional Assessment Inventory (IAFAI; Sousa, Simões, Pires, Vilar, & Freitas, 2008)	Measurement of the level of Functional Incapacity
Coding (WAIS-III; Wechsler, 1997a)	Processing Speed
Word List (WMS-III, Wechsler, 1997b)	Episodic Memory
Verbal Fluency – Phonemic, Semantic and Shifting Fluency (D-KEFS; Delis, Kaplan & Kramer, 2001)	Semantic Memory; Initiation and Cognitive Flexibility
Confrontation Naming (PAL 09; Caplan & Bub, 1990; Portuguese version, PAL-PORT, Festas, Martins, & Leitão, 2007).	Naming
Sentence Comprehension (PAL 09; Caplan & Bub, 1990; Portuguese version, PAL-PORT, Festas, Martins, & Leitão, 2007)	Verbal Comprehension
Telephone Search and Dual Task Telephone Search subtests (TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1996)	Selective and Divided Attention
Block Suppression Test (BST; Beblo, Macek, Brinkers, Hartje, & Klaver, 2004) / Digit Suppression Test (DST; Beblo et al., 2004)	Spatial and Verbal Working Memory
Stroop (Stroop, 1935; Castro, Martins & Cunha, 2003)	Inhibition
Tower test (D-KEFS; Delis, Kaplan & Kramer, 2001)	Planning
Similarities (WAIS-III; Wechsler, 1997a)	Abstraction

Young and older adults provided written informed consent to participate in the study and were assessed in two neuropsychological sessions. In order to avoid fatigue, two sessions of about 1 hour were planned. The two assessment sessions took place on different days, although separated by a maximum of three days. Since we were interested in stablishing a neuropsychological profile with tests spread across two assessment sessions, it is important to reduce the time between the two sessions in order to assure comparability between the mental and emotional state of the participants across the two testing sessions. The 1st testing session began with cognitive screening followed by the assessment of phonemic, semantic and shifting verbal fluency. Then, immediate and short-term episodic memory tests were performed followed by a 20-minute interval filled by the functional capacity and depressive symptomatology questionnaires, and by the gathering of both demographic and clinical information with the structured interview. At the end of this interval, a long-term memory and recognition tests were administered. This session ended with the administration of the processing speed and with IQ estimation measures. Most of the executive function measures were included in the 2nd testing day, with exception for the verbal fluency tests. This session included Confrontation Naming, Sentence Comprehension, Telephone Search and Dual Task Telephone Search, Block Suppression Test, Digit Suppression Test, Stroop test, Tower test and Similarities. All the tests were administered in a counterbalanced order in order to avoid influence of fatigue in the tests' performance. The young adults were assessed in the Laboratory of Memory, Language and Executive Functions (LMLFE; Faculty of Psychology and Educational Sciences of the University of Coimbra). Older adults were assessed in Aposenior (a university of the third age, where they were attending classes regularly), which provided a quiet and appropriate environment for neuropsychological assessments.

Statistical analysis was performed with the Statistical Package for the Social Sciences (SPSS version 20.0, SPSS Inc., Chicago, IL). To compare the performances between the age groups, a one-way analysis of variance (ANOVA) was performed. Pearson correlation coefficients were used to analyse the degree of association between several measures and/or performance indicators.

3.4. Results

3.4.1. Analysis of older adults and young adults' neuropsychological performance

Older and young adults' neuropsychological profiles were compared in order to determine any age-related changes. The results are presented in Table 3.

Table 3. Differences between the two age groups in the neuropsychological assessment tests. Significant differences are highlighted in bold.

Neuropsychological tests		*Young Adults (N=20)*		*Older Adults (N=20)*		*Differences*	
		M	*SD*	*M*	*SD*	*F*	*p*
Word List	**Immediate Recall**	**38.15**	**3.392**	**34.35**	**4.705**	**8.586**	**.006**
	Short Term Recall	**10.30**	**1.658**	**9.00**	**1.556**	**6.510**	**.015**
	Long Term Recall	**10.15**	**1.725**	**9.00**	**1.622**	**4.715**	**.036**
	Retention	88.66	13.844	84.88	14.508	2.287	.139
	Recognition	23.75	.444	23.50	.716	1.610	.312
Verbal Fluency	Phonemic Fluency	36.85	11.811	39.75	12.268	.580	.451
	Semantic Fluency	57.25	10.203	57.05	11.763	.003	.954
	Shifting Fluency (%)	97.90	4.686	98.54	5.258	.165	.687
Confrontation Naming		33.60	2.458	35.35	4.051	2.425	0.128
Sentence Comprehension		53.90	2.409	53.65	2.305	1.303	0.261
Similarities		22.35	3.689	22.15	3.329	.032	0.858
Working Memory (WM)	Visual WM	9.90	3.886	8.95	2.982	.757	0.390
	Verbal WM	9.95	4.110	10.60	3.775	.271	0.605
Coding		**91.95**	**12.742**	**63.20**	**13.501**	**47.967**	**.000**
Stroop	**Total score**	**103.55**	**9.290**	**88.15**	**18.120**	**11.110**	**.002**
	Time	**110.05**	**12.174**	**118.25**	**5.656**	**7.518**	**.009**
Telephone Search	Total score	19.15	1.089	18.50	1.968	1.680	.203
	Time	**53.45**	**12.812**	**69.05**	**16.113**	**8.729**	**.005**
Dual Task Telephone Search	Total score	17.95	1.820	16.40	3.485	3.108	.086
	Time	**59.05**	**16.256**	**71.55**	**19.514**	**4.845**	**.034**
Divided Attention		5.68	5,987	5.739	3.313	.002	.969
Tower	Achievement Score	17.40	3.733	17.40	3.545	.000	1.000
	Nº Movements	**105.05**	**21.680**	**69.70**	**33.288**	**15.836**	**.000**
	Nº of violations	**.15**	**.366**	**1.65**	**1.694**	**14.974**	**.000**
	Movements Accuracy	**1.45**	**.258**	**1.263**	**0.218**	**6.117**	**.018**
	Time per Movement	**3.857**	**.932**	**5.139**	**1.4149**	**11.455**	**.002**

Performance of older adults was similar to young adults sample performance in fourteen of the twenty six neuropsychological measures comprising memory, executive

function, language and attention measures. Specifically, no differences were found in Long-term Retention percentage [$F(1, 38)=2.287$, $p=.139$]; Long-term Recognition [$F(1, 38)=1.610$, $p=.312$]; number of words in Phonemic Verbal Fluency [$F(1, 38) < 1$, *ns*], Semantic Verbal Fluency [$F(1, 38) < 1$, *ns*] and Shifting Fluency [$F(1, 38) < 1$, *ns*]; Confrontation Naming total score [$F(1, 38)=2.425$, $p=.128$]; Sentence Comprehension total score [$F(1, 38)=1.303$, $p=.261$]; Similarities total score [$F(1, 38) < 1$, *ns*]; Digit Suppression test total score [$F(1, 38) < 1$, *ns*]; Block Suppression test total score[$F(1, 38) < 1$, *ns*]; Telephone Search total score [$F(1, 38)=1.680$, $p=.203$]; Dual Task Telephone Search total score [$F(1, 38)=3.108$, $p=.086$]; the achievement score in the Tower test [$F(1, 38) < 1$, *ns*]; and in the divided attention measure [$F(1, 38) < 1$, *ns*].

Performance of older adults was inferior to young adults in ten of the twenty six neuropsychological measures comprising the assessment of memory, executive function, attention and processing speed. In detail, older adults' performance was worst in the following measures: number of words recalled in the Immediate Recall [$F(1, 38)=8.586$, $p <.01$], Short-term Recall [$F(1, 38)=6.510$, $p <.05$] and Long-term Recall [$F(1, 38)=4.715$, $p <.05$]; Coding [$F(1, 38)=47.967$, $p <.01$]; Stroop total score [$F(1, 38)=11.110$, $p <.01$] and time required to complete the test [$F(1 , 38)=7.518$, $p <.01$]; time required to complete the Telephone Search [$F(1, 38)=8.729$, $p <.01$] and the Dual Task Telephone Search [$F(1, 38)=4.845$, $p <.05$]; number of violations in the Tower test [$F(1, 38)=14.974$, $p<.01$] and time needed per movement in the same test [$F(1, 38)=11.455$, $p <.01$].

Performance of older adults was superior to young adults in two measures of the Tower test: total number of movements [$F(1, 38)=15.836$, $p<.01$], with older adults following the instructions of using as less movements as possible, and movements' accuracy [$F(1, 38)=6.117$, $p <.05$], with better accuracy of older adults.

3.4.2. Influence of age in the neuropsychological assessment tests' performance: processing speed and inhibition as possible mediators

In order to better understand the results obtained, and particularly the age-related effects, Pearson correlation coefficients were computed between age and the twelve neuropsychological measures, where age-related differences were found. The results are shown in Table 4 (For a complete description of the correlations found between all the

neuropsychological tests and also their correlation with age, see Table B in Appendix section)

Table 4. Pearson correlation coefficients between age and neuropsychological tests in which there were age-related differences (N=40)

Neuropsychological Measures	*Age*	
	r	r^2
Word List - Immediate Recall	-.470**	.220
Word List - Short Term Recall	-.454**	.206
Word List - Long Term Recall	-.394*	.155
Coding	-.790**	.624
Stroop – Total score	-.539**	.290
Stroop – Time	-.421*	.177
Telephone Search – Time	.481**	.231
Dual Task Telephone Search – Time	.353*	.124
Tower – Nº Violations	.550**	.303
Tower – Nº Movements	-.544**	.296
Tower – Time per Movement	.474**	.225
Tower – Movements Accuracy	-.334*	.112

*p<.05; ** p<.01

All correlations were statistically significant but eight were moderately correlated and four were strongly correlated (Cohen, 1988). There was a strong and negative correlation between age and three neuropsychological measures: Coding test [r(38)= -.790, p<.01]; number of movements in the Tower test [r(38)= -.544, p<.01]; and the total score on the Stroop test [r(38)= -.539, p<.01]. There was also a strong but positive correlation between age and the number of violations in the Tower test [r(38)= .550, p<.01] There were moderate and negative correlations between age and five neuropsychological measures: number of words recalled on Immediate Recall [r(38)= -.470, p<.01], Short Term Recall [r(38)= -.454, p<.01] and Long Term Recall [r(38)= -.394, p<.05]; time needed to complete the Stroop test [r(38)= -.421, p<.05]; and movements accuracy in the Tower test [r(38)= -.334, p<.05]. There were also moderate but now positive correlations between age and three neuropsychological measures: the time needed to complete the Telephone Search test [r(38)= .481, p<.01] and the Dual Task Telephone Search test [r(38)= .353, p<.05]; and the time per movement in the Tower test [r(38)= .474, p<.01].

Considering the significant correlation coefficients found, partial correlation coefficients were also computed while controlling for performance in the total score in the Coding test (see Table 5) and later for the total score in the Stroop test (see Table 6). These two tests were chosen as mediators, since performance in these two tests was

largely explained by age in our data [62.4 % of the variance in the Coding test' performance, $r^2(38)= .624$, $p<.01$, and 29 % of the variance in the Stroop test' performance, $r^2(38)= .290$, $p<.01$] and taking in account that both Inhibition (measured in the Strop test) and processing speed (measured in the Coding test) have been indicated in previous studies as important mediators of age-related changes in cognition (Hodzik & Lemaire, 2011; Robitaille et al., 2013).

Table 5. Partial correlation coefficients between age and neuropsychological tests in which there were age-related differences, while controlling the total score in the Coding test (N=40)

Neuropsychological Measures	*Age (Controlling for Coding total score)*	
	r	r^2
Word List - Immediate Recall	-.136	.018
Word List - Short Term Recall	-.081	.007
Word List - Long Term Recall	-.019	.0003
Stroop – Total Score	-.112	.012
Stroop – Time	-.010	.0001
Telephone Search – Time	.123	.015
Dual Task Telephone Search – Time	-.152	.023
Tower – Nº Violations	.156	.024
Tower – Nº Movements	-.343*	.118
Tower – Time per Movement	-.087	.008
Tower – Movements Accuracy	-.243	.059

*$p<.05$; ** $p<.01$

Table 6. Partial correlation coefficients between age and neuropsychological tests in which there were age-related differences, while controlling the total score in the Stroop test (N=40)

Neuropsychological Measures	*Age (Controlling for Stroop total score)*	
	r	r^2
Word List - Immediate Recall	-.284	.081
Word List - Short Term Recall	-.260	.067
Word List - Long Term Recall	-.131	.017
Coding	-.690**	.476
Stroop - Time	.181	.033
Telephone Search – Time	.241	.058
Dual Task Telephone Search – Time	.157	.024
Tower – Nº Violations	.383*	.147
Tower – Nº Movements	-.389*	.151
Tower – Time per Movement	.299	.089
Tower – Movements Accuracy	-.364*	.132

*$p<.05$; ** $p<.01$

The analysis of Table 5 shows that when we controlled for the total score in the processing speed measure, the Coding test, age is not significantly correlated with almost any neuropsychological measure. The exception is the total number of movements in the Tower test that has a moderate and negative correlation with age [$r(38)= -.343$, $p<.05$]. Consequently, increased age is related to a decrease number of

movements in the Tower test, even when the total score in the Coding score is controlled.

In relation to the partial correlations while controlling the total score in the Stroop test (see Table 6) just four of the twelve correlations remained significant, with three moderate correlations and one strong correlation (Cohen, 1988). The correlation between age and the Coding test remained strong and negative [$r(38)= -.690$, $p<.01$]. There were moderate and negative correlations between age and two measures form the Tower test: the total number of movements [$r(38)= -.389$, $p<.01$] and movements' accuracy [$r(38)= -.364$, $p<.01$]. There was also a moderate but positive correlation between age and the number of violations in the Tower test [$r(38)= .383$, $p<.01$]. Even when inhibition is controlled, increased age still reflect a lower performance in the processing speed measure and an increased number of violations in the Tower test. On the positive side, when inhibition is controlled, increased age is still associated with higher movement accuracy (i.e., values closest to 1 in older adults).

3.5. Discussion

A deeper understanding of the effects of ageing on executive functions is critical and several studies have been conducted with this purpose (Allain et al., 2005; Fisk & Sharp, 2004; Hull, Martin, Beier, Lane, & Hamilton, 2008; Salthouse et al., 2003; Turner & Spreng, 2012). In the present study it was possible to investigate age-related changes in the performance on several neuropsychological tests by comparing older and young adults' performance. As expected the performance of older adults was worse than the performance of young adults in some neuropsychological tests and was similar to young adults in others. Older adults showed reduced processing speed. Concerning episodic memory, older adults showed a similar capacity for retention and long-term recognition of verbal material but recalled in average less words than young adults in both immediate, short term and long term recall. Older adults were as capable as young adults in language tests assessing confrontational naming and sentences comprehension abilities. Older and young adults' performance was also equivalent in the total score of visual selective attention test and in the divided attention measure suggesting the preservation of these attentional mechanisms with ageing. However, it should be emphasized that the task of divided attention administered in this study involved two different modalities (i.e., visual and auditory), which facilitates the task for older adults

(Hein & Schubert, 2004). In respect to inhibition, older adults' had a worse performance in the Stroop test than young adults. In addition to inhibition and divided attention, other functions that could be considered as executive functions were assessed. No differences were found between the older and young adults' performance in neuropsychological tests measuring executive functions such as abstraction, verbal and spatial working memory and cognitive flexibility. In respect to the Tower test mixed results were found. Older adults committed more violations in average during towers construction and needed more time per movement. However, they used a few number of movements and had greater movements' accuracy. As a result, similar results were found for older adults and young adults in the achievement score obtained in the Tower test suggesting equivalent planning abilities.

In our study it was also possible to investigate if processing speed and inhibition can mediate age-related differences. As previous studies, we found a reduced processing speed in older adults (Baudouin et al., 2009; Henninger, Madden, & Huettel, 2010; Rush, Barch, & Braver, 2006; Salthouse, 1996; Yano, 2011). This reduced processing speed was pointed out by Salthouse (1996) as a key mediator of age-related changes in cognition. The results obtained in the present study support Salthouse's (1996) processing speed theory by showing that when processing speed is controlled, age is no longer related to the variance in the performance of most neuropsychological measures in which age-related changes were found.

Another important mediating factor of age-related changes pointed in previous studies is inhibition (Hasher & Zacks, 1988). Older adults presented a lower score in the Stroop test when compared with young adults. So we tested if this lower performance could explain the age-related changes that were previously identified. Our results showed that after controlling the total score on the Stroop test, age was no longer associated with some measures of episodic memory, attention and executive functions in which age-related changes were found.

Overall, the results found replicated previous findings by identifying an age-related cognitive slowing and inhibition deficits and some preserved functions such as retention, recognition, naming or comprehension abilities. Concerning the other executive functions despite inhibition, our results are in line with Collette & Salmon (2014), suggesting that even executive functions are only selectively affected by ageing, with some functions being more resistant to ageing such as working memory, abstraction or planning. Despite this similarity in test performance, recent neuroimaging

studies suggested differences in brain areas activation with ageing (Spreng, Wojtowicz, & Grady, 2010). For example, in respect to executive functions, the prefrontal cortex can be extra activated in order to allow similar levels of task performance, which has been interpreted as a possible compensatory mechanism in older adults.

3.6. Conclusions

Cognitive ageing is accompanied by cognitive slowing and inhibition deficits. Despite these age-related changes, older adults can perform similarly to young adults in different neuropsychological tests (Word List, Telephone Search and Dual Task Telephone Search, Confrontation Naming and Sentence Comprehension), including those pertaining to executive functions assessment (Similarities, Working Memory, and Tower tests).

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You can't control the unexpected, but you can control your response to it."

(Aikido Principle)

PART II: PROCESSING OF EXECUTIVE FUNCTIONS AND AGE-RELATED CHANGES

1. EVENT-RELATED BRAIN POTENTIALS IN THE STUDY OF INHIBITION: COGNITIVE CONTROL, SOURCE LOCALIZATION AND AGE-RELATED MODULATIONS

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1.1. Abstract

In the previous fifteen years, a variety of experimental paradigms and methods have been employed to study inhibition. In the current review, we analyse studies that have used the high temporal resolution of the event-related potential (ERP) technique to identify the temporal course of inhibition to understand the various processes that contribute to inhibition. ERP studies with a focus on normal ageing are specifically analysed because they contribute to a deeper understanding of inhibition. Three time windows are proposed to organize the ERP data collected using inhibition paradigms: the 200 ms period following stimulus onset; the period between 200 and 400 ms after stimulus onset; and the period between 400 and 800 ms after stimulus onset. In the first 200 ms, ERP inhibition research has primarily focused on N1 and P1 as the ERP components associated with inhibition. The inhibitory processing in the second time window has been associated with the N2 and P3 ERP components. Finally, in the third time window, inhibition has primarily been associated with the N400 and N450 ERP components. Source localization studies are analysed to examine the association between the inhibition processes that are indexed by the ERP components and their functional brain areas. Inhibition can be organized in a complex functional structure that is not constrained to a specific time point but, rather, extends its activity through different time windows. This review characterizes inhibition as a set of processes rather than a unitary process.

Keywords: Inhibition; Cognitive Control; Event-related Potentials; Source Localization; Ageing

1.2. Introduction

Everyday functioning requires the ability to successfully inhibit irrelevant stimuli, thoughts, and behaviours (Logan et al. 1984; Hasher and Zacks 1988). Inhibition has a central role in the organization of various cognitive domains, including attention, memory and language (MacLeod et al. 2003). Furthermore, inhibition may function at different levels of cognitive processing, such as thoughts, verbal responses, visual processing, sounds, actions or semantic processing (Amieva et al. 2004). However, because of the variety of methods, experimental paradigms and contexts in which the concept of inhibition has been studied, it is difficult to fully understand how and when inhibition occurs. In the present review, we demonstrate inhibitory processes are not unitary. Rather, they are multifaceted and entail various functions that can be linked to automatic or controlled processing depending on the context.

1.2.1. Theoretical issues in inhibition

Inhibition has received labels such as "interference resolution" (Piai et al. 2012) and "suppression" (Ludowig et al. 2010) to highlight its automatic nature (implicit or unintentional inhibitory processes) and controlled nature (explicit or intentional inhibitory processes), respectively (Nigg 2000; Friedman and Miyake 2004; Andres et al. 2008; Collette et al. 2009). This theoretical construct of the level of control that is needed in a cognitive process, in this case inhibition, was initially proposed by Shiffrin and colleagues (for a review, see Shiffrin and Schneider 1977). According to this model, automatic processes typically occur without intention and conscious awareness. As a result, these processes are quick and can occur in parallel with other operations without impairment. Perhaps the most relevant characteristic of an automatic process is that it can occur without the subject's conscious control. In contrast, controlled processes require intention and awareness. Therefore, these processes are slow and have limited capacity, which reduces the possibility to simultaneously perform other operations (Posner and Snyder 1975). However, controlled processes can be easily changed and applied to novel situations when an automatic sequence cannot be applied (Shiffrin and Schneider 1977). In this theoretical framework, controlled inhibition is the conscious and deliberate suppression of irrelevant stimuli or responses. An example of a

laboratory controlled inhibition task is the Stroop task (Stroop 1935). In this task, coloured words are presented and the participant must consciously inhibit the tendency to produce a more dominant automatic response (i.e., naming the colour word) to be capable of naming the colour of the ink in which the word is printed. Automatic inhibition occurs without the subject's awareness and appears to be involuntary. An example of a laboratory automatic inhibition task is the negative priming (NP; Tipper 1985) paradigm. In a typical NP task, the participant views two images and must respond to a target, thereby inhibiting the distractor (prime trial). In a subsequent trial (probe trial), the distractor of the previous trial becomes the target. In the probe trial, the reaction times are prolonged because of the residual inhibition from the prime display.

Other distinctions among types of inhibition have emerged. A number of studies have established and examined specific categories of inhibitory phenomena, such as response or motor inhibition (the process of inhibiting a planned response or movement; Robinson et al. 2013), lateral inhibition (the capacity of an excited neuron to reduce the activity of its neighbours; Bridgeman 2006), prepulse inhibition (when a stimulus inhibits the startle blink reflex to a subsequent stronger startle stimulus; Dawson et al. 2004), inhibition of return (inhibition produced by a peripheral cue or target; Possin et al. 2009), knowledge or semantic inhibition (inhibition responsible for reducing the activation of the inappropriate knowledge for the context; Debruille 2007), and proactive interference (i.e., the disruption of behaviour due to the influence of antecedent information that is no longer relevant and has to be inhibited; Yi and Friedman 2011). In opposition to these types of inhibition, several authors (Hasher and Zacks 1988; Collette et al. 2009) have proposed that inhibition is a unitary process that integrates the following three different but related functions: the access function (responsible for the prevention of irrelevant information entry); the deletion function (responsible for the suppression of information that either is or has become irrelevant); and the restrain function (responsible for the prevention of access to relevant but contextually inappropriate responses).

As a final point in this overview of the conceptualizations of inhibition, we highlight the literature's general acceptance of the distinction between cognitive and behavioural inhibitory processes. Cognitive inhibition is responsible for the suppression of previously activated cognitive contents, the clearing of non-relevant information and the resistance to interference of information from a potentially attention-capturing stimulus or cognitive content that is contextually inadequate (Koch et al. 2010; Bjorklund and

Harnishfeger 1995). Harnishfeger (1995) defined behavioural inhibition in terms of overt behaviour control, such as resistance of a prepotent response, delay of a reward, motor inhibition, and impulse control.

1.2.2. Measuring the time course of inhibition

Some of the most important inhibitory processes occur within the first second after the presentation of the stimuli or information that must be inhibited (Kok 1999; Amieva et al. 2004; Huster et al. 2013). To study inhibitory processes in the narrow time window when they occur, event-related brain potentials (ERPs) have been used. The ERP technique has a high temporal resolution, which therefore enables neural activity to be tracked on a millisecond time scale (Albert et al. 2013) and represents a continuous measure of processing (Luck 2005). An ERP is a measured brain electrical response that is directly the result of sensory, motor or cognitive processes. It is a voltage fluctuation, which is derived from the ongoing electroencephalogram (EEG) that is time-locked to a specific event (Kuperberg 2004). These voltage fluctuations are represented in the ERP waveform as a series of positive and negative peaks that vary in amplitude and latency (Dauwels et al. 2010). The amplitude can be measured as the difference between the maximum peak of the ERP waveform over a period of time and the mean baseline voltage (which occurs prior to the stimulus) (Polich 2007). The latency is defined as the interval from the stimulus onset to the point of highest amplitude within a time window. As Kappenman et al. (2012) noted, the characteristics of the ERP waveform do not reflect a specific brain process. To understand the voltage deflections that occur in an ERP waveform (i.e., different peaks and troughs), the term ERP component has been proposed. An ERP component can be described as a scalp-recorded voltage change that reflects a specific neural or psychological process (Luck 2005). ERP components have traditionally been classified as exogenous components, which depend on external factors (i.e., determined by the physical nature of the eliciting stimulus and generally occur within the first 200 ms after stimulus onset), or endogenous components, which primarily depend on internal factors (i.e., sensitive to proprieties, such as the meaning of the stimulus and/or the processing required to accomplish the task) (Picton et al. 2000). An ERP component can be sensitive to different cognitive processes. For example, P3 modulations induced by an oddball paradigm can index attentional processes responsible for updating stimulus representations, while P3 modulations induced by a

memory recall task can index encoding mechanisms and P3 modulations observed while a Go/No-go task is performed can index inhibition mechanisms (for a review see Polich 2007). Throughout this review we will focus only on ERPs observed in inhibition studies.

A variety of paradigms have been employed to study inhibition with ERPs (for a review, see Kok 1999), such as location and identity NP, Stop-signal, Go/No-go, Stroop effect, Task Switching, the Eriksen Flanker Task, Spatial cueing tasks, Antisaccade, Proactive Interference and Direct Forgetting. Fig 1 presents a schematic display of the most commonly used inhibition-related paradigms in ERP research.

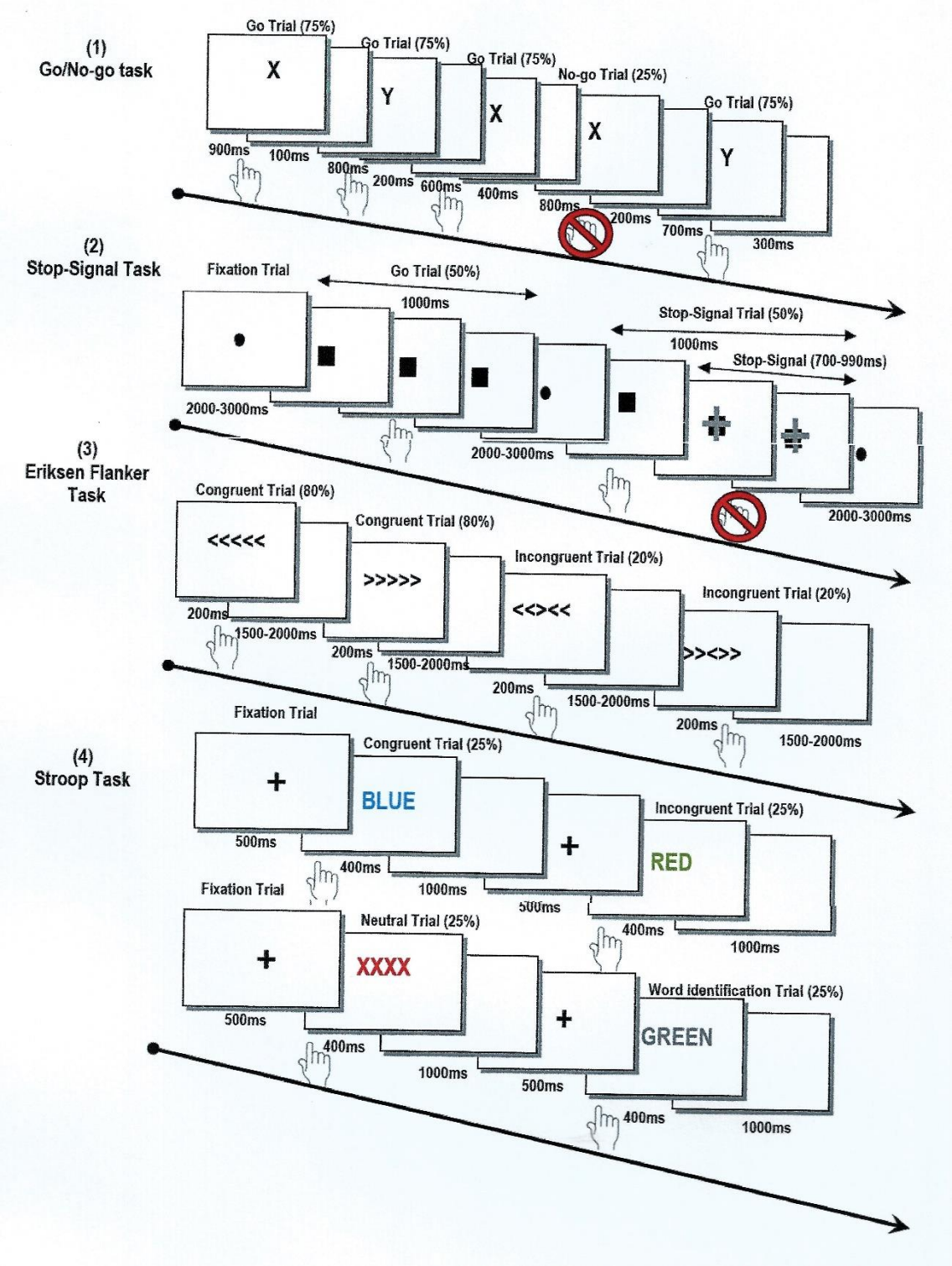

Fig 1 Schematic display of inhibition-related paradigms: (1) Go/No-go task (Roche et al. 2005); (2) Stop-signal task (Kok et al. 2004); (3) Eriksen Flanker Task (Tillman and Wiens 2011); and (4) Stroop task (West and Alain 1999).

It is widely accepted that these different paradigms can be related to different types of inhibition. For example, the Stop-signal, Go/No-go and Eriksen Flanker

tasks have been related to behavioural inhibition (specifically, motor inhibition), whereas the NP, Stroop and Direct Forgetting paradigms have been related to cognitive inhibition. The nature of inhibition, as an automatic or controlled process, can also be modulated by the paradigm that is used to evoke the inhibition ERPs. According to Nigg (2000), the Stroop and Stop-signal tasks, for example, engage controlled inhibition, whereas the NP and Spatial cueing tasks engage automatic inhibition (see also, Andres et al. 2008). In addition, the effectiveness of inhibition may largely depend on sensory or bottom-up processing associated with the modality of the paradigm (e.g., auditory versus visual). For example, Ramautar et al. (2006) suggested that an auditory version of a paradigm allows for faster processing than the visual version of the same paradigm. Regardless of this variability, the electrophysiological responses that are evoked during inhibition paradigms have been used to clarify the temporal course of inhibition and highlight the differences in the temporal course of different types of inhibition (see Fig 2 for a schematic illustration of the ERP components that are linked to inhibition processes within different paradigms).

Recently, there has been an increasing interest in inhibition, which has specifically focused on the neural underpinnings of inhibitory processes and the role of inhibition in cognitive domains, such as memory, language and attention (Verhoef et al. 2009; Neuhaus et al. 2010; Yi and Friedman 2011; Albert et al. 2013). Several of these studies have examined the relevance of inhibitory processes in normal ageing (Mayas et al. 2012; Turner and Spreng 2012; Haring et al. 2013; Wostmann et al. 2013), as well as a variety of clinical conditions, such as Alzheimer's disease (AD; Collette et al. 2009; Thomas et al. 2010; Cheng et al. 2012), mild cognitive impairment (MCI; Belleville et al. 2007), traumatic brain injury (TBI; Dimoska-Di Marco et al. 2011), depression (Dai and Feng 2011; Bobb et al. 2012), anxiety (Robinson et al. 2013), schizophrenia (Hughes et al. 2012), fibromyalgia (Mercado et al. 2013), attention deficit-hyperactivity disorder (ADHD; Senderecka et al. 2012), alcoholism (Padilla et al. 2011) and psychopathy (Verona et al. 2012).

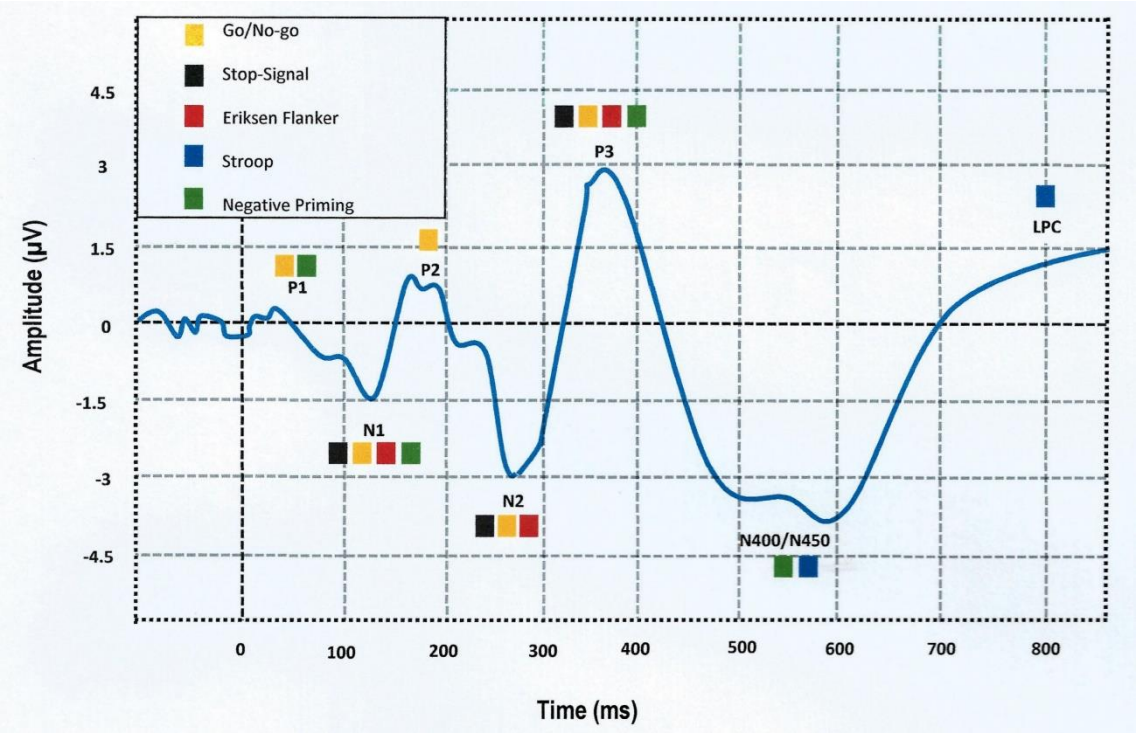

Fig 2 Schematic illustration of grand average event-related potential waveforms linked to inhibition in different paradigms: Go/No-go (Tian and Yao 2008; Thomas et al. 2009); Stop-signal (Bekker et al. 2005; van Boxtel et al. 2001); Eriksen Flanker (Wild-Wall et al. 2008; Neuhaus et al. 2007); Stroop (Hanslmayr et al. 2008); and NP (Gibbons et al. 2006; Kathmann et al. 2006). The P1, P2 and N1 were located at posterior electrode sites (i.e., O1, O2, T5, T6, P7, and P8); the N2 and P3 were located at fronto-central electrode sites (i.e., FC1, FC2, F3, F4, CZ, PZ, FZ, and FCz); the N400 was located at central electrode sites (i.e., Cz and CPz); the N450 was located at fronto-central electrode sites (FC1, FCz, FC2, C1, CZ, C2, CP1, CPz, and CP2); and the LPC was located at central-parietal sites (i.e., P3, P4, Pz, Cz, and Pz).

1.2.3. Inhibition and the ageing process

A decrease in inhibition capacities has been proposed to be one of the main factors that underlies age-related cognitive decline (Andres and Van der Linden 2000). To explain this idea, Hasher and Zacks (1988) proposed the inhibition deficit theory. According to this theory, the ageing process weakens inhibition, which is responsible for the suppression and the clearing of non-relevant information, as well as the resistance to interference of information that is contextually inadequate. Consequently, a greater amount of irrelevant information is not restrained and/or deleted, which produces more interference. These inhibition deficits have been used to explain various impairments in older adults' cognition, such as increased distractibility (Wascher et al. 2012), time needed for an appropriate response (Anguera and Gazzaley 2012), forgetting because of codification inefficiency and competition of related concepts

(Raaijmakers and Jakab 2013), difficulty in understanding speech when background speech or noise is present (Tun et al. 2002), and difficulty in ignoring visually distracting information while reading (Li et al. 1998). Despite this decline in the efficiency of inhibitory processes with cognitive ageing, not all inhibitory processes are impaired. Specifically, older adults are impaired in inhibition processes that involve controlled or top-down mechanisms (e.g. with impaired performance in Stroop or Stop-Signal paradigms when compared with young adults; Andres et al. 2008) but not in processes that can be considered more automatic or unintentional (e.g. equal performance when compared with young adults in NP or Spatial Cueing paradigms; Amieva et al. 2002; Andres et al. 2008; Collette et al. 2009).

1.2.4. Aim and rationale of the review

The aim of the present article is to critically review the published research that has probed the fine-grained temporal course of inhibition, with a particular emphasis on ERP studies. Because most of these studies have not intended to provide a timeline for the entire unfolding of an inhibitory processing event, we attempt to reconstruct this timeline by abstracting it away from a larger set of studies and then using it to frame the information in individual studies. This review attempts to clarify inhibition as a complex process that can be automatically initiated in the first 100 ms post-stimulus and extend its action through both automatic and controlled processes until 800 ms. The recurrent question regarding the existence of one general or different types of inhibition is also addressed. A distinctive interest of this review is the effects of normal ageing on inhibition, as reflected by changes in processing that occur at a fine-grained temporal scale. As previously discussed, normal ageing selectivity affects some inhibitory processes while sparing other processes (Andres et al. 2008; Collette et al. 2009), and temporally detailed analyses of inhibitory processing may greatly enhance the characterization of these differential effects. Thus, the study of the temporal course of inhibition in normal ageing can facilitate the clarification of both the overall nature of cognitive ageing and the complex nature of inhibition, which we consider to be crucial. Furthermore, several issues that pertain to the distinction of types and subprocesses in inhibition can be significantly clarified by considering the patterning of hindered/spared inhibitory processes with other age-related changes in cognitive function and brain structure.

A straightforward approach to gather and systematize information about the timing of inhibitory processes is to examine the ERPs observed in inhibition studies. As previously described, the ERP technique has a high temporal resolution (in the order of a few milliseconds). Therefore, it is possible to capture the various processes that contribute to inhibition. This emphasis on the temporal course of inhibition is related to the hypothesis that the time of activation of different brain structures related to inhibition is as important as the level of activity of these brain structures to accomplish the inhibition process. To link the time of activation of inhibitory processes to the brain structures that underlie inhibition, studies that explored the anatomical substrates of inhibition with electroencephalography (EEG) are addressed in this review. Specifically, we focus on studies that used source localization analysis of ERP data, which were collected with high-density EEG or magnetoencephalography (MEG).

The present review will focus on three time windows where inhibition ERP correlates have been found: 0-200ms; 200-400ms; and 400-800ms. This article structure is based on the current ERP literature and facilitates an understanding of inhibition as it unfolds in real time, highlighting the plurality of processes that may correspond to the term "inhibition" in different tasks and moments. Furthermore, it highlights the automatic and controlled nature of different types of inhibition or different processes that contribute to inhibition because we hypothesize that the automatic processes (i.e., fast and unconscious processes) will occur in the first and possibly the second but not in the third window. These three time windows are used mainly as a means to organize the information that we will present and discuss; we do not intend to imply that there are three types of inhibition, one for each time window, or that there is a general process of inhibition that necessarily spans over the three time windows. Occasionally inhibition can be completed before 200ms and other times it can be extended until after 400ms. For each time window (0-200ms; 200-400ms; 400-800ms) a description of the main inhibition-related paradigms yielding ERP modulations therein will be provided as well as a discussion of those modulations, addressing systematically the brain sources involved and the nature of inhibition as an automatic or controlled process. Finally, the age-related changes in inhibition are addressed.

1.2.5. Literature search

A literature search was performed using the Web of Science, ProQuest, Ovid, Science Direct and PubMed databases. The search included internationally published peer-reviewed research papers through August 15, 2014. Additional studies were identified by hand-searching the references that were cited in the previously collected articles. The main keywords that were used in this literature search were 'inhibition', 'suppression', 'interference' as well as 'event-related potentials' and terms labelling different inhibitory paradigms. Within this first level of literature analysis, we conducted a second search that identified the articles that contain the term 'Ageing'. Fifty ERP studies that used paradigms like 'Stop-signal', 'Go/No-go', 'Eriksen Flanker Task', 'Stroop Task' and 'proactive interference resolution' are examined in this review. Whenever possible, depending on the information made available in the original articles, we provide a detailed description of the sample that was used in each study we review, comprising sample size, age (mean, standard deviation or range), years of education (mean, standard deviation or range) and gender-balance. Since the amount of information concerning the sample and the specific parameters used to convey that information may vary from study to study, our rendering of that information will vary accordingly.

1.3. Inhibition in the first 200 ms

1.3.1. ERPs for inhibition in the first 200 ms

In this early time window, ERP components, such as the N1 and P1, have been associated with the ability to inhibit responses to incoming sensory information (Di Russo et al. 2003). N1 and P1 effects have primarily been identified in behavioural inhibition paradigms, such as the Stop-signal (Bekker et al. 2005), Go/No-go (Thomas et al. 2009; Tian and Yao 2008; Kirmizi-Alsan et al. 2006; Lavric et al. 2004; Bokura et al. 2002; Filipovic et al. 2000), Eriksen Flanker (Abad-Rodriguez et al. 2004; Hsieh and Fang 2012; Johnstone et al. 2009; Wild-Wall et al. 2008) and Spatial cueing (Fu et al. 2005; McDonald et al. 1999; Wascher and Tipper 2004) tasks. However, there is also involvement of these early ERP components in cognitive paradigms, such as Location-based Priming (Gibbons et al. 2006; Kathmann et al. 2006) and emotional Stroop

(Thomas et al. 2007) tasks. To better understand the inhibitory processes that are linked to this early time window, we analysed data from the ERP studies that were conducted with inhibitory paradigms, such as the Go/No-go, Stop-signal and Eriksen Flanker paradigms.

In the Go/No-go paradigm, participants are asked to respond to a type of stimulus (Go stimuli) and withhold the response to a different type of stimulus (No-go stimuli). Several studies have shown the importance of the first 200 ms after the stimulus onset for the No-go processing (Hoshiyama et al. 1996; Schluter et al. 1998; Filipovic et al. 2000). Kirmizi-Alsan et al. (2006) studied the electrophysiological markers of response inhibition in a sample of young adults (N=24; M±SD=25.8±5.6 years old; M±SD=17.8±3.3 years of education; 11 women) who participated in a visual Go/No-go task. They observed a significant N1 amplitude increase in the No-go ERPs compared with the Go ERPs. Because the participant must recruit inhibitory processes to withhold the No-go response, the N1 was indicated as an ERP component associated with inhibition despite its early onset (Kirmizi-Alsan et al. 2006). Thomas et al. (2009) also used a visual Go/No-go task to study inhibition in healthy adults (N=20; 13 women). The level of inhibition required to withhold the No-go trials was manipulated by varying the number of immediately preceding Go trials. A greater number of consecutive Go trials before a No-go trial increased the inhibitory load. The authors demonstrated an increased latency of N1 and P2 in the first 200 ms in the No-go trials preceded by a greater number of consecutive Go trials, which supports a potential relationship between these components and inhibition (Fallgatter and Strik 1999; Thomas et al. 2009). Tian and Yao (2008) used ERPs with a peripheral cued Go/No-go task to study the neural mechanism of Inhibition of Return (IOR), which represents an inhibitory effect produced by a peripheral cue or target that hinders the accuracy and speed of response to targets that appear on the peripherally cued locations. Twelve young adults (M=21.4 years old, range 18-25; 2 women) participated in this experiment, in which the stimulus (Go and No-go stimulus) was designed to appear with equal probability at the cued and uncued locations. This study identified a smaller and earlier P1 and a larger and earlier N1 in valid (i.e., the stimulus was preceded by a valid cue) compared with invalid (i.e., the stimulus was preceded by an invalid cue) trials regardless of the Go/No-go response. These observations confirmed that these early components were associated with the IOR effect on sensory/perceptual processes (McDonald et al. 1999; Wascher and Tipper 2004).

In the Stop-signal paradigm, participants are asked to respond to a stimulus (Go stimuli). However, when these Go stimuli are followed by a stop-signal, participants must withhold the response. Bekker et al. (2005) studied the electrophysiology of an auditory Stop-signal task in a sample of young adults (N=20; M±SD=21.4±5.6 years old; 16 women) and identified a larger N1 for successful compared with failed stops. This ERP component was interpreted as reflecting the amount of attention that is paid to (or switched to) the stop-signal, which is partially determinative of the subsequent success of inhibition in stopping the response. Thus, Bekker et al. (2005) suggested the strength of the inhibitory control on the Stop-signal paradigm might be determined, in part, by the ability to switch attention to the stop-signal. Complementing these results, Ramautar et al. (2006) suggested the N1 was associated with exogenous/sensory aspects of the stop signal. In their experiment, fifteen young adults (M=21.2±1.78 years old; 8 women) participated in a bimodal Stop-signal task (with 12 visual and 12 auditory stop blocks of 120 trials each). The researchers identified an N1 component that did not differentiate between successful and unsuccessful stopping and was therefore associated with sensory processing of the stop-signal.

In the Eriksen Flanker Task (Eriksen and Eriksen 1974), a central target (e.g., letter or arrow) is flanked at both sides by items that indicate a response that is the same (congruent condition), opposite (incongruent condition) or neutral in relation to the response that is required by the target. For example, if participants are instructed to press a left button every time they view the letter "H" in a central position and a right button every time they view the letter "C" in a central position, the two main conditions are as follows: a congruent condition includes the same letter "H" or "C" for both flankers and the central target (e.g., HHHHH or CCCCC), whereas an incongruent condition includes opposite letters for the flankers and central target (e.g., HHCHH or CCHCC). In the incongruent condition, the incongruent flankers cause interference, which leads to slower and more inaccurate responses compared with the congruent condition. This effect is known as the flanker congruency effect (FCE) (White et al. 2011). Wild-Wall et al. (2008) conducted an ERP study using two variants of a Flanker Task with two age groups: a younger group (N=15; M±SD=23.7±3.7 years old; 7 women) and an older group (N=15; M±SD=60.9±6.5 years old; 7 women). In the first variant of the task, the flankers were presented 100 ms before the target (Experiment 1). In the second variant, the flankers were presented at the same time as the target (Experiment 2). Both experiments included congruent, incongruent and neutral

conditions. The researchers' main goals were to identify the temporal course of the FCE and the differences between the two age groups in the flanker and target processing. In both experiments, the P1 and N1 ERP components were identified in the first 200 ms. In Experiment 1, the onset of the two ERPs preceded the appearance of the target stimulus. Therefore, the authors suggested that P1 and N1 are primarily associated with flanker processing. The ageing effects that were identified in this research on flanker and target processing are discussed later in this paper. These studies suggest that both N1 and P1 are associated with sensory information processing regardless of the task type. In particular, the P1 and N1 effects reflect the inhibition and enhancement of sensory information.

1.3.2. Automatic and controlled nature of inhibition in the first 200 ms

The nature of the inhibitory processing in this early time window can easily be related to automatic processing. The fact that automatic processing has a short duration and can be elicited without the subject's awareness supports this assumption. As previously described, Ramautar et al. (2006) studied the ERPs that were elicited during a Stop-signal task in a sample of young adults. They did not identify changes in the amplitude or latencies of the N1 component between successful and unsuccessful stopping. As a result, Ramautar et al. (2006) proposed that this ERP component was more strongly linked with exogenous sensory aspects of the stop-signal and, therefore, with automatic processing. Several studies have suggested that even this automatic processing may entail some executive control because a higher N1 amplitude for successful than for failed Stop-signal/Flanker conditions has been identified (Bekker et al. 2005; Wild-Wall et al. 2008). Despite these results, inhibition has been more frequently associated with automatic processing in the first 200 ms (Roche et al. 2005).

1.3.3. Source localization of ERPs associated with inhibition in the first 200 ms

Some studies have attempted to better characterize the neural basis and dynamics of inhibition by exploiting the high temporal resolution of ERPs and the advances in source localization (Scherg 1990). Applying the Low Resolution Brain Electromagnetic Tomography method (LORETA; Pascual-Marqui et al. 1994) to ERP data that were collected during a cued Continuous Performance Test (CPT), Strik et al. (1998) reported

that the main source of the P1 component was in the occipital area in both the Go and No-go conditions. Consistent with these results, using LORETA, Bokura et al. (2002) did not identify differences in the P1 component sources between the Go and No-go conditions and demonstrated that the P1 component for both the Go and No-go trials has generators that are located in the occipital lobes. Bokura et al. (2002) demonstrated, in both Go and No-go trials, an N1 component with bilateral brain generators in the occipito-temporal lobes, which likely encompass the primary and secondary visual areas. Tian and Yao (2008) studied the neural mechanisms of inhibition of return with a cued Go/No-go task. The 3D scalp topographic maps and LORETA images indicated that P1 and N1, which are linked to the inhibition of return processing, were localized in occipito-parietal regions, specifically, the P1 on the middle occipital gyrus and the N1 on the cuneus.

In summary, the P1 component that is elicited when inhibition processes are triggered may represent the visual processing of the stimulus, whereas the N1 may be related to the orientation of attention via the fronto-parietal attention network (Natale et al. 2006).

1.3.4. Age-related inhibition changes in the first 200 ms

A limited number of studies have investigated age-related differences in these early ERP components in the context of inhibition. As previously discussed, Wild-Wall et al. (2008) studied inhibition in two age groups with two variations of the Flanker Task. In the first 200 ms, they identified a P1 and subsequent N1 components in the two variations of the Flanker Task for both groups. In Experiment 1 (when flankers appeared 100 ms before the target), the P1 and N1 onset was prior to the presentation of the target; therefore, both components were associated with flanker processing. Because both the P1 and N1 exhibited similar latencies and amplitudes for both groups, age does not appear to affect flanker processing. In Experiment 2 (when the flankers appeared at the same time as the target), the P1 latency and amplitude were similar in both groups; however, the N1 amplitude was markedly larger in the older group. This increased N1 amplitude in the older group was interpreted as an increased processing of the target. In Experiment 1, this target-related processing in the older group appears to be indexed by a negativity that appears after the N1. This result suggests the N1 amplitude increase in Experiment 2 is the result of a superposition of the flanker-related N1 activity with this

dissociable target-specific signature. Behaviourally, an age-related slowing was identified and the older group exhibited surprisingly lower error rates compared with the younger group in the incongruent condition in both Experiments 1 and 2. Hence, it appears that the older participants do not exhibit inhibitory deficits in flanker processing, even though it is well known that this population displays a lower processing speed. However, in Experiment 2, a higher N1 amplitude during target presentation was identified in the older participants. Wild-Wall et al. (2008) proposed that during information processing, older participants pay greater attention to the target compared with younger participants. These enhancement processes, which are related to the target information, are complementary to the inhibition processes, which are related to the flanker information. The increased attention to the target might explain the lower error rates that are present in the older participants because they focus on the target and, therefore, reduce flanker interference.

Similar results were identified by Hsieh and Fang (2012), who investigated ERP correlates of the Flanker Task and potential compensatory strategies that older adults use to maintain the ability to inhibit irrelevant information. To achieve these goals, they compared young and older adults in three experiments in which the probability of congruent, incongruent and neutral trials in the Flanker Task was manipulated. A group of young adults (N=16; M±SD=20.44±1.71 years old; 10 females; M±SD=14.25±1.24 years of education) and a group of older adults (N=16; M±SD=64.63±4.13 years old; 7 females; M±SD=14±1.93 years of education) participated in the first experiment, in which the number of congruent trials was greater than incongruent trials. In the second experiment, a group of young adults (N=16; M±SD=21.06±1.61 years old; 9 females; M±SD=14.81±1.05 years of education) and a group of older adults (N=16; M±SD=64.13±2.47 years old; 7 females; M±SD=13.81±1.80 years of education) completed a Flanker Task with the same number of congruent and incongruent trials. Finally, a group of young adults (N=16; M±SD=21.19±2.20 years old; 7 females; M±SD=15.188±1.40 years of education) and a group of older adults (N=16; M±SD=64.19±5.72 years old; 8 females; M±SD=13±1.26 years of education) participated in the third experiment, in which the number of incongruent trials was greater than congruent trials. Consistent with Wild-Wall et al.'s (2008) findings, Hsieh and Fang (2012) did not observe an increased flanker effect in older adults compared with young adults across the three experiments. Additionally, throughout the three experiments, the older adults exhibited greater N1 amplitudes compared with the young

adults during target presentation, which suggests the older adults engaged in increased top–down visual processing of the central target.

Gazzaley et al. (2008) compared young adults (N=20; M=23.1 years old, range 19-30; 10 women) and older adults (N=26; M=65.7 years old, range 60-72; 13 women) in the selective attention delayed-recognition task that was developed to measure both inhibition and enhancement. In this task, the participants viewed sequences of two faces and two natural scenes structured in three conditions presented in a randomized order. In one condition, the participants had to remember the faces (attend condition) and ignore the scenes (ignore condition). In a second condition, the participants had to remember the scenes (attend condition) and ignore the faces (ignore condition). In the third condition, the participants did not have to ignore any of the images (passive condition). Within the first 200 ms, the young adults exhibited the largest P1 amplitude and earliest N1 latency for the attended faces, followed by passive faces and then ignored faces, whereas the older adults only exhibited the largest P1 amplitude and earliest N1 latency for the attended faces compared with passive faces. Gazzaley et al. (2008) interpreted these results as an indication of sensory suppression deficits in older adults (because there were no differences between the passive and ignore conditions), as well as an indication of preserved enhancement processes (the same change in young and older adults between the passive and attend conditions). In an additional experiment with the selective attention delayed-recognition task, Anguera and Gazzaley (2012) studied the neural markers of inhibition in the first 200 ms (P1, N170) in a sample of older adults (N=16; M±SD=70.6±6.7 years old; 7 women). ERP age-related modulation analyses for face stimuli were conducted that focused on P1 amplitude and N170 latency as indices of top-down enhancement (attend vs. passive) and inhibition (ignore vs. passive). The authors demonstrated that older adults did not exhibit the signatures of early neural inhibition (reflected by the absence of differences in N170 latency and P1 amplitude) when viewing irrelevant visual stimuli. However, there was neural enhancement for the relevant stimuli, which was reflected by the early N170 latency for attended versus passively viewed faces.

1.3.5. Summary

In the preceding section, we summarized ERP research results that provide significant insights regarding inhibition processing during the first 200 ms post-stimulus

in a variety of paradigms. Despite the limited number of ERP studies in the context of inhibition that have addressed this early time window, the P1 and N1 ERP components have consistently been found to reflect inhibition-related phenomena. As early as 100 ms post-stimulus, these components index sensory information processing and have primarily been associated with automatic processing. The P1 has been associated with the inhibition of irrelevant sensory information and linked to the occipital lobes. The N1 has been associated with a complementary process that facilitates or enhances relevant sensory information (Hillyard et al. 1994) and has been linked to the frontal and parietal components of the attention network. The age-related differences that have been identified in the ERP components support this dissociation. Specifically, the N1 is related to enhancement processes, which are preserved in older adults compared with young adults, and the P1 is related to the onset of inhibition processes, which are less effective in older adults compared with young adults.

1.4. Inhibition between 200 and 400 ms

1.4.1. ERPs for inhibition between 200 and 400 ms

ERP research has identified two components within this time window that might be related to inhibition: the N2, which represents a pronounced fronto-central negativity that peaks approximately 200-350 ms post-stimulus, and the P3, which peaks at approximately 250-500 ms and exhibits a fronto-central to centro-parietal scalp topography (Johnstone et al. 2007; Polich 2007; Folstein and Van Petten 2008). In early research, these two components were often referred to together as the "N2-P3 complex" (Folstein and Van Petten 2008; Huster et al. 2013).

The N2 is an endogenous ERP component and can be separated into the following subcomponents according to Folstein and Van Petten (2008) review: (i) a fronto-central component that is associated with novelty detection (N2a); (ii) a second fronto-central component that is associated with executive control (which encompasses motor inhibition, response conflict and error monitoring) (N2b); (iii) and a posterior N2 that is associated with stimulus classification operations related to target processing (N2c). Furthermore, there is an attention-related ERP, the N2-posterior-contralateral (N2pc), which is typically observed in the N2 time window at posterior scalp sites that are contralateral to the position of a potential target item on which attention is focused

(Patel and Azzam 2005). The N2a that is elicited by deviant auditory stimuli, attended or unattended, is referred to as mismatch negativity (MMN; for a review, see Naatanen et al. 2012). P3 is an umbrella term that encompasses at least two functionally distinct subcomponents with different scalp distributions, P3a and P3b (Polich 2007; O'Connell et al. 2012). P3a and P3b differ in terms of latency (P3a has a shorter latency) and topography (P3a has a fronto-central distribution compared with the more parietal distribution of P3b; Fjell et al. 2009). Polich and Comerchero (2003) have suggested that P3a and P3b are connected to a circuit pathway between the frontal and temporal/parietal brain areas. The P3a reflects involuntary, transient allocation of attention to salient changes in stimuli and novel stimuli, which is linked to frontal lobe activity. The P3b is related to a controlled cognitive attentional process that is tied to the stimulus evaluation process, which is linked to temporal/parietal areas (Kirino et al. 2000; Polich 2007).

For both the N2 (typically the N2b) and P3 (typically the P3a) components, larger amplitudes have been identified when inhibiting a response compared with executing a response (Maguire et al. 2009). The relationship between the N2, the P3, and inhibitory processing remains a matter of debate (Bruin et al. 2001; Smith et al. 2007). Some experts have argued that inhibitory processes are associated with the N2 (Kopp et al. 1996; Van Veen and Carter 2002; Falkenstein et al. 2002; Roche et al. 2005), whereas other experts have argued that the P3 has an association with inhibition (i.e., the N2 is associated with other processes, such as recognition of the need for inhibition or even response conflict) (Bruin et al. 2001; Smith et al. 2008). There is, however, a general consensus that both components are associated with inhibition to some degree (van Boxtel et al. 2001; Kok et al. 2004; Kirmizi-Alsan et al. 2006; Dimoska et al. 2006; Smith et al. 2006, 2007; Maguire et al. 2009).

The N2 and P3 ERP components have predominantly been studied in inhibitory paradigms, such as the Stop-signal, Go/No-go and Eriksen Flanker tasks. Both the Stop-signal and Go/No-go paradigms elicit inhibitory processes that can be explained by the well-established horse-race model (Logan 1994). In this model, the "Go" process races against the "No-go/Stop-signal/Inhibition" process. If the "No-go/Stop-signal/Inhibition" process is completed before the "Go" process, this finding signifies inhibition of the response. Typically, in the Stop-signal and Go/No-go tasks, although the latency and variability of the Go response can be observed directly, the inhibition response that is observed in the No-go/Stop-signal trial is internally generated;

therefore, it cannot be directly observed. However, in the Stop-signal task, it is possible to quantify the latency of the inhibition mechanism with the Stop-signal Reaction Time (SSRT; Logan et al. 1984), which can be estimated using the assumptions of the race model (Logan 1994; Logan et al. 1984). Some authors have suggested the Go/No-go and Stop-signal paradigms involve equivalent inhibitory processes (Verbruggen and Logan 2008a). In both paradigms, participants are instructed to respond to the Go stimuli and to withhold a response when a No-go/Stop-signal is presented. To be successful, participants must identify the strategy that optimally balances the following two goals: respond as quickly and as accurately as possible to the Go stimuli and withhold the response to the No-go or Stop-signal as effectively as possible.

In accordance with this assumption, van Boxtel et al. (2001) identified similar ERP patterns in No-go and Stop-signal trials, which suggests the underlying mechanisms of these two paradigms are similar. They examined a sample of young adults (N=10; M=22.2 years old, range 19-28) in a combined visual Stop-signal and visual Go/No-go task in which 20% of the trials included a Stop-signal and 10% were No-go trials. Following the combined Stop-signal and Go/No-go task, van Boxtel et al. (2001) divided the young adult group into efficient and less efficient inhibitors using a median split of the SSRT. A larger N2 amplitude was identified for the efficient inhibitors, which suggests inhibition bears a N2 signature in both the Stop-signal and Go/No-go paradigms. Despite this association between the No-go and Stop signal N2s, to our knowledge, only the van Boxtel et al. (2001) study directly compared the Go/No-go and Stop-signal paradigms. Therefore, we cannot undoubtedly declare that the inhibition processes that are recruited during No-go and Stop-signal trials are the same. Additionally, according to Folstein and Van Petten (2008), the Stop-signal N2, in contrast with the No-go N2, might comprise various subcomponents that are associated with inhibition and evaluation of the stop-signal. Therefore, we review the Stop-signal and Go/No-go ERP studies that have identified N2 and P3 modulations related to inhibition independently.

ERP correlates of inhibition processes that are recruited in the Stop-signal task have been extensively studied (Kok et al. 2004; Ramautar et al. 2004; Bekker et al. 2005; Ramautar et al. 2006; Luus et al. 2007; Dimoska and Johnstone 2008; Knyazev et al. 2008). Luus et al. (2007) conducted an MEG study of inhibition elicited by a visual Stop-signal paradigm (with 25% Stop-signal trials) in a sample of young adults (N=11; M±SD=28±5.3 years old; 5 women). The results indicated greater differences between

successful stop-signal responses and fail stop-signal responses in the 100-220 ms range of the grand average waveforms. Specifically, the researchers identified an earlier and larger N2 in successful stop-signal responses compared with failed responses, which suggests the association of N2 amplitude and latency with successful inhibition. Knyazev et al. (2008) contributed to the understanding of successful and unsuccessful stopping performance in young adults (N=51; M±SD=20±2.6 years old; 35 females) through a study of the ERP correlates of an auditory Stop-signal task with a fixed stop-signal delay. As Knyazev et al. (2008) noted, failed stop responses are typically associated with a longer stop-signal delay, which has been conceptualized as an explanation for failure. Comparing successful and unsuccessful stop-signal responses with a fixed stop-signal delay, they identified differences not only in the Stop-signal trial but also in the preceding Go trial. Specifically, they identified smaller N2 and P3 amplitudes in Go trials that preceded successful Stop-signal trials, a larger P3 amplitude in successful Stop-signal trials and shorter latencies for both N2 and P3 in successful, relative to failed, Stop-signal trials. Knyazev et al. (2008) interpreted these results as evidence for a direct relation between the level of attention toward the stop-signal and the success in stopping.

Kok et al. (2004) examined the ERP correlates of inhibition in a sample of young adults (N=12; M±SD=23±7 years old; 6 women) using a visual Stop-signal task in which the Stop-signal and Go trials had equal probabilities of occurrence (see Fig. 1 for a schematic display of the task). They identified a larger N2 followed by a larger P3 in Stop-signal trials compared with Go trials. Therefore, both N2 and P3 appear to be related to the processing that occurs in the Stop-signal trials, particularly inhibition. A deeper analysis of the Stop-signal trials that contrasted successful and unsuccessful responses revealed higher amplitudes for the N2 and P3 in unsuccessful compared with successful stop-signal responses. Kok et al. (2004) interpreted this amplitude difference in the N2 as reflecting aspects of response monitoring and conflict. The P3 exhibited different scalp distributions for successful and unsuccessful stop-signal responses. Therefore, the authors formulated two interpretations of this result. The P3 fronto-central distribution in successful responses might reflect inhibition processes that are triggered by the stop-signal appearance, whereas a more posterior distribution of the P3 in unsuccessful responses might reflect response monitoring.

As previously discussed, Bekker et al. (2005) examined the ERP correlates of an auditory Stop-signal task with a 40% probability of occurrence of Stop-signal trials.

They identified a larger P3 amplitude in successful compared with unsuccessful stop-signal responses. Therefore, the P3 amplitude change was interpreted as an index of inhibition processes. These similar results identified in both visual and auditory Stop-signal tasks suggest that the processes that are indexed by the P3 in the stop-signal processing are endogenous (i.e., independent of the modality). Ramautar et al. (2006) specifically studied the effects of modality in a sample of young adults (N=15; M±SD=21.2±1.78 years old; 8 women) using a mixed Stop-signal task with auditory and visual Stop-signal trials, which had the same probability of occurrence as go trials. Concerning N2 modulations in the Stop-signal trials, they identified a smaller N2 amplitude in the auditory Stop-signal trials compared with the visual trials. Longer N2 and P3 latencies were identified for unsuccessful Stop-signal trials, regardless of the modality. Regarding the N2 and P3 amplitudes, a different pattern was identified. The authors identified a larger N2 in unsuccessful compared with successful Stop-signal trials, regardless of the stop-signal modality, and suggested that this result reflects conflict detection. Regarding the P3, they identified a larger amplitude in successful compared with unsuccessful Stop-signal trials, regardless of the stop-signal modality. Therefore, these authors concluded that the P3 appears to be an index of modality-unspecific inhibition processes.

The effects of stop-signal probability are also important in the study of ERP correlates of inhibition using the Stop-signal paradigm. Ramautar et al. (2004) examined the ERP correlates of a visual Stop-signal task in a sample of young adults (N=14; M±SD=20.14±1.99 years old; 7 women) to specifically explore the effects of stop-signal probability. There were two conditions in this experiment: one condition in which the Stop-signal trials had a probability of 20% (low probability condition) and a second condition in which the Stop-signal trials had the same probability as the Go trials (i.e., 50%; high probability condition). The results were similar to Kok et al. (2004) concerning the dissociation between the successful and unsuccessful stop-signal responses. With respect to their stop-signal probability manipulation, Ramautar et al. (2004) identified a larger P3 amplitude for low compared with high probability stop-signals. In addition, the P3 that was elicited during successful stop-signals had a more anterior distribution in the low probability condition. These findings were interpreted as a reflection of increased inhibitory load in the low probability condition. However, these ERP modulations that reflect the stop-signal probability manipulation may, in fact, be novelty effects (i.e., stop-signal presented rarely) (Dimoska and Johnstone 2008).

To determine whether a low probability condition is related to an increase in inhibitory load, Dimoska and Johnstone (2008) examined not only the effects of varying stop-signal probabilities on ERP correlates of an auditory Stop-signal task but also the effects of varying the probability of a task-irrelevant ignore-signal. In their experiment, young adults (N=30; M±SD=22.1±3.3 years old; 20 women) performed the Stop-signal task with frequent and rare stop-signal conditions. In the frequent condition, the stop-signal was presented in 42% of the trials and the ignore-signal (i.e., a tone that differed from the stop-signal that participants were instructed to ignore) was presented in 18% of the trials. In the rare condition, the stop-signal was presented in 18% of the trials and the ignore-signal was presented in 42% of the trials. The authors identified an increased P3 amplitude in the rare compared with frequent conditions, but this amplitude difference did not differ between the stop and ignore-signal trials. These findings suggest the larger P3 amplitude in successful responses may reflect novelty effects. Nevertheless, Dimoska and Johnstone (2008) suggested an activation of inhibitory processes in the Stop-signal trials that was indexed by the P3 amplitude change, regardless of the probability differences effect, which results from the different topographic distributions of P3 identified in stop and ignore-signal trials.

ERP research using the Go/No-go task has also yielded results that are relevant to understanding the N2 and P3 association with inhibition (Falkenstein et al. 1999; Bruin and Wijers 2002; Nieuwenhuis et al. 2003; Roche et al. 2005; Folstein et al. 2008; Smith et al. 2008). Falkenstein et al. (1999) studied the ERP correlates of inhibition in a sample of young adults (N=10; M=24.1 years old, range 18-33; 4 women) using visual and auditory versions of the same Go/No-go task to determine the modality effects on the ERPs. The authors divided the participants into the following two groups based on their performance: the “Good” group, with low error rates in the No-go trials, and the “Poor” group, with high error rates. They identified a larger amplitude and earlier latency of the No-Go N2 for the “Good” compared with the “Poor” participants, which supports the hypothesis that the No-go N2 reflects inhibition, which is better in the “Good” group. In contrast, the No-go P3 amplitude and latency were similar for both the “Good” and “Poor” groups. Falkenstein et al. (1999) suggested that this component is not related to inhibition processes. A smaller No-go N2 amplitude after auditory compared with visual stimuli was identified, which suggests the inhibition processes likely indexed by the No-go N2 are modality-specific and, therefore, occur at earlier non-motor processing stages.

Roche et al. (2005) suggested that the latency of the N2 and P3 might determine the success or failure of inhibitory control. Their experiment used a visual Go/No-go task (see Fig. 1 for a schematic display of the task) in which the letter X and the letter Y were presented sequentially at the middle of the screen. The participants (N=20; M=21.5 years old, range 17-31; 17 women) were asked to press a button every time the letters appeared (Go condition - 94% of the trials), with the exception of when two identical stimuli followed each other (e.g., an X followed an X); in this condition, they were required to withhold the response (No-go condition – 6% of the trials). Roche and colleagues (2005) identified a larger amplitude and later latency for the No-go N2 and P3 compared with the Go N2 and P3. Additionally, they identified a shorter latency of the N2 and the P3 for successful No-go responses compared with unsuccessful responses, which suggests the relevance of the latency of these two ERP components for successful inhibition. Roche et al. (2005) suggested that the No-go N2 onset is the most valid index of active inhibitory processes. They also interpreted the No-go P3 onset for errors that were more than 100 ms higher than the corresponding mean response latency as a reflection of No-go P3's role in performance evaluation, error detection and/or preparation for future trials.

Bruin and Wijers (2002) also examined the ERP correlates evoked in a visual Go/No-go task and specifically addressed the response mode and Go/No-go stimulus probability effects. In their experiment, young adults (N=12; M=21.5 years old, range 19-28; 8 women) participated in a visual Go/No-go task with two response mode conditions, including a manual condition (i.e., lifting their right or left index finger from a response panel in Go trials) and a mental count condition (i.e., count the total number of go stimuli in each task block and report the answer following the block). The stimulus probability effect had the following three conditions per response mode: 25, 50 and 75% No-go trials. As expected, the authors identified smaller N2 and P3 amplitudes for the high probability condition compared with the lower probability conditions. Concerning the different response modes, they identified larger N2 and P3 amplitudes in the No-go compared with Go trials in both response modes. However, the No-go P3 was smaller in the counting condition compared with the manual condition. Bruin and Wijers (2002) interpreted their results as supportive of Pfefferbaum et al. (1985) study in which similar results were identified, which indicates both N2 and P3 reflect both cognitive and motor inhibition processes. The authors interpreted the smaller No-go P3

that was identified in the counting condition as a reflection of a smaller level of inhibition needed to withhold a response compared with the manual condition.

Smith et al. (2008) further explored the contribution of movement-related potentials to N2 and P3 modulations within the Go/No-go paradigm while controlling for stimulus probability. In their study, a sample of young adults (N=20; M±SD=22.4±5.6 years old; 12 women) participated in an auditory Go/No-go task with rare (20%) No-go, rare (20%) Go, and frequent (60%) Go stimuli (a different tone than a rare Go stimulus). The participants pressed a response button (overt condition) or counted (covert condition) if either rare or frequent go stimuli appeared. The authors compared the No-go and Go trials with the same probability (20%) to ensure that the effect identified in the N2 and P3 could not be explained by differences in stimulus probability. The No-go P3 effect (i.e., the No-go P3 higher than the Go P3) was identified in both response conditions, but it was reduced in magnitude in the covert condition. Smith et al. (2008) suggested that the No-go P3 reflects inhibition and movement-related potentials that are responsible for the difference identified between overt and covert versions of the Go/No-go task. In respect to the No-go N2 effect (the No-go N2 higher than the Go N2), they identified the same effect in overt and covert versions of the Go/No-go task. Therefore, Smith et al. (2008) suggested the No-Go N2 effect does not reflect motor inhibition, but it may reflect recognition that no response is needed or the conflict between executing and withholding the response.

Nieuwenhuis et al. (2003) investigated the conflict hypothesis in a sample of young adults (N=12; M=20.9 years old, range 18-24; 9 women) using a visual Go/No-go task. In their experiment, the following three conditions were used to manipulate the No-go and Go stimulus probability: rare No-go trials (20%), frequent No-go trials (80%) and equally frequent No-go and Go trials (50%). Nieuwenhuis et al. (2003) identified the traditional No-go N2 effect in the 20% and 50% (with smaller magnitude) No-go trial conditions. However, in the 80% No-go trial condition, the No-go N2 amplitude was slightly smaller than the Go N2 (Go trials were less frequent in this condition). The hypothesis defending an association between the No-go N2 and inhibition processes cannot easily explain why a small N2 amplitude increase can be observed in infrequent Go trials relative to the amplitude in frequent No-go trials because no inhibition is needed in Go trials. Additionally, a source localization analysis revealed that the localization of the No-go N2 might be in the anterior cingulate cortex (ACC), which has been associated with conflict processing (Botvinick et al. 2001). Based on these ERP

results and source localization analyses, Nieuwenhuis et al. (2003) suggested that the N2 observed in Go/No-go tasks reflects response conflict.

Donkers and van Boxtel (2004) also tested the conflict hypothesis in a sample of young adults (N=13; M=21 years old, range 18-32; 6 women) with two tasks, including visual Go/No-go and visual go/GO tasks. In the Go/No-go task, the participants were asked to withhold the response to the "No-go" stimuli. In contrast, in the go/Go task, the participants were asked to respond with maximal force to the "GO" stimuli. In both tasks, the participants were asked to respond to the "go" stimulus with "nominal" force. The "go" probability varied between 80% and 50% to test the hypothesis of higher conflict levels for low compared with high frequency stimuli. They identified a larger N2 and P3 for both "No-go" and "GO" trials compared with "go" trials. The "No-go" P3 amplitude was larger than the "GO" P3 amplitude. Therefore, Donkers and van Boxtel (2004) suggested that the "No-go" P3 might index response inhibition. Consistent with Nieuwenhuis et al.'s (2003) results, the "No-go" N2 and the "GO" N2 amplitudes were higher in the 80% "go" probability condition compared with the 50% "go" probability. Therefore, Donkers and van Boxtel (2004) suggested that the No-go N2 is primarily associated with conflict monitoring and any association of the No-go N2 with inhibition is limited.

Smith et al. (2007) suggested that the No-go N2 is not related to inhibition or conflict processes. In their experiment, young adults (N=26; M±SD=22.6±7.2 years old; 15 women) participated in a cued auditory Go/No-go task (adapted from Bruin et al. 2001) with three different targets, which included Go Left (i.e., tone presented in the left ear, which required a left button press), Go right (tone presented in the right ear, which required a right button response), and a No-go (tone presented binaurally, which required a withheld response). The Go targets were preceded by cues that were valid (e.g., left tone preceded a left target), invalid (e.g., left tone preceded a right target) or non-specific (e.g., binaural tones preceded a left target). There was a specific No-go cue that was always valid. These informative cues were used to examine variations in response inhibition and conflict when the planned response was inappropriate. The authors identified a larger N2 amplitude in No-go compared with Go targets, regardless of whether the cue that preceded the Go target was specific (i.e., valid or invalid) or non-specific. Despite this significant No-go N2 effect, a larger N2 amplitude was identified after No-go cues (when participants knew no response was needed, which reduced response preparation at minimum) compared with after Go cues. Furthermore,

larger N2 amplitudes were identified for invalid compared with valid cues, which is in contrast to the response conflict theory. Accordingly, Smith et al. (2007) suggested that the No-go N2 was not related to inhibition or conflict. In contrast, these results concerning P3 amplitude suggest that the No-go P3 effect may be associated with inhibitory and/or conflict processes.

To distinguish between inhibition and conflict accounts for both N2 and P3 components, Smith et al. (2010) studied the sequence effects of a visual Go/No-go task in a sample of young adults (N=23; M±SD=22.5±8.1 years old; 17 women). As previously described by Nieuwenhuis et al. (2003) and Donkers and van Boxtel (2004), greater inhibition and/or conflict occur with unexpected stimuli. In a Go/No-go task, even when the sequence of Go and No-go stimuli is randomized, participants can spontaneously generate expectancies for the upcoming stimulus based on the previous sequence of stimuli. Therefore, if the N2 and P3 reflect inhibition in No-go trials, there must be an increase in their amplitudes in unexpected compared with expected No-go stimuli beyond the typical increase of these amplitudes in No-go compared with Go trials. However, if the N2 and P3 amplitude is higher for all unexpected stimuli, regardless of whether Go or No-go, then it must reflect conflict. Smith et al.'s (2010) results supported the conflict interpretation for both N2 and P3.

An additional paradigm that is used to study inhibition and response conflict is the Eriksen Flanker Task. In this task, a prominent N2 component is observed after the incongruent condition (incongruent flankers surround the target) compared with the congruent condition (congruent flankers surround the target) (Wild-Wall et al. 2008). The frontal negative component that is observed in the incongruent condition of the Eriksen Flanker Task is likely to correspond with the N2 that is observed after No-go stimuli in the Go/No-go task or after the stop-signal in the Stop-signal task (Kopp et al. 1996; Van Veen and Carter 2002; Bartholow et al. 2005). Van Veen and Carter (2002) studied the ERP correlates of the Eriksen Flanker Task in a sample of young adults (N=12; M±SD=23.4±2.8 years old; 6 women). This experiment included the following three conditions: a congruent condition (50%), in which the flankers were equal to the target; a stimuli incongruent condition (25%), in which the flankers were different but mapped onto the same response hand; and a response incongruent condition (25%), in which the flankers were mapped onto the opposite response hand than the target stimulus. The researchers identified a fronto-central N2 enhanced only to the response incongruent condition and a N2 dipole located in the ACC, which suggests the N2 that

is elicited in the Eriksen Flanker Task is sensitive to response conflict. Supporting the same conflict interpretation, Bartholow et al. (2005) also identified an enhanced N2 in the incongruent condition of the Eriksen Flanker Task in a sample of young adults (N=45; range 21-30 years old; 21 women). However, in contrast to the conflict interpretation of N2 in this task, Bartholow et al. (2005) identified a larger N2 when the incongruent trials were highly probable (80%) in contrast with low (20%) or equally probable (50%) incongruent trials. This finding questions the association between the N2 and conflict because conflict prior to the response should be less in the highly probable incongruent trials condition; therefore, the N2 amplitude elicited therein should be smaller.

Purmann et al. (2011) identified a larger N2 in low frequency incongruent trials of the Eriksen Flanker Task. In their study, participants (N=12; M=25 years old, range 22-38; 2 women) responded to frequent (75%) and rare (25%) incongruent blocks. Consistent with conflict theory, the authors identified a larger N2 in incongruent compared with congruent trials, and this difference in amplitude was larger with infrequent conflict (i.e., in the rare incongruent blocks). Additionally, they identified a longer P3 latency for incongruent compared with congruent stimuli, which suggests the evaluation of incongruent stimuli requires more time.

Tillman and Wiens (2011) challenged the notion that the N2 that is elicited in the Eriksen Flanker Task is a valid index of response conflict in a study that yielded results consistent with Bartholow et al. (2005). In Tillman and Wiens' (2011) experiment (see Fig. 1 for a schematic display of the task), young adults (N=27; M±SD=27.22±5.96 years old; 16 women) responded to a Flanker Task that was presented in two blocks: one block with low (20%) and one block with high (80%) probable incongruent trials. The authors identified a larger N2 in the 80% compared with 20% incongruent trial condition. As an alternative to the conflict hypothesis, Tillman and Wiens (2011) suggested that the N2 might index attentional control or inhibition processes. Neuhaus et al. (2010) studied the ERP correlates of the Attention Network Test, addressing both visual attention in a cued detection task and inhibition in an Eriksen Flanker Task. In the Eriksen Flanker Task, the participants (N=44; M±SD=30.39±7.1 years old; M±SD=15.16±2.1 years of education; 22 women) were instructed to indicate the direction of a central arrow while ignoring the flanking stimuli (lines in the neutral condition; congruent or incongruent flankers). They identified a frontal P3 amplitude increment and parietal P3 amplitude decrement following incongruent targets. The

authors interpreted the frontal P3 amplitude increment as an index of response inhibition and suggested that because of its frontal distribution, it is likely the same modulation that is present in Go/No-go tasks (i.e., the No-go P3 effect).

1.4.2. Automatic and controlled nature of inhibition between 200 and 400 ms

Several authors have assumed that inhibition in this time window is a top-down executive control process (Ridderinkhof et al. 1999; Enriquez-Geppert et al. 2010). As previously described, the Go/No-go and Stop-signal paradigms are frequently used to study inhibition. Both paradigms appear to imply the use of controlled processes to proactively change between goals for an optimal performance, i.e., to respond as quickly as possible to the Go stimuli and withhold the response to the No-go stimuli or when the stop-signal is present. However, stimulus repetition may also be a crucial variable that affects performance in these motor inhibition paradigms. In support of this possibility, Shiffrin and Schneider's (1977) theory proposes that automatic processing may develop with practice.

In the Go/No-go paradigm, stimuli are consistently associated with going and stopping (i.e., there is a Go and a different No-go stimulus, and this functional distinction remains the same throughout the entire experiment); thus, automatic inhibition is likely to develop after many repetitions. In contrast, if the stimulus is inconsistently mapped onto different responses, such as in a typical Stop-signal task in which the stop-signal is not associated with a specific stimulus, automatic processing is unlikely to develop. However, even in the Stop-signal task, the stimuli can be associated with stopping. Verbruggen and Logan (2008b) studied a Stop-signal task in which the participants viewed words that represented living and non-living objects. Each word was presented once or twice, and a random selection of the words was repeated after a variable number of trials (i.e., the word from trial n was repeated on trial n+1, n+5, n+10 or n+20). The participants responded by pressing one key for "living" and a different key for "non-living" (Go trials). On some trials, an auditory tone was presented as a stop-signal and the participants were required to withhold the response. After a first successful stop, a longer RT was identified in the Go trial that repeated the same target compared with the Go RT that followed a first presentation of the target coupled with either a successful Go response or an unsuccessful stop. This inhibition aftereffect was significant up to the n+20 repetition lag condition. In a separate

experiment, Verbruggen and Logan (2008a) developed a modified Stop-signal task using the same stimuli (i.e., words that represented living and non-living objects) divided in training and test phases. The authors varied the stimulus-stop mapping and hypothesized that automaticity in the Stop-signal task may develop when there is consistent stimulus-stop mapping (i.e., in both the training and test phases, the living stimuli were associated with the go response and the non-living stimuli were associated with the stop-signal). In the test phase, a slower response to go stimuli was identified when the same type of stimuli was consistently associated with stopping in the training phase. Additionally, consistent with the authors' hypothesis, response inhibition benefited when the stimuli that were associated with stopping were the same in the training and test phases. In the Stop-signal task, the mapping between stimulus and stop-signal is typically inconsistent, which hinders the development of automaticity. Regarding the Go/No-go task, Verbruggen and Logan (2008a) suggested that the development of automaticity may be avoided using a large set of No-go and Go stimuli to avoid repetitions.

1.4.3. Source localization of ERPs associated with inhibition between 200 and 400 ms

In one of the first experiments conducted to understand brain sources of inhibition processes, Kiefer et al. (1998) conducted a source analysis of the N2 and P3 that were elicited by No-go trials using Brain Electrical Source Analysis (BESA), a spatio-temporal dipole fit model, in an auditory Go/No-go task. They reported an inferior prefrontal cortex (PFC) generator for the N2 and a fronto-central P3 source located in the ACC and left motor and premotor sources. Bokura et al. (2002) also conducted an experiment to understand the anatomical structures that are involved in N2 and P3 generation in a Go/No-go paradigm, but they used a visual modality of the paradigm and a different source localization technique referred to as LORETA. They identified right lateral orbitofrontal and cingulate generators for the N2 and left lateral orbitofrontal sources for the P3. In an MEG study of inhibition elicited by a visual Stop-signal paradigm, Luus et al. (2007) identified a main source for success-related N2 modulation located in the dorsal ACC using BESA. Van Veen and Carter (2002) used source localization analysis with BESA to study inhibition and response conflict in the Eriksen Flanker Task. They determined that the N2 amplitude associated with

incongruent trials (i.e., both inhibition and response conflict occur) can be explained by a dipole that is located in the ACC. These experiments with different modality Go/No-go tasks, a visual Stop-signal task and an Eriksen Flanker Task suggest that the orbitofrontal area and the ACC (in both hemispheres) are important regions for No-go, Stop-signal and incongruent flanker processing. Other brain areas have also been associated with these paradigms. Recently, Albert et al. (2013) used a modified visual Go/No-go task to dissociate brain electrical activity related to motor inhibition from the processing of infrequent stimuli (via the contrast of infrequent No-go with infrequent Go). Source localization data, which were obtained using LORETA, revealed increased activation for No-go compared with Go trials in the pre-supplementary motor areas (preSMA) during the P3 time range, but not the N2 time range. At the scalp level, the authors also determined that only brain electric activity associated with P3 exhibited differences between No-go and Go trials. Therefore, Albert et al. (2013) suggested that the preSMA plays an important role in motor inhibition.

These source localization studies suggest related but different brain generators for the inhibition reflections on the N2 and P3 components. The orbitofrontal cortex, the ACC, and the preSMA have been suggested as the core regions associated with inhibition (Albert et al. 2013; Bokura et al. 2002; Kiefer et al. 1998; Luus et al. 2007). It has been suggested that during the first 200 ms in a No-go or Stop-signal trial, a posterior portion of the pre-SMA, the right orbitofrontal and the ACC are activated to resolve the conflict between the execution and inhibition of a motor response. After this process and before 400 ms post-stimulus, the left orbitofrontal cortex and the anterior portion of the pre-SMA are activated to yield a successful inhibition (Kok et al. 2004; Lavric et al. 2004; Nieuwenhuis et al. 2003; Ramautar et al. 2006; Falkenstein et al. 2002; Vallesi et al. 2009). In unsuccessful inhibition trials, during the first 200 ms, supplementary motor areas are activated to permit response execution rather than inhibition (Lavric et al. 2004; Zhang and Lu 2012).

1.4.4. Age-related inhibition changes between 200 and 400 ms

ERP studies of age-related inhibition changes with the Go/No-go task have consistently demonstrated longer latencies for both the No-go N2 and No-go P3 components in older adults (Pfefferbaum and Ford 1988; Tachibana et al. 1996; Fallgatter et al. 1999; Horvath et al. 2009). Tachibana et al. (1996) studied ERP age-

related changes in a visual Go/No-go task in participants (N=29) who ranged in age from 21-74 years old. Two classes of stimuli, semantic and physical, were presented. The authors identified longer latencies for both No-go N2 and P3 for the group over 40 years of age (N=14; M±SD=56.4±12.2 years old) compared with the group under 40 years of age (N=15; M±SD=26.9±5.1 years old). However, this ageing effect was only present with semantic stimuli. Tachibana et al. (1996) interpreted this result within Shiffrin and Schneider's (1977) model. Specifically, they suggested that semantic stimuli processing involves controlled processes, and therefore, it is more sensitive to ageing; in contrast, physical stimuli processing involves automatic processes, which are less sensitive to ageing. Horvath et al. (2009) compared behavioural and ERP measures of inhibition in children (N=18; M=6 years old; 9 girls), young adults (N=9; M=21.2 years old, range 19-24; 5 women) and older adults (N=9; M=68.4 years old, range 62-82; 7 women) using an auditory Go/No-go task. They identified a longer latency for the No-go N2b and a longer latency and higher amplitude for the No-go P3 with a more parietal distribution in older compared with young adults. It has been suggested that this age-related effect (i.e., latency increased for N2 and P3 with age) may represent a general slowing rather than a selective slowing, which only affects inhibition processes (Falkenstein et al. 2002; Vallesi et al. 2009).

Falkenstein et al. (2002) studied ageing effects on inhibition with a speeded (maximum reaction time of 400 ms) Go/No-go task with both visual and auditory stimuli. In their study, older adults (N=12; M=58.3 years old, range 54 to 65; 6 women) required more time than young adults (N=12; M=22.5 years old, range 19 to 25; 6 women) to decide whether to press a key (as reflected in the latency of the Go P3) or to inhibit the response (as likely reflected in the latency of the No-go P3). The No-go N2 was also delayed in the older adults, but to a lesser extent than the No-go P3 and only after visual stimuli. The No-go N2 results demonstrate that age effects in the No-go N2 are modality-specific and affect inhibition after visual but not auditory stimuli. In contrast, the comparable No-go P3 and Go P3 results suggest that the final decision process, i.e., whether to respond or inhibit, is modality-unspecific and affected by age. These results concerning both N2, which reflect modality-specific processes, and P3, which reflect modality-unspecific processes, are in accordance with the Falkenstein et al. (1999) study with a Go/No-go task and the Ramautar et al. (2006) study with a Stop-signal task.

To investigate age-related changes in inhibition, Vallesi et al. (2009) compared young adults (N=14; M=27 years old, range 20-34 years; 8 women) and older adults (N=14; M=71 years old, range 60-80 years; 9 women) on two Go/No-go tasks, including a simple and a complex task, that were designed to control for conflict level. The simple task comprised a Go condition (a red O and a blue X), a conflict No-go condition, in which the No-go stimuli were defined by combinations of colours and letters that corresponded to the stimuli used in the Go stimuli (a blue O and a red X), and an irrelevant condition, in which the identity of the No-go stimuli differed from the target stimuli (coloured numbers rather than coloured letters). In the complex task, there were 8 different Go and No-go stimuli rather than the 2 different stimuli per condition in the simple task. Vallesi et al. (2009) identified a longer P3 latency for the "conflict No-go" and a larger No-go P3 amplitude in older adults, regardless of the No-go and Go stimuli similarity, which suggests an age-related change in No-go stimuli processing. Additionally, they identified greater reaction times to both No-go and Go trials in older adults, which supports the age-related general slowing hypothesis (Salthouse 1996). Although these results point to a general slowing that affects inhibition processes, Vallesi (2011) experiment that tested age-related changes in inhibition did not identify changes in the No-go P3 latency, which suggests not all inhibition processes become slower with age. Vallesi (2011) tested young (N=14; M=25 years old, range 19-34; 8 women) and older adults (N=14; M=73 years old, range 65-81; 8 women) on a visual Go/No-go task. There was no age difference for the latency of the P3, but the results indicated a larger No-go P3 for older adults. These results suggest that older adults must devote considerably more resources (enhanced No-go P3 amplitude) to suppress the processing of non-target information compared with young adults.

In the Stop-Signal paradigm, a greater SSRT has been identified for older adults, which suggests an age-related deficit in inhibition that is not explained by a general decline in processing speed (Kramer et al. 1994; Andres et al. 2008). In an ERP experiment, Anguera and Gazzaley (2012) studied age-related modulations of the N2 and P3 associated with inhibition in a visual Stop-signal task and determined that the older adults' greater SSRT was associated with the P3 latency but not with the P3 amplitude or the N2 latency or amplitude. In their experiment with older adults (N=20; M±SD=70.6±6.7 years old; 9 women), the Stop-signal N2 and P3 were qualitatively comparable to previous ERP studies that used a visual Stop-signal task with young adults (van Boxtel et al. 2001; Kok et al. 2004; Ramautar et al. 2004). However, in

contrast with the results that have generally been reported for young adults, the N2 and P3 amplitude was not greater in successful compared with unsuccessful inhibition trials. Anguera and Gazzaley (2012) identified a later latency peak onset for unsuccessful inhibition trials in both N2 and P3. Only the P3 latency correlated with the SSRT, which is similar to other studies of age-related effects that used the Stop-signal task (Kramer et al. 1994). These results suggest the latency of the P3 might be an index of age-related inhibition changes.

As previously discussed, the Eriksen Flanker Task has also been used to study inhibition within this time window. ERP studies have been conducted to establish age-related modulations of the ERPs that are associated with the inhibitory processes elicited by the Flanker Task. In Wild-Wall et al. (2008) experiment, inhibition differences between two age groups, a younger and an older adults group, were explored using a Flanker Task. In addition to the modulation of the N1 and P1 components, Wild-Wall and colleagues (2008) identified a frontal N2 that was substantially smaller for the older group. This smaller N2 amplitude in the older group may reflect reduced flanker conflict in the incongruent condition. The reduced flanker conflict identified in the older group may explain the inferior error rate in the incongruent condition in older compared with younger adults. In Hsieh and Fang (2012) study, young and older adults' inhibitory processes were compared using a Flanker Task in three experiments. Throughout the three experiments, and beyond the N1 modulations previously described, a decreased N2 in incongruent trials and a prolonged P3 peak latency to the central target were identified. These results support the notion that older adults use compensatory strategies (e.g., paying more attention to the central target) to be as capable as young adults in reducing flanker impact (Wild-Wall et al. 2008; Hsieh and Fang 2012).

1.4.5. Summary

In the preceding section, we summarized the ERP research that investigated the interval between 200 and 400 ms post-stimulus with respect to the processing events that may be involved in the instantiation of inhibition. The experimental paradigms utilized to examine the 0-200-ms time window were again considered. The following two ERP components have been consistently hypothesized to reflect inhibition in this time window, regardless of the paradigm used: The N2 and the P3. To understand the

processes that are reflected by these components, studies have addressed the effects of different modalities (i.e., visual and auditory), different response modes (i.e., covert and overt), different stimulus probabilities (high, equal or low), successful and unsuccessful inhibition-related trials, sequence effects and age-related modulations. Taken together, these studies suggest that the N2 and P3 reflect different processes; however, both N2 and P3 processes contribute to successful inhibition and are associated with the orbitofrontal cortex, the ACC and the pre-supplementary motor areas. The N2 reflects conflict processes that are modality-specific and independent of motor processing, whereas the P3 reflects inhibition processes that are modality-unspecific and reflect motor processing. These components have primarily been associated with controlled processing. However, with stimulus repetition, automaticity may develop.

1.5. Inhibition between 400 and 800 ms

1.5.1. ERPs for inhibition between 400 and 800 ms

At times, inhibitory processes operate between 400 and 800 ms after stimulus onset. Knowledge or semantic inhibition is a type of cognitive inhibition that has been suggested to occur in this late time window. In our daily living, in a particular context, knowledge is activated; however, only a portion of this knowledge is integrated in the representation of the context. An inhibition process is responsible for reducing the activation of unsuited knowledge (Debruille et al. 2008). For example, the presentation of a lexically ambiguous word (i.e., an instance of two or more meanings being mapped onto identical phonological forms in the mental lexicon) has been shown to unconsciously trigger the activation of all of that word's lexical meanings, even when the previous context is compatible with only one of them (Ihara et al. 2007). As a consequence, inhibition, which yields the selective activation of the appropriate meaning, must occur.

Recent consideration has been given to the possibility that the N400, an ERP component with a negative polarity that reaches its maximum approximately 400 ms after stimulus onset and is typically observed when meaningful stimuli are processed (e.g., words), indexes semantic inhibitory processes (Barber et al. 2004; Debruille 2007; Barber and Kutas 2007). The N400 is typically considered to reflect the processing effort associated with the integration of new semantic content. However, the types of

processes that it indexes remain under debate. Debruille et al. (1996) tested the hypothesis that the N400 is an index of inhibition. They examined N400 amplitude differences for famous and unknown faces in a sample of young adults (N=12, range 20-30 years old, 6 women). The participants signalled whether the face that they were viewing was known or unknown to them. The task was divided in three blocks that contained different percentages of famous faces (33, 50 and 67%). Unknown faces are stimuli that, similar to infrequent words (or pseudo words), are new and entail the activation of previous knowledge that must inhibited. Therefore, if the N400 indexes inhibition, its amplitude should be larger for unknown compared with known faces (because more irrelevant knowledge is activated while initially attempting to match the new face to stored representations of known faces); it should also be larger for the blocks with higher percentages of famous faces (because in these contexts, the expectation of knowing the new face is higher, which stimulates an increased search effort, as well as more irrelevant knowledge activation that must be inhibited). Consistent with the hypothesis, unknown faces elicited larger N400 activity compared with known faces, especially in the presence of a higher percentage of famous faces. It was proposed that the N400 amplitude would depend on the amount of knowledge that must be inhibited and the strength of its previous activation. Thus, as the activation becomes stronger, the amount of inhibition that is required increases, which elicits larger N400 amplitudes (Debruille 2007).

Inhibition might also occur when words activate the representation of similar words (Debruille 1998; Holcomb et al. 2002). In Debruille's (1998) study, participants (N=26; range 19-30 years old; 12 women) responded to a single-item lexical decision task, in which they identified pseudo-words by pressing a left button and real words by pressing a right button. The real words included look-alike words (i.e., low frequency words that can trigger the representations of the higher frequency words that they resemble), eccentric words (i.e., low frequency words that do not resemble higher frequency words) or frequent words, which were used as fillers. The author identified larger N400s for look-alike compared with eccentric words. He concluded that low frequency words with high frequency orthographic neighbours (i.e., look-alike words) triggered more inhibition than low frequency words with no such neighbours (i.e., eccentric words). Further evidence for the N400 as an index of inhibition was identified in a recent study by Shang and Debruille (2013). In their experiment, each trial consisted of three written words that were serially presented to the participants (N=20; M±SD=27.7±5 years old;

M±SD=15.6±1.8 years of education). In one block, the participants were asked to judge whether the meaning of the first word was related to the meaning of the third word, thus ignoring the second word. In the other block, the participants were asked to determine whether the meaning of the second word was related to the meaning of the third word. The researchers studied the N400 that was elicited by the second word in both conditions (i.e., the conditions in which the meaning of the second word was inhibited versus not inhibited). The results demonstrated a small but significant N400 effect associated with the second word processing. Specifically, the N400 that was elicited when the meaning of the second word was ignored was larger than when the meaning of the second word had to be attended. Therefore, the authors concluded that the results support the inhibition N400 hypothesis.

An additional type of cognitive inhibition that has been suggested to occur in this time window is known as interference control and has been studied using the Stroop task. In this task, the subject is asked to name the print colour of a colour-word (e.g., BLUE printed in red, which requires the name red to be pronounced while controlling the interference from the word meaning, yielded by automatized reading). The critical condition is composed of incongruent trials in which the print colour and the meaning of the word mismatch, such as in the previous example. Typically, there is a control condition with congruent trials in which the meaning of the word and its colour are the same (e.g., the word BLUE printed in blue). At times, other control conditions are used, including conditions in which only the colours (e.g., XXX printed in blue, with colour-naming instructions) or colour-words (e.g., BLUE written in black, with simple reading instructions) are presented. Behaviourally, the Stroop colour-word interference effect refers to an increased response latency in incongruent compared with congruent or neutral trials.

In ERP research that has employed the Stroop task, the N450 and the late positive complex (LPC) components have reflected this interference effect (West and Alain 1999; Liotti et al. 2000; Hanslmayr et al. 2008; Tillman and Wiens 2011; Li et al. 2013). West and Alain (1999) investigated the temporal course of the Stroop effect, as reflected in ERP waveforms, in a sample of young adults (N=12; range 24-31 years old; 6 women). In their task (see Fig. 1 for a schematic display of the task), in addition to the common incongruent, congruent and neutral conditions, there was a word identification condition in which the participants named the four colour-words presented in light grey. This additional condition enhanced the Stroop effect by creating a context that increased

the competition between colour and word processing in the incongruent trials. It also allowed an additional comparison between the congruent and incongruent trials with a condition in which word information guided the response in contrast to the neutral condition in which colour guided the response. West and Alain (1999) identified a larger N450, a fronto-central slow wave with an onset of approximately 500 ms, in incongruent compared with other trials. Therefore, they interpreted the N450 as an index of inhibition processes that are involved in word processing suppression.

Liotti et al. (2000) studied the temporal course of the Stroop colour-word interference effect in a Stroop task with three response modalities, including overt, covert and manual. In the overt condition, the participants (N=8; M±SD=27.6±6.8 years old; 5 women) were asked to speak aloud the colour of the word. In the covert condition, they were asked to speak the colour of the word silently in their mind. In the manual condition, the participants were asked to press a designated button for each colour. Liotti et al. (2000) created five control conditions to analyse the effects of colour-word incongruence and response modality. They identified an increased N450 amplitude in incongruent trials, with an anterior medial and mid-dorsal scalp distribution and maximum amplitude at 410 ms. This result was interpreted as a reflection of the processes related to the suppression of word information. The effect was present for the three response modalities, but with a different scalp distribution for speech (i.e., overt and convert) and manual responses. Additionally, the authors identified a left-lateralized LPC effect with a maximum amplitude at 600 ms in incongruent compared with congruent trials, regardless of the response modality. This finding was interpreted as a reflection of the semantic processing of the word.

Li et al. (2013) investigated the functional meaning of this LPC in the Stroop task. In their experiment, young adults (N=22; M=21 years old, range 19-24; 13 women) participated in a traditional Stroop task and a rotation judgment task, in which they were asked to judge the rotation state of words equal to those found in the incongruent and congruent conditions of the Stroop Task (i.e., the participants pressed designated buttons to indicate upright, left or right rotation states). Consistent with previous studies, the researchers identified a larger N450 and LPC in incongruent compared with congruent trials. In the rotation judgment task, there was no response conflict because the resolution of perceptual conflict between the print colour and the word meaning was not necessary to successfully respond. However, Li et al. (2013) identified a larger LPC in incongruent compared with congruent trials in the rotation judgment task, which

suggests the LPC is sensitive to perceptual conflict. The N450 effects that were identified in the Stroop task were not identified in the Rotation task.

Hanslmayr et al. (2008) also investigated the temporal dynamics of the Stroop effect in a sample of young adults (N=21; M=24.9 years old, range 20 to 33; 16 women). In addition to the traditional conditions of the Stroop task, they studied a fourth condition in which they manipulated the order of incongruent trials to create an NP condition. This manipulation was performed to determine whether NP effects strengthen the Stroop colour-word interference effect. Behaviourally, the participants were slower in the NP compared with non-primed incongruent trials and in both the NP and non-primed incongruent trials relative to the neutral and congruent trials. The ERP data analysis indicated increased N450 amplitude in NP and non-primed incongruent trials over fronto-central regions with a maximum amplitude at approximately 400 ms, which suggests this ERP effect reflects interference detection. This negativity over fronto-central regions was also evident later in time at approximately 600 ms post-stimulus. Hanslmayr et al. (2008) suggested that it might reflect the elicitation of central executive processes to overcome interference at that stage.

Tillman and Wiens (2011) used ERPs to study the effects of varying the probability of incongruent and congruent trials in the Stroop and Eriksen Flanker tasks. In each task, participants (N=27; M±SD=27.22±5.96 years old; 16 women) performed two blocks, including one block with rare incongruent trials (20%) and a second block with frequent incongruent trials (80%). The analysis of behavioural data demonstrated similar results in the Stroop and Eriksen Flanker tasks, with slower RTs and less accurate results on incongruent compared with congruent trials and on rare compared with frequent incongruent trials. With respect to the ERP measures, the researchers identified a modulation of the N450 in the Stroop task, with a larger amplitude on incongruent than congruent trials. However, this effect was only identified when the incongruent trials were rare. The authors suggested that the N450 is a measure of response conflict because it was only enhanced when conflict was high (i.e., with rare incongruent trials). In the Eriksen Flanker Task, a larger N2 amplitude was identified for frequent compared with rare incongruent trials, which replicated Bartholow et al.'s (2005) findings. Tillman and Wiens (2011) proposed that Flanker N2 reflects attentional control processes; therefore, it indexes a process that differs from the process reflected by the N450 observed in the Stroop task.

The temporal course of interference has also been studied using working memory paradigms that are known to elicit proactive interference (PI). PI is a type of interference in which previously memorized information is no longer relevant and must be inhibited. A task that is commonly used to elicit PI is the Sternberg's working memory task (Sternberg 1966). In this task, the subject is first asked to memorize several lists of items. Following each of the to-be-memorized lists of items, there is a delay in which the list is not accessible. The subject is subsequently presented with one item and must decide whether it belongs to the to-be-memorized list. The behavioural finding that defines PI is a longer reaction time to decide whether the item belongs to the list when the item was presented in previous lists (i.e., familiar probe) compared with when the item was not presented in previous lists (i.e., non-familiar probe).

In ERP research that used modified versions of the Sternberg's working memory paradigm, two ERP components have been identified as related to the PI effect, the N450 (Tays et al. 2009; Yi and Friedman 2011) and the LPC (Zhang et al. 2010). This finding is similar to the Stroop interference effect. Yi and Friedman (2011) examined the temporal course of the processes that contribute to the PI effect with a cued Sternberg's task. In this task, participants (N=20; M=24.1 years old; 11 women) viewed target sets with four digits, two on the right and two on the left. After the target set, a cue appeared (i.e., an arrow) that was either relevant, which pointed to the two to-be-memorized digits (thereby defining the two digits to-be-ignored), or irrelevant, which pointed in both directions (all digits must be in memory). Three probes existed, which included a "positive probe" (i.e., matched to the to-be-memorized digits), a "non-intrusion probe" (i.e., did not match any of the digits in the target set) and an "intrusion probe" (i.e., matched with the to-be-ignored digits). After a relevant cue, inhibition can occur for the irrelevant digits. Consistent with this view at the cue stage, Yi and Friedman (2011) identified a larger N450 after relevant compared with irrelevant cues (for which inhibition processes are not necessary). At the probe stage, they identified an N450 that was larger for "intrusion probes" compared with "non-intrusion probes", which likely reflects PI triggered by the familiar but now irrelevant intrusion probe.

Zhang et al. (2010) designed an experiment to identify the ERP effects associated with PI. In their experiment, young adults (N=19; M±SD=22.9±1.9 years old; 9 women) participated in a "recent probe task" in which the target set (to-be-memorized) consisted of four consonants. Two consonants were "recent", which were presented in a preceding target set, and two consonants were "not recent", which were absent in the two

preceding target sets. The researchers identified a larger LPC amplitude when the probe was present in the preceding target set than when it was not present. This effect was modulated by recency effects, with a smaller LPC amplitude for recently encountered probes. Based on these modulations, Zhang et al. (2010) suggested that the LPC is an electrophysiological signature of the PI effect. Tays et al. (2009) studied the effects of stimulus repetition on the PI effect and compared ERP waveforms in two variations of Sternberg's Task. In their experiment, participants (N=21; M=1.94 years old, range 18-23; 15 women) completed two counterbalanced tasks, including one task with a small stimulus pool (i.e., 20 words) and a second task with a large stimulus pool (i.e., 750 words). The authors identified a smaller difference in N450 amplitude between the baseline and experimental PI conditions for the small compared with large stimulus pool tasks, in which the typical N450 amplitude difference was identified. Therefore, the authors suggested that repetition (inherent to the use of a small stimulus pool) can result in an attenuation of PI effects.

1.5.2. Automatic and controlled nature of inhibition between 400 and 800 ms

Initial studies that investigated the controlled or automatic nature of semantic inhibitory processes demonstrated that the N400 was modulated by task demands (Chwilla et al. 1995), selective attention, and pattern masking. These findings led to a view that associated the N400 with controlled processing. Congruent with this view, McCarthy and Nobre (1993) observed semantic and identity priming effects on the N400 only for words that appeared in the attended spatial location. However, subsequent studies that manipulated the likelihood of intervention of controlled processes demonstrated that N400 amplitude modulations were clearly observed in the experimental conditions that minimized controlled processes (e.g., used low stimulus-onset asynchronies, low proportions of related stimuli, or shallow levels of processing). Although typically larger when the instructions explicitly required semantic analyses, reliable N400 effects were observed in situations in which semantic processing was not necessary or even beneficial. In all of these types of studies, participants directed their attention to the stimuli (if not to the semantic level of analysis), which appears to be important for N400 elicitation.

The Stroop colour-word interference effect indexed by the N450 and LPC can be classified as controlled processing. As previously described, the Stroop task is a classic

example of a controlled processing task (Nigg 2000) because the participant must consciously inhibit the meaning of a colour-word to identify the print colour. However, Li et al.'s (2013) findings suggest that some processes involved in the Stroop interference effect can have an automatic nature, such as the perceptual conflict processing indexed by the LPC that can be elicited even when the perceptual conflict is irrelevant for task performance. Regarding the proactive interference effect, no experiments have been developed to address the nature of the involved inhibition processes.

1.5.3. Source localization of ERPs associated with inhibition between 400 and 800 ms

To the best of our knowledge, no ERPs studies have addressed the source localization of the ERP correlates of semantic inhibition processes. However, Shang and Debruille (2013) examined the scalp distribution of the N400 amplitude related to semantic inhibition and identified maximal effects in centro-parietal regions and a slightly larger effect in the right compared with left hemisphere. As Debruille's inhibition hypothesis did not refer to a specific N400, as opposed to the N400 linked to semantic integration, we briefly address the results of source localization studies conducted with paradigms that did not directly address the inhibition hypothesis. These studies used MEG (Halgren et al. 2002; Lau et al. 2009) and high density EEG (Silva-Pereyra et al. 2003; Kuperberg et al. 2003) and identified generators for the N400 effect in temporal (i.e., Wernicke's area and anterior temporal cortex) and frontal (i.e., dorsolateral, orbital and anterior prefrontal cortices) areas.

Concerning the Stroop colour-word interference effect, source localization studies have suggested different but related brain generators for the N450 and LPC (Liotti et al. 2000; Markela-Lerenc et al. 2004; Hanslmayr et al. 2008). Liotti et al. (2000) used dipole source analysis with BESA and identified two independent generators in the ACC for the N450 in speech and manual versions of the Stroop task. Hanslmayr et al. (2008) also identified a source in the ACC for the N450 effect in a manual Stroop task using BESA. In an examination of a young adults sample (N=16; M±SD=26±5.4 years old; 12 women), Markela-Lerenc et al. (2004) conducted dipole source analysis with BESA for both N450 and LPC that were larger in incongruent compared with congruent trials in a manual Stroop task. The researchers identified a generator localized in the left

PFC that contributed to the N450 effect and a generator in the right ACC that contributed to the LPC effect. The authors suggested that the PFC signals to the ACC when executive control is required, and the ACC is responsible for the ensuing executive control elicitation. In a proactive interference study that utilized dipole source analysis, Tays et al. (2008) identified two major ACC activation peaks (at approximately 340 and 440 ms during the N450 in interference conditions) and a left inferior frontal cortex activation (at approximately 420 ms following the probe in interference conditions). The authors suggested that both the ACC and the inferior frontal cortex contribute to the proactive interference resolution.

1.5.4. Age-related inhibition changes between 400 and 800 ms

To our knowledge, only one study has focused on age-related changes in the N400 as an index of semantic inhibition. In Cameli and Phillips (2000) study, older adults (N=20; M±SD=71.5±6.4 years old; M±SD=12.4±1.7 years of education; 12 women) and young adults (N=20; M±SD=23±2.3 years old; M±SD=15.8±1.8 years of education; 12 women) were asked to read sentences and word pairs. In each sentence or word pair, the final word was preceded by a context (i.e., the previous word in the word pair or the previous words in the sentence). The experiment comprised three conditions, which included unrelated, moderately and highly related conditions in which the context was not semantically related, moderately related or highly related to the final word, respectively. Cameli and Phillips (2000) demonstrated that young adults exhibited a higher N400 amplitude for the unrelated condition, followed by a smaller N400 amplitude for the moderately related condition, and an even smaller N400 amplitude for the highly related condition in both sentences and word pairs. However, older adults did not display this pattern. Older adults exhibited a similar N400 amplitude in all conditions (unrelated, moderately and highly related) in relation to sentences and a slightly higher N400 amplitude in the unrelated compared with highly related condition in relation to word pairs. These results were interpreted as a reflection of an age-related semantic inhibition deficit.

Concerning the Stroop interference effect, several behavioural studies have shown an increased Stroop effect in older adults (see for example Mayas et al. 2012); however, this age-related modulation has received little attention from ERP researchers. A rare example is West and Alain (2000), who used ERPs to test whether the increased Stroop

effect identified in older adults is because of a general slowing or an inhibition deficit. In their study, young adults (N=12; M±SD=27.08±2.35 years old; 6 women) and older adults (N=12; M±SD=69.50±3.48 years old; 6 women) who differed on years of education (i.e., young adults had two additional years of education, on average) participated in a Stroop Task that was similar to West and Alain (1999). Specifically, neutral, congruent, incongruent and word identification trials were presented. Behaviourally, they identified an increased Stroop effect in older adults even after controlling for age-related differences in reaction times to neutral trials. The analysis of the ERP data revealed a smaller N450 (labelled as N500 by West and Alain 2000) amplitude in incongruent trials over the midline fronto-central in older adults, which likely reflects deficits in the suppression of word information. Following this modulation of the N450, no age-related modulations were identified in a negative slow wave, which likely reflects response selection processes, or in an enhanced positivity over the temporo-parietal region, which likely reflects the perceptual processing of the colour information used to guide the response. These findings are consistent with the proposal that an age-related decline in the efficiency of inhibition of word information contributes to the increased Stroop interference effect observed in older adults.

This inhibition age-related decline has also been identified in proactive interference studies (Tays et al. 2008; Yi and Friedman 2014). Tays et al. (2008) used high density electrophysiology to examine differences between older (N=18; M=72.4 years old, range 65-87; 14 women) and young (N=16; M=20 years old, range 18-26; 10 women) adults in a Sternberg Task. They identified a frontal negativity at 450 ms. This negativity was labelled medial frontal negativity (MFN) and had characteristics that were similar to the N450 identified in Stroop task studies. The MFN was observed in the interference conditions only for young adults. Older adults exhibited a large frontal positivity that was associated with poorer behavioural performance. The authors interpreted the absence of the frontal negativity in older adults as an indication of a proactive interference processing deficit in older adults. Yi and Friedman (2014) studied these age-related differences in greater detail via comparisons of young adults (from Yi and Friedman's 2011 study) to two groups of older adults, which included a group with older adults ranging in age from 60 to 70 years old (N=20; 15 women) and a yet older group ranging age from 71 to 82 years old (N=20; 15 women) adults. They used the cued Sternberg's Task from Yi and Friedman's (2011) study and examined both cue- and probe-related inhibition ERP correlates. They identified a larger N450 amplitude

after a relevant cue (i.e., that points to the left or right, thereby indicating the relevant digits) than after an irrelevant cue (i.e., that points in both directions), which likely reflects the inhibition mechanisms that are responsible for removing irrelevant digits from the focus of attention. With respect to age-related differences, they identified a delayed latency for this activity in the 71-82 age-range group. Similar to Yi and Friedman's (2011) finding, Yi and Friedman (2014) identified an N450 at the probe stage that was larger for "intrusion probes" compared with "non-intrusion probes", which likely reflects processes that enable proactive interference resolution. They identified a delayed latency for this activity in both of the older adults' groups.

1.5.5. Summary

In the preceding section, we summarized the ERP research that addressed the occurrence and nature of inhibition processing activity between 400 and 800 ms post-stimulus. In this time window, the following two types of cognitive inhibition have been studied: semantic inhibition and interference. Semantic inhibition has been related to processes indexed by the N400. These semantic inhibition processes cannot be precisely mapped onto the automatic or controlled processing categories because they have characteristics that are associated with both categories. Semantic inhibition may be associated with controlled processing because it can be modulated by controlled attention processes (e.g., selective attention). However, it may also be linked to automatic processes because it can be elicited with even low awareness levels (Kutas and Federmeier 2011). The temporal course of interference has been studied in this time window with two paradigms, the Stroop and Sternberg's paradigms. ERP studies that have investigated the Stroop interference effect have identified two ERP components with larger amplitudes in incongruent relative to congruent or neutral trials. These components are the N450, which likely reflects the suppression of word information, and the LPC, which reflects semantic processing of the word meaning or perceptual conflict. To understand the processes that are reflected by these ERP components, studies have been conducted to address the ERP effects of different response modes (i.e., speech and manual), sequence effects (i.e., NP), stimulus probabilities (high or low), and age-related modulations. Taken together, these studies suggest that the N450 and LPC reflect different processes; however, both components index the Stroop interference effect that is related to the activation of the ACC and the PFC. The N450

and the LPC have also been identified in ERP studies that used Sternberg's paradigm, which suggests these components reflect processes that are related to proactive interference resolution. For this time window, the small number of ERP studies that have explored age-related modulations in semantic inhibition and interference have identified an age-related deficit in both types of inhibition, which is indexed by the N450 and the LPC modulations.

1.6. Discussion

The present review aimed to clarify not only the temporal course of inhibition but also its nature as a complex process that entails both automatic and controlled processing. The reviewed ERP data, which were collected using different experimental paradigms, illustrate different inhibition processes, starting as early as 100 ms after stimulus onset and extending their activity beyond 400 ms post-stimulus (for a summary, see Table 1). One of our main goals was to contribute to the understanding of the temporal course and nature of inhibition; therefore, we proceed to discuss sensory, motor and cognitive inhibition-related processes that were identified in the reviewed ERP research. Additionally, we address the brain areas that were activated during inhibition processes and the automatic and controlled nature of inhibition across the three time windows proposed. Despite the scarce ERP research on age-related inhibition changes to date, we also discuss the experiments that have been conducted thus far. Finally, special attention is given to the conflict theory as an alternative explanation for ERP modulations that are typically interpreted as reflections of inhibition.

Table 1 Summary of inhibition paradigms used, type and nature of inhibitory processes, ERP components, source localization results and inhibition age-related changes observed in three time windows: 0-200, 200-400, and 400-800 ms.

	Time window		
	0-200 ms	*200-400 ms*	*400-800 ms*
Paradigms	Eriksen Flanker Task; Stop-signal; Go/No-go; Selective attention tasks	Eriksen Flanker Task; Stop-signal Go/No-go	Semantic priming; Stroop task; Sternberg's task
Type of inhibitory process	Inhibition of return Interference	Motor inhibition Interference	Semantic inhibition Interference
Nature of inhibitory process	Automatic	Controlled Automatic (with practice)	Controlled Automatic
ERP components	P1: stimulus visual processing N1: orientation of attention	N2/N200: modality-specific N2a: novelty detection N2b/anterior N2: executive control; premotor inhibition; conflict detection; error monitoring N2c/posterior N2: stimulus classification operations N2pc: attentional processes P3/P300: non-modality-specific, motor inhibition; stimulus evaluation process P3a: motor inhibition; involuntary allocation of attention to relevant changes in the stimulus; conflict resolution P3b: stimulus evaluation process	N400: semantic inhibition N450: Stroop interference and proactive interference (PI) LPC: Stroop interference and PI
Source localization	P1 and N1: occipital lobes; primary and secondary visual areas N1: fronto-parietal attention network	N2: frontal and prefrontal cortex (PFC), specifically the orbitofrontal cortex P3: anterior cingulate cortex (ACC); motor and premotor cortices, especially the pre-supplementary motor areas	Semantic inhibition N400: scalp distribution over central-parietal areas Stroop N450: ACC and left PFC Stroop LPC: ACC PI N450: left inferior frontal cortex and ACC
Inhibition age-related changes (older vs. young adults)	Sensory inhibition deficits; normal interference; more attention to relevant information	Slowing inhibitory processes; more resources required to inhibit	Semantic inhibition deficit Interference control deficit

1.6.1. Inhibition and sensory processing

The early inhibitory processes in the 200 ms after stimulus onset have been associated with sensory processing of the stimulus (e.g., flankers in the Eriksen Flanker

Task). Therefore, they are referred to as sensory inhibition processes. These processes are reflected by the P1 and N1 ERP components (Roche et al. 2005; Johnstone et al. 2009). Despite this association, the P1 and especially the N1 have been linked to inhibitory events that occur later and may therefore signal the early stages of the processes that subsume these events. Filipovic et al. (2000) suggested that the P1-N1-P2 complex early time window might be as important as the N2-P3 complex time window to the Go/No-Go decision (i.e., decision to withdraw attentional resources from the task on No-go trials). In addition, in a Go/No-go task, Lavric et al. (2004) identified an association between the N1 modulation and an early signal from visual processing areas that triggers later inhibitory processes, which was reflected by the N2. In the Stop-signal task, Bekker et al. (2005) identified a larger N1 for successful compared with failed stops. This result suggests that the N1 may reflect the orienting of attention toward the stop-signal, thereby determining the success of inhibition in the Stop-signal trials.

The inhibition ERP studies that have addressed the N1 and P1 age-related modulations have shown a clear dissociation between the processes that are linked to P1 and N1. The P1 can be linked to the onset of inhibition processes with the detection of irrelevant information that is not affected by age; the age-related amplitude enhancement in N1 can be interpreted as increased attention to relevant information, such as a compensatory mechanism that older adults employ to reduce interference from irrelevant information (Wild-Wall et al. 2008; Hsieh and Fang 2012). The data that pertain to the ageing effects on inhibition provide further support for the hypothesis that inhibition processes triggered within sensory processing are essential for later cognitive and motor inhibition processes. Namely, if this first level of processing is delayed because of sensory impairments (e.g., less visual or auditory acuity), the subsequent temporal course of inhibition will also be delayed, even though later inhibition processes may not be impaired. Therefore, it is indispensable to control for the sensory abilities that are required to perform the task. This concept is particularly important in ageing studies because the ageing process changes sensory abilities. However, as Picton et al. (2000) suggested, even in studies with healthy young adults, a proper sensory abilities questionnaire must be administered to improve the accuracy of self-report and ensure the normal function of the sensory abilities that the task requires. Only then can we accurately interpret changes in processes that occur after sensory processing. These early sensory processes are also influenced by the experimental task modality. For example, ERP studies that have compared auditory and visual modalities of the Stop-

signal and Go/No-go tasks have suggested that the N2 reflects modality specific processes (e.g., smaller N2 amplitude in auditory compared with visual Stop-signal trials), whereas the P3 reflects processes that are independent of stimulus modality (Falkenstein et al. 1999, 2002; Ramautar et al. 2006).

1.6.2. Motor and cognitive inhibition

ERP studies that used the Go/No-go task have compared overt and covert response modes and have identified No-go N2 and No-go P3 effects in both response modes, which suggests the processes that these components reflect occur at motor and non-motor processing stages. However, slightly different results have been demonstrated for N2 and P3. The same No-go N2 effect has been identified in both covert and overt conditions, which suggests the N2 reflects non-motor processes. The No-go P3 effect is smaller for the covert compared with overt conditions, which suggests the No-go P3 reflects, at least in part, movement-related potentials (Van 't Ent and Apkarian 1999; Bruin and Wijers 2002; Smith et al. 2008). ERP studies that have manipulated the probability of inhibition-related stimuli (e.g., compared conditions with low, equal and high probability Stop-signal trials) and explored the sequence effects in inhibition paradigms have also helped to characterize the processes that are associated with N2 and P3 (Bruin and Wijers 2002; Nieuwenhuis et al. 2003; Donkers and van Boxtel 2004; Ramautar et al. 2004; Smith et al. 2007; Dimoska and Johnstone 2008; Smith et al. 2010). Together, these ERP studies suggest that the N2 may be associated with premotor inhibition processes and conflict detection, whereas the P3 may be associated with motor and non-motor inhibition processes, such as conflict resolution (e.g., withhold/execute the response) and evaluation processes (e.g., if the inhibition was correctly performed and appropriate to the context).

Between 400 and 800 ms post-stimulus, the following two types of cognitive inhibition have been reported: semantic inhibition and interference. Semantic inhibition has been related to the N400 component; however, the specific processes that N400 indexes (e.g., semantic integration or inhibition) remain under debate. The few ERP studies that have addressed the inhibitory account of the N400 suggest that this component reflects semantic inhibition processes rather than semantic integration per se. Thus, semantic integration processing deploys semantic inhibition, which is the process that the N400 specifically indexes. The ERP correlates of interference are

observed in all three time windows considered in this review (Table 1). However, the interference that is reflected in the first two windows, as summarized in Table 1, pertains to flanker processing in the Eriksen Flanker Task. In contrast, the last time window interference pertains to colour-word interference in the Stroop task and proactive interference in Sternberg's working memory task. Tillman and Wiens (2011) compared interference ERP correlates found in the Eriksen Flanker and Stroop tasks and determined that the results (namely, the flanker N200 and the Stroop N450) differed according to the task. Thus, it appears that the resolution of interference in the Eriksen Flanker and Stroop tasks did not trigger the same inhibition processes.

1.6.3. Brain structure activation during inhibition: evidence from source localization analysis

An ERP effect may be generated by one or several electrical sources in the brain (Otten and Rugg 2005). The problem of reconstructing the brain localization of the electrical activity responsible for an observed topography of scalp voltages is known as the "inverse problem"(Srinivasan 2005). This problem is intrinsically ill-posed: An infinite number of patterns of local brain activations could be responsible for the same scalp voltage topography. In order to obtain increasingly precise approximate solutions to the "inverse problem", several source localization algorithms have been developed. These methods have become reasonably accurate in locating the neural activity associated with the scalp EEG topography on a given instant (i.e., with approximately 1 cm of possible error, using a four-shell spherical head model, and improving upon that mark when electrode arrays with at least 64 sensors are employed), but far more coarse in locating brain activity than direct imaging methods, such as fMRI, which, using a 7 tesla MRI machine, can map activity with an accuracy down to 1mm. However, the temporal resolution of fMRI is inherently limited by the slow blood flow response to increased localized brain metabolism (i.e., one sec in the best case). Therefore, unlike measurements directly derived from the brain's electrical activity, such as the EEG and ERPs, fMRI cannot track the dynamics of mental activity on the sub-millisecond timescale on which neurons operate. EEG and ERP data have a temporal grain-size of a few milliseconds and therefore approach the real-time scale of neural dynamics. Such data, obtained with high-density electrode arrays and in conjunction with source localization analysis allows for the identification of the brain areas where the successive

segments of an ERP were generated, with enough spatial resolution for meaningful interpretation and, crucially, granting information about the temporal succession of active areas, unparalleled with respect to its grain size.

With respect to inhibition, across the three time windows that we have examined, the frontal cortex has the most prevalent involvement, and particularly, the ACC and the PFC. To the best of our knowledge, no studies have included source localization analyses of semantic inhibition ERP correlates. Recent studies have adopted a multimodal approach, which has coupled EEG and fMRI recordings to study brain generators of inhibition triggered during a Stop-signal task (Huster et al. 2013) and combined Eriksen Flanker and Go/No-go tasks (Baumeister et al. 2014). These studies have combined the advantages that are offered by the high spatial resolution of fMRI techniques and the high temporal resolution of EEG techniques. Future studies that combine EEG and fMRI can aid in differentiating between the types of inhibition processes involved in interference resolution in the Eriksen Flanker and Stroop tasks and can decisively contribute to the debate over the conflict/inhibition relationship.

1.6.4. Automatic and controlled inhibition processing

Consistent with our hypothesis, in the first 200 ms, inhibitory processing is primarily an automatic process that is associated with the exogenous sensory aspects of the stimuli. However, automatic processing may also occur between 200 and 400 ms and between 400 and 800 ms following stimulus onset. The different paradigms used across the three time windows can modulate the automatic and controlled nature of the inhibition processes that are evoked. However, even in a classic example of a controlled inhibition task, such as the Stroop task, automatic processes (e.g., the detection of perceptual conflict) can occur. The nature of the stimuli that are used in the task can also modulate the nature of the inhibitory processes that are involved in the task. As Tachibana et al. (1996) suggested, semantic stimuli involve greater executive control compared with physical stimuli. Finally, automaticity may develop with practice in paradigms such as the Go/No-go and Stop-signal tasks.

1.6.5. Age-related inhibition changes

Age-related deficits in inhibition can be observed across the three time windows, with the extent of deficits depending on the paradigm used and the type of inhibition under study. In the first 200 ms, the performance of older adults on the Eriksen Flanker Task is similar to young adults. However, ERP studies suggest that older adults invest extra attentional resources on relevant information and are therefore less sensitive to the interference of irrelevant information. Some ERP studies support the hypothesis of a slowing down in inhibitory processing with ageing; however, this slowing may be general and affect all cognitive processes (Salthouse 1996) rather than specific to inhibition. ERP studies of motor inhibition suggest older adults require more time not only to inhibit but also to execute responses (Falkenstein et al. 2002; Vallesi et al. 2009). ERP studies of interference that used the Stroop and Sternberg tasks, have identified a slowing down of interference resolution in older adults that appears to be specific to inhibition processing (Yi and Friedman 2011; West and Alain 2000). Regarding semantic inhibition, only one study has been conducted (Cameli and Phillips 2000). Therefore, additional research is needed to understand age-related modulations in this type of cognitive inhibition.

1.6.6. Inhibition and conflict

Although the N2 and P3 effects in the Eriksen Flanker Task and Go/No-go and Stop-signal paradigms can be attributed to inhibitory processes, they can also be interpreted in light of the conflict hypothesis. In the Eriksen Flanker Task, a conflict between the responses that are required by the target and the flanker stimuli can occur. A similar conflict, which involves the act of withholding the response and the act of executing the response, can arise in the Go/No-go task (i.e., between the Go and No-go responses) and the Stop-signal task (i.e., between the Go and Stop responses) (Van Veen and Carter 2002; Nieuwenhuis et al. 2003; Donkers and van Boxtel 2004; Yeung et al. 2004). Recently, using a Go/No-go task, Smith et al. (2010) demonstrated that N2 and P3 amplitudes increased for unexpected stimuli regardless of whether that stimuli belonged to Go or No-go trials. To reflect inhibition, N2 and P3 should exhibit enhancements only for No-go compared with Go trials. Thus, the results of Smith et al. (2010) support a conflict interpretation of the N2 and P3 effects because conflict can

occur in both Go and No-go trials when they are unexpected. In an attempt to reconcile these two alternative explanations for the N2 effects that are present in the inhibition-eliciting paradigms, Falkenstein (2006) proposed that the N2 is related to both conflict and inhibition, and these two processes may be sequentially ordered, i.e., conflict may precede inhibition. The same reasoning can be extended to the P3 interpretation, but its relation to inhibition may be stronger than the relation of the N2 (Smith et al. 2008).

1.7. Conclusion

Throughout the reviewed time windows, inhibition emerged as a set of processes that represented a complex functional structure, as opposed to a unitary process or a single processing event. The temporal resolution of the ERP technique helped to reveal the different processes that directly contribute to the success of inhibition, such as the detection of conflict and the investment of extra attentional resources on relevant information. Additionally, the relative autonomy and the structured interplay of these processes were highlighted by the ERP technique, in particular, by its use in conjunction with brain source localization analyses. These latter results permitted the mapping of various processes involved in inhibition, across time and tasks, onto different brain areas, which significantly advanced the understanding of the manifold nature of inhibitory processing. In particular, a more fine-grained understanding of time-scale has been added to the previous fMRI studies, which suggests the involvement of different brain areas in different inhibition paradigms.

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2. COGNITIVE CONTROL DURING A SPATIAL STROOP TASK: COMPARING CONFLICT MONITORING AND PREDICTION OF RESPONSE-OUTCOME THEORIES

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2.1. Abstract

Cognitive control allows information processing and behaviour to vary adaptively from moment to moment depending on current goals. Two of the most prominent theories that have been proposed to account for the processing of cognitive control are the Conflict Monitoring Theory (CMT) and the Prediction of Response-Outcome (PRO) theory. According to both theories, the implementation of cognitive control during a trial in a conflict task reflects processing events that occurred in the preceding trial. Both CMT and PRO advocate that the detection of conflict situations leads to the recruitment of cognitive control, but they differ regarding the processing underpinnings of cognitive control during conflict resolution. CMT proposes that conflict between alternative responses is resolved by enhancing the task's relevant dimension, reducing interference from the task's irrelevant dimension(s). This control setup promotes conflict adaptation in the subsequent trial. PRO proposes that conflict is resolved by means of a cost-effectiveness analysis that identifies and suppresses action plans linked to the less appropriate responses, facilitating conflict resolution in the subsequent trial. To adjudicate between these alternatives, we manipulated contingencies pertaining to two-trial sequences (*n*-1; *n*), namely, the congruency between task relevant/irrelevant dimensions in trial *n*-1 and response repetition in trial *n*. A spatial Stroop task was used, in which task-relevant and irrelevant information were integrated within the same stimulus. In this task, participants were required to attend to the direction of an arrow while ignoring its position. The arrow's direction and position could be congruent (C) or incongruent (IC). In one experiment, trials in which the participant was required to respond according to the position of a circle (PO; position only trials), occupying the sequential position *n*, were the focus of the analyses.

Three experiments were conducted manipulating the trials' sequence structure. In Experiment 1, we studied a low control/low conflict condition (cC trials), and two high control/low conflict conditions (icC with and without response repetition). In Experiment 2, we studied two low control/no conflict conditions (cPO with and without response repetition) and two high control/no conflict conditions (icPO with and without response repetition). In Experiment 3, we studied a high control/high conflict condition (icIC) and two low control/high conflict conditions (cIC with and without response repetition). Overall, our findings are in agreement with previous studies in which both bottom-up processing, linked to response and stimulus position repetition, and top-down processing, linked to cognitive control, were shown to contribute to sequence effects in conflict tasks. Specifically, our observations mainly support PRO's account of conflict resolution, in which the intervention of top-down processing is substantially more complex than in CMT's account.

Keywords: Cognitive control; Conflict monitoring; Prediction of Response-Outcome; Conflict resolution; Spatial Stroop; Sequence effects.

2.2. Introduction

Our current experience is influenced by prior experience at both large and surprisingly small time scales. Priming is an experimental effect that appropriately illustrates this latter type of influence. It reflects a "preparation" of the cognitive system to process the target that makes use of primes' attributes and of their mapping onto the responses available within the task. Priming effects and their variation as a function of the prime/target relations are valuable means to investigate the nature of the processes that underpin such small time-scale "preparations". In conflict-tasks, such as the Stroop task (Stroop, 1935), priming effects allow us to probe the functioning of the cognitive control system, which is mobilized to manage and resolve conflict. With respect to such tasks, it is still a matter of debate how cognitive control is implemented. The Conflict Monitoring Theory (CMT; Botvinick, Cohen, & Carter, 2004) and the Prediction of Response-Outcome theory (PRO; Alexander & Brown, 2011) provide particularly insightful, yet different, accounts regarding the processing of cognitive control in the management of conflict, in which the anterior cingulate cortex (ACC) seems to be involved. The CMT advocates that conflict between alternative responses is resolved by

focusing on the task's relevant dimension and thus reducing interference from the task's irrelevant dimension(s). This results in conflict adaptation in the subsequent trial. According to the PRO, conflict between alternative responses is resolved after a cost-effectiveness analysis that identifies and eventually leads to the suppression of the incorrect action plan(s), leaving only the correct action plan(s) available for execution. According to both theories, sequence effects in conflict tasks reflect the implementation of cognitive control. Although the conflict monitoring function, advocated by the CMT, and the response-outcome prediction function, advocated by the PRO, are not necessarily mutually exclusive (for a unitary ACC function proposal, see Botvinick, 2007), the two theories offer distinct accounts regarding conflict resolution, a key feature of cognitive control implementation in conflict tasks.

2.2.1. Conflict Monitoring Theory (CMT)

Human neuroimaging studies with conflict tasks, such as the Stroop task (Stroop, 1935), the Eriksen flanker task (Eriksen & Eriksen, 1974) and the Simon task (Simon & Rudell, 1967), have found increased activation in the ACC when participants needed to suppress frequent responses, when they had to select one from a number of potentially correct responses, and when they committed errors (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns, 2006; Larson, Kaufman, & Perlstein, 2009; Liotti, Woldorff, Perez, & Mayberg, 2000; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Based on the idea that this increased activation indexes the detection of conflict, Botvinick, Braver, Barch, Carter, and Cohen (2001) proposed the CMT. According to this theory, a conflict monitoring system is automatically activated in trials in which response conflict is present. Response conflict is defined by Botvinick et al. (2001) as the simultaneous activation of mutually inhibiting responses. The role of the conflict monitoring system is to signal the need for increased cognitive control, relaying this request to the prefrontal regions that instantiate the required processes. The prefrontal control system then resolves the conflict by biasing attentional focus towards the task's relevant stimulus information and reducing the interference of the task's irrelevant stimulus information (Egner & Hirsch, 2005). Botvinick et al. (2001) propose that lateral inhibition plays an important role in conflict resolution. In their computational models, lateral inhibition is present within both the response layer and the stimulus layer. Specifically, the response representation, enhanced by increased upcoming activation

from stimulus' relevant information, actively contributes to the suppression of the competing response via their mutually inhibitory connections. In a similar manner, the stimulus' feature unit, enhanced by an attentional bias, further magnifies its saliency as a result of the inhibitory connections with the other units, reducing interference from irrelevant information.

2.2.2. The Prediction of Response-Outcome Theory (PRO)

Another stream of data suggests that the ACC is engaged in computing the expectable outcomes of a response before its occurrence, yielding information valuable in guiding response selection when several options are available (for a review, see Yeung, 2013). Different functions have been attributed to ACC regarding its capacity to guide behaviour by response-outcome association: the detection of discrepancies between actual and expected outcomes (Holroyd & Coles, 2002); error likelihood prediction (Brown & Braver, 2005, 2007); the detection of unpredicted responses (Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003); the detection of volatility (Behrens, Woolrich, Walton, & Rushworth, 2007); and the capacity to learn from errors (Hester, Barre, Murphy, Silk, & Mattingley, 2008). To account for all these findings, the PRO was proposed (Alexander & Brown, 2010, 2011). The core processes in PRO involve mappings between existing action plans in a stimulus context and predictions of the responses and outcomes that are likely to result (Alexander & Brown, 2011). These action plans are abstract functions projecting the value of a given stimulus feature onto a response (e.g., if stimulus at position x, response at position x). PRO is to a large extent a learning theory and therefore has a primary focus on the process of learning the aforementioned mappings, as it unfolds in tasks in which the correct response is not instructed but must be learned by trial-and-error using feedback. However, PRO also describes the mechanisms that make use of those mappings when they were fully learned or directly defined by the task's instructions. Accordingly, PRO also models performance in tasks in which the required response is clearly defined by instructions such as conflict tasks in which participants must select the task-appropriate responses when competing alternatives are also present (Alexander & Brown, 2011; Yeung, 2013). It is the set of mechanisms that PRO proposes with respect to this type of task that is of interest in our present work. According to PRO, conflict effects are due to the prediction of multiple responses. Incongruent stimuli signal an overall prediction of

responding to the distractor and, therefore, the presence of correct and incorrect action plans, which must be distinguished from each other (Alexander & Brown, 2011). To isolate the appropriate action plan, the ACC predicts the responses and outcomes that each plan should yield (Kennerley, Walton, Behrens, Buckley, & Rushworth, 2006). Action plans yielding predicted responses with an unacceptable cost (e.g., high error probability) are suppressed, leaving only the action plan yielding the least amount of effort or risk (Botvinick, 2007; Brown & Braver, 2007). The suppression process is instantiated by an "amend/veto" function (Alexander & Brown, 2010) associated with the response-outcome predictions. This settles response selection, leaving only the most appropriate action plan available.

2.2.3. Sequence Effects

The role of conflict in the recruitment of control has become apparent in studies of trial-by-trial adjustments of cognitive control. The terms "conflict adaptation", "*Gratton* effect", and "sequential trial effects" are frequently used to refer to these trial-by-trial adjustments (Egner, 2007; Gratton, Coles, & Donchin, 1992; Kerns et al., 2004). These sequence effects were first found in the Eriksen flanker task (Gratton et al., 1992). Usually, in this conflict task, the participant must respond to the direction of a central arrow, the target, while ignoring the direction of arrows appearing on the sides, the flankers. The flankers can be pointing to the same side as the target (i.e., C trial) or they can be pointing to the opposite side (i.e., IC trial). Two relevant sequence effects have been described with respect to the Eriksen flanker task and other conflict tasks: (i) a faster and more accurate response to an incongruent (IC) trial preceded by another IC trial (icIC) relative to the response to an IC trial preceded by a congruent (C) trial (cIC); (ii) a faster and more accurate response to a C trial preceded by another C trial (cC) relative to a C trial preceded by an IC trial (icC; Gratton et al., 1992; Sturmer, Leuthold, Soetens, Schroter, & Sommer, 2002; Ullsperger, Bylsma, & Botvinick, 2005). Sequence effects supposedly due to the management of conflict/incongruency are likely to reflect other variables associated with the trial sequence, namely, response repetition and/or repetition of the stimulus position. In particular, the accounts of cognitive control and conflict resolution we intend to confront, CMT and PRO, yield predictions pertaining to the deployment of cognitive control and its manifestations in sequence effects in conflict trials that reflect not only the trials' congruency but also whether or

not trial *n* repeats the response or stimulus position that occurred in trial *n-1*. Namely, for CMT, lateral inhibition between conflicting motor response representations should translate into negative priming effects when a response inhibited in trial *n*-1 is the correct response in trial *n*. According to PRO, conflict resolution involves goal structures and action plans that are abstract and not immediately connected to specific motor response representations. Thus, response repetitions should mainly interact with aspects of the control goal structure assembled in trial *n*-1, as for instance the repeated recruitment in trial *n* of an action plan and specific predicted response that were activated in trial *n*-1. There are, additionally, some configurations of stimulus-response repetition that might affect trial sequences due to processes that have no relevance for examining the CMT/PRO contrast and that would instead obscure the results bearing on that contrast. That would be the case of exact stimulus-response repetitions that occur in IC-IC and C-C sequences (benefiting processing in the second trial). In both Mayr, Awh, and Laurey (2003) and Nieuwenhuis et al. (2006), sequence effects were absent in a flanker task if sequences with exact stimulus-response repetitions were excluded and if only response repetitions in the absence of stimuli repetition (occurring in IC-C and C-IC sequences, increasing difficulty while processing the second trial) were considered in the analyses. Other studies found sequence effects in the flanker task when stimulus and/or response repetitions effects were controlled (Ullsperger et al., 2005; Verbruggen, Notebaert, Liefooghe, & Vandierendonck, 2006). Using other conflict tasks, studies that controlled for both exact and partial stimulus-response repetitions also identified sequence effects, namely with the Stroop and Simon tasks (Notebaert, Gevers, Verbruggen, & Liefooghe, 2006; Sturmer et al., 2002; Wuhr & Ansorge, 2005). Overall, these findings highlight the relevance for sequence effect studies of eliminating the effect of complete stimulus-response repetitions and incorporating into their design the distinctive features of the remaining repetition combinations, response repetition without stimulus repetition and complete response-stimulus mismatch.

In the experiments we conducted to probe these sequence effects, we omitted full stimulus-response repetitions. A spatial Stroop task was used. Although the sequence effects that interest us were first described with respect to the Eriksen flanker task, we considered that a task in which spatial position segregates irrelevant (flankers) and relevant information (target) information would not be the most appropriate ground to conduct a comparison between CMT and PRO accounts of cognitive control. This is because in an Eriksen flanker task conflict trial, a response according to flanker

information is never a prevalent response and, therefore, is not a particularly strong competitor to the appropriate response. Additionally, the spatial segregation of relevant (central) and irrelevant information (left and right) probably facilitates the use of low-level attentional strategies that could effectively eliminate flanker interference. Taken together, these aspects of an Eriksen flanker task could contribute to results reflecting a fairly simple perceptual tuning effect or some visual attention biasing strategy that might not heavily rely on top-down control. Since we were interested in probing the nature of such control mechanisms, we devised a task more likely to reflect their intervention. Namely, we conflated in a single stimulus irrelevant left/right position information with relevant direction information. This yielded the spatial Stroop task that we used in our experiments, necessarily requiring some degree of central processing to dissociate relevant and irrelevant information and creating strong competitors to the appropriate response in conflict trials, due to the presence of a Simon effect.

2.2.4. The spatial Stroop task and cognitive control

In a spatial Stroop task, direction-words or arrows may be used as stimuli. In the arrow-version of such tasks (Funes, Lupianez, & Milliken, 2007; Luo, Lupianez, Funes, & Fu, 2013; Luo & Proctor, 2013), participants are asked to respond to the left/right direction of an arrow regardless of its left/right position on a computer screen. As in the Simon task (Simon & Small, 1969), there is a tendency to respond with the hemibody matching the side of the stimulus presentation. This effect provides, in the context of a Stroop task, a prevalent response associated with the irrelevant stimulus' dimension that must somehow be suppressed in conflict trials. In the spatial Stroop task, both Stimulus-Stimulus (S-S) and Stimulus-Response (S-R) interference are present (Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005). Conflict in IC trials may therefore emerge at two distinct levels: S-S, pertaining to selectively attending one or the other information source present, and S-R, pertaining to the competing response mappings for each of the information sources. In congruent trials, S-S conflict may arise, but S-R conflict is absent since both information sources map onto the same response. Crucially, CMT and PRO theories differ in their account of conflict resolution. According to both the CMT and PRO theories, in IC trials, two incompatible responses are prepared: (i) the response according to the arrow's direction and (ii) the response according to the arrow's position. The presence of different response options is identified as impeding a

successful trial, and the level of control is increased to overcome the situation. After this initial step, the CMT and PRO theories advocate different mechanisms to achieve conflict resolution. CMT proposes that increased control translates into an enhancement of the task-relevant dimension (i.e., direction), reducing interference from the task-irrelevant dimension (i.e., position). This biased activation flowing between layers, from the stimulus onto the response layer, induces higher activation of the response linked to the arrow's direction. According to the computational model proposed by Botvinick et al. (2001), lateral inhibition magnifies the differential activation of units within the response layer (left/right responses) and within the stimulus features' layer (direction and position units). This interplay of biased between-layer activation and within-layer lateral inhibition eventually resolves conflict. PRO advocates that conflict in an IC trial comes from the existence of multiple response plans and corresponding expected responses. When an IC trial signals the expectation of responding to the task-irrelevant information, top-down control is recruited, establishing the goal of suppressing the action plan with the least favourable outcome. Assigning such an outcome requires activation of the task's criterion that identifies the action plan associated with a predicted incorrect response, which, in our spatial Stroop task, is the one yielding a response to the side where the arrow is located. This action plan is associated with an unacceptable cost (i.e., an erroneous response), and its execution must therefore be prevented. Crucially, the PRO advocates that cognitive control always acts by choosing the best cost-effectiveness process. The suppression of the incorrect action plan is the most cost-effective process, leaving only the task-appropriate action plan (e.g., responding to the side indicated by the arrow's direction) available for execution. It should also be noted that the response representations that are in use during conflict processing lie at different abstraction levels for the CMT and for the PRO. While for the CMT these representations are closer to the motor programs responsible for execution—as indicated by the mutual lateral inhibition connections between incompatible responses, upon which conflict detection relies—for the PRO, the relevant representations are notably more abstract (action plans and corresponding response-outcome predictions).

We present three experiments designed to contrast CMT and PRO predictions with respect to sequence effects in a spatial Stroop task, in which the congruency type of the first in a two-trial sequence was varied, as well as response/position repetition. Only trials without complete stimulus-response repetitions were used.

2.3. EXPERIMENT 1 – Sequence effects on congruent (C) trials

2.3.1. Purpose

In Experiment 1, we analysed the effect of the trial *n*-1 congruency type on an *n* C trial. Three different types of C trials were considered: cC trials without response repetition ($cC^{R\neq}$); icC trials with response repetition ($icC^{R=}$); and icC trials without response repetition ($icC^{R\neq}$).

We expected that the processing of both $icC^{R\neq}$ and $icC^{R=}$ trials would be impaired relative to $cC^{R\neq}$ trials. According to CMT, in *n*-1 IC trials, the biased activation of the relevant stimulus information (i.e., direction) leads to increased saliency of the direction response, with a corresponding decrease in the position response pathway. According to PRO, the goal of suppressing the action plan associated with an expected incorrect response that was established to obtain the best outcome in the *n*-1 IC trial should be primed in the *n* C trial, as should the criterion defining incorrectness (i.e., same-sided response-stimulus). In the *n* C trial, this setup initially results in inappropriate marking for suppression the correct response, since in a C trial, direction and position information lead to the same response.

For the comparison of the $icC^{R=}$ and $icC^{R\neq}$ trials, we expected, according to CMT, an impairment in $icC^{R\neq}$ trials due to lateral inhibition within the response layer. In the $icC^{R\neq}$ trials, direction and position are mapped onto the same response, but this response is the one that was suppressed due to lateral inhibition between the left-right responses in the *n*-1 IC trial. The response required in the *n* C trial is the one inhibited in the *n*-1 IC trial, leading to accrued impairment in the $icC^{R\neq}$ trials relative to the $icC^{R=}$ trials. PRO does not predict a differential impairment of $icC^{R\neq}$ and $icC^{R=}$ trials, given that in the IC trial, an action plan ("respond according to stimulus side") was suppressed and not a specific (left/right) representation of a motor response.

In addition to the C and IC trials included in the critical sequences described above, we included in non-critical sequences position-only (PO) trials (i.e., trials in which the participant has to respond according to the position of black circles that do not convey any direction information). PO trials were introduced in order to reduce the possibility of developing and automatizing facilitating strategies (e.g., focusing attention on the head of the arrow and systematically suppressing information

concerning its spatial position), since that could reduce the spatial Stroop effect (Lu & Proctor, 1995). In the PO condition, the stimulus position is the relevant dimension, thus preventing the participants from automatizing the blocking of position information. The proportion of PO trials was kept low (11 % of the total trials) in order to preserve the nature of the task. We expected to find a spatial Stroop effect (i.e., impairment of IC trial processing relative to C trial processing), to which the PO trials should have contributed. The inclusion of PO trials implied the presence of task-switching, as participants had to use the instruction to respond according to the stimulus on-screen positioning for PO trials and shift to the main instruction of responding to the arrows' direction when such a stimulus followed a PO (and vice-versa). To prevent a direct task-switching effect affecting the first trial (*n*-1) in a critical sequence, which could somehow affect RTs and the accuracy in the trial *n*, we controlled the type of trials *n*-2 (i.e., trials preceding *n*-1). PO trials never occurred immediately before trials *n*-1. PO trials were oddballs in Experiment 1 (11 %), and their rarity should therefore prevent the necessity of keeping the PO task instruction in working memory while performing the dominant task. The presence of PO trials probably amplified conflict in the IC trials due to the fact that position could not be systematically ignored throughout the task. However, this possible amplification, although it may have had some influence on the magnitude of the sequence effects under study, should not have affected their nature. Finally, the number and distance of PO trials appearing before critical sequences could not consistently differ between different conditions of the experiments, and a confounding variable could not therefore emerge.

2.3.2. Method

2.3.2.1. Participants

Forty undergraduate Psychology students at the University of Coimbra participated for course credit. All participants provided written informed consent in accordance with institutional guidelines. Exclusion criteria comprised current or previous diagnosis of a psychiatric or neurologic disorder, psychoactive medication use, brain injury, and uncorrected visual impairment. Participants were screened for depressive symptoms with the Beck Depression Inventory II (Beck, Steer, & Brown, 1996), and a cut-off of 20 points (i.e., moderate depression symptoms) was used to determine exclusion. Due to the presence of moderate depressive symptoms, three

participants were excluded from data analysis. As a result, data from thirty-seven young adults (32 female; 18 - 26 years old, *M* = 19.14, *SD* = 1.62; 11 - 17 years of formal education, *M* = 12.5, *SD* = 0.99) were analysed. All participants in this and subsequent experiments took part in only one of them.

2.3.2.2. Materials and Procedure

Participants were tested on a computer running E-prime software (Psychology Software Tools, Inc.; www.pstnet.com/products/e-prime/). They sat comfortably in front of a 17'' computer screen at a distance of approximately 100 cm in a dimly lit room. During the task, three white boxes were horizontally displayed on a navy blue screen (see Fig. 1): one was presented centrally and the other two were presented on each side of the central box, equidistant from the centre of the screen. The stimuli consisted of black arrows presented inside the lateral boxes. Participants were asked to maintain their fixation on the centre of the screen before the target was presented. They were instructed to make left/right button presses using two switches, one held in each hand, in response to the right/left direction of an arrow.

The sequence of events in each trial/sequence is shown in Fig. 1.

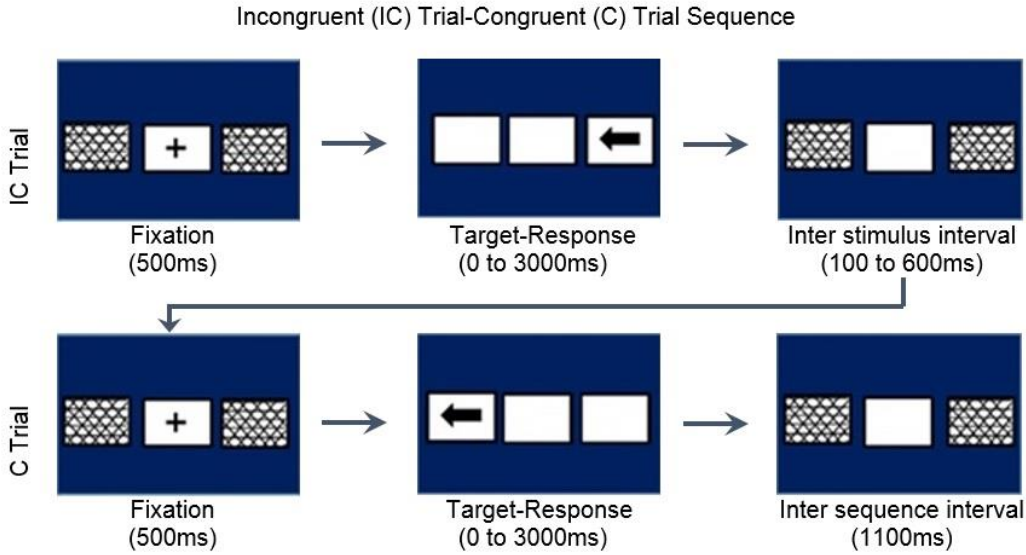

Fig. 1 - The sequence of events in each trial/sequence in the spatial Stroop task: an example of a sequence composed of an IC trial and a C trial.

At the beginning of each trial, the fixation point (a cross displayed inside the box located in the centre of the screen) and two lateral boxes filled with masks were presented for 500 ms. Then, the fixation point disappeared from the central white box

and the target appeared in the right or left lateral boxes and remained on-screen until the participant responded, with a time limit of 3000 ms. Participants' responses triggered the offset of the stimulus display, which was followed by an inter-stimulus interval (ISI) that could vary between 100 and 600 ms. During ISI, masks were displayed in the lateral boxes and the central box remained blank. Mask presentation was used to overcome afterimage effect issues (Pilling, 2007). A second trial then began with the same structure of the first one, starting with a fixation cross, followed by the stimuli display. Stimulus offset was followed by a fixed inter-sequence interval of 1100 ms to prevent accumulated eye strain while remaining unnoticeable to participants, as confirmed during debriefing. As during ISI, in the inter-sequence interval, masks were displayed in the lateral boxes and the central box remained blank during the inter-sequence interval. The task comprised 664 trials that were presented in prearranged sequences of which participants were unaware, the succession of different trial types being perceived as random. The focus of our experiment was the following critical sequences: $icC^{R\neq}$, $icC^{R=}$, and $cC^{R\neq}$ (see Table C in the Appendix section for a visual representation). Full stimulus-response repetitions (e.g., a C trial requiring the right response preceded by other C trials that required the same response) were not included. To obtain an equal proportion of C and IC trials, filler sequences were created. These non-critical sequences included icIC trials and cIC trials, as well as other sequence types combined with PO trials.

The proportion of C and IC trials was 44.58 % each, and the proportion of PO trials was 10.84 %. The proportion of response types was balanced in our task, with 50 % requiring a left response and 50 % requiring a right response. The experiment comprised three short breaks, dividing the overall duration of each participation into four parts comprising an equal number of trials and keeping the proportions of C, IC, and PO trials stable in each part (166 trials, of which 72 were critical trials; overall: 74 C trials, 74 IC trials and 18 PO trials). The overall duration of the time-on-task was 20 mins. Before engaging in the main task, participants performed 28 practice trials and were instructed to respond as quickly as possible while trying to avoid errors.

2.3.2.3. Data analysis

Sequence effects were analysed by comparing three conditions ($cC^{R\neq}$, $icC^{R\neq}$ and $icC^{R=}$). Pairwise comparisons were always performed using the Bonferroni correction. Potential confounding factors while examining sequence effects may emerge as a

consequence of including error and post-error trials (Egner & Hirsch, 2005). Error trials are frequently associated with faster reaction times (RTs; Ridderinkhof, 2002), while post-error trials are associated with consistent RT slowing (Rabbitt, 1966). Thus, we excluded error and post-error trials from our analyses. This procedure excluded 9 % of the responses. One percent of the responses were excluded in the $cC^{R\neq}$ condition, while 13 % were excluded in the $icC^{R\neq}$ and the $icC^{R=}$ conditions. Anticipations (RTs < 100 ms and RTs 3SD lower than the participant's mean for a given experimental condition) and lapses of attention (RTs more than 3SD higher than the participant's experimental condition mean) were also excluded. This cut-off procedure excluded < 2 % of the remaining responses with similar exclusion rates for the different conditions (±1.8 % in each condition). To assess sequence effects, we performed two separate one-way repeated-measures analyses of variance (ANOVAs), one pertaining to correct responses' RTs and the other to accuracy rates.

In addition to the sequence effect analyses, differences in the processing of C and IC trials were analysed in order to assess the spatial Stroop effect. Two paired-samples t-tests were performed for correct responses' RTs and for accuracy. Trial *n*-1 responses (i.e., first trial responses) in C-C and IC-C critical sequences were used in these analyses. We used an alpha level of .05 for all statistical tests.

2.3.3. Results

The C and IC trials in Experiment 1 were compared before the analysis of the critical sequence effects. We found slower RTs for IC trials (M= 501 ms, SD = 81.2 ms) relative to C trials (M = 435 ms, SD = 77.2 ms), $t(36) = 11.726$, $p < .001$, and lower accuracy rates for IC trials (M = 88 %, SD = 8.4 %) relative to C trials (M = 99 %, SD = 1.3 %), $t(36) = -7.926$, $p < .001$. Thus, a reliable spatial Stroop effect was found relative to both RTs and accuracy. The association between Stroop interference and possible sequence effects is therefore duly grounded. The remaining analyses concern the examination of such sequence effects.

RTs and accuracy rates for each sequence condition are shown in Fig. 2.

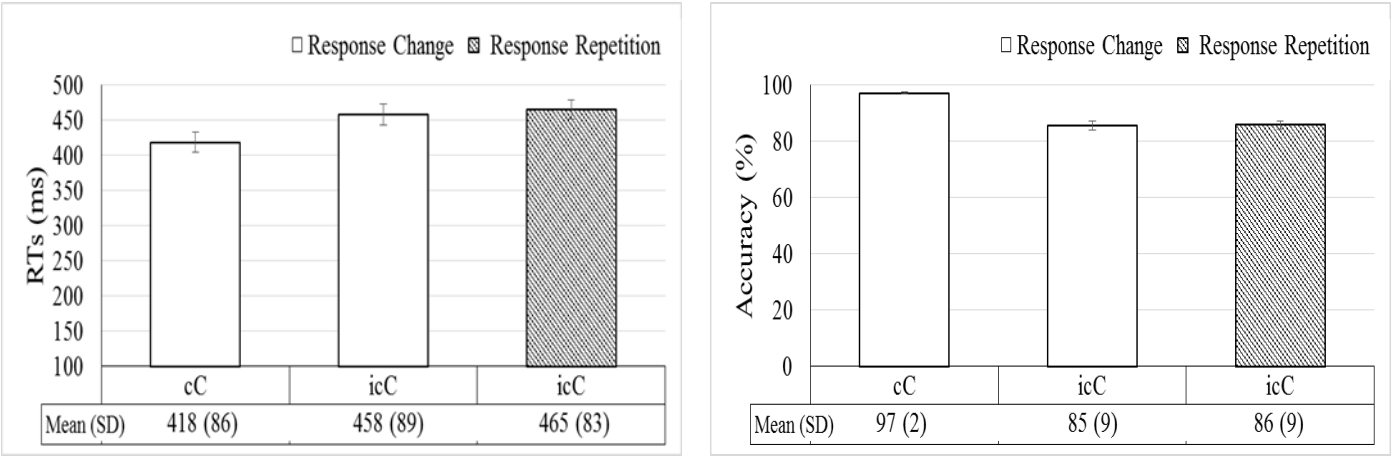

Fig. 2 - RTs and accuracy for the critical conditions: cC trials with response change (cC white bar); icC trials with response change (icC white bar); icC trials with response repetition (icC pattern bar). Error bars represent the standard errors (SE).

A repeated measures ANOVA determined that RTs differed significantly between the sequence conditions [$F(2, 72) = 47.061$, $p < .001$, $\eta^2_p = .567$]. Pairwise comparisons revealed that the responses to the $cC^{R\neq}$ trials ($M = 418$ ms, $SD = 85.9$ ms) were 39 ms faster relative to the $icC^{R\neq}$ trials ($M = 458$ ms, $SD = 89$ ms) [$F(1, 36) = 60.918$, $p < .001$, $\eta^2_p = .629$] and 46 ms faster relative to the $icC^{R=}$ trials ($M = 465$ ms, $SD = 83.4$ ms) [$F(1, 36) = 95.196$, $p < .001$, $\eta^2_p = .726$]. The $icC^{R\neq}$ and $icC^{R=}$ trials' RTs did not differ significantly [$F(1, 36) = 1.648$, $p = .207$]. A repeated measures ANOVA determined that accuracy differed significantly between the sequence conditions [$F(2, 72) = 48.471$, $p < .001$, $\eta^2_p = .574$]. Pairwise comparisons revealed that responses to the $cC^{R\neq}$ trials were 12 % more accurate ($M = 97.1$ %, $SD = 1.8$ %) than those to the $icC^{R\neq}$ trials ($M = 85.4$ %, $SD = 9.2$ %) [$F(1, 36) = 60.865$, $p < .001$, $\eta^2_p = .628$] and 11 % more accurate than the responses to the $icC^{R=}$ trials ($M = 85.8$ %, $SD = 8.9$ %) [$F(1, 36) = 64.971$, $p < .001$, $\eta^2_p = .643$]. The difference in accuracy between the $icC^{R\neq}$ and $icC^{R=}$ trials was non-significant [$F(1, 36) < 1$, *ns*].

As predicted by both PRO and CMT, the $icC^{R\neq}$ and $icC^{R=}$ trials were impaired relative to the $cC^{R\neq}$ trials. No differences were found in the processing of the $icC^{R\neq}$ and $icC^{R=}$ trials. This result counters the CMT, from which we derived the prediction of an accrued impairment in $icC^{R\neq}$ trials due to lateral inhibition in the response layer. Accordingly, the results observed are better explained by the PRO, highlighting the role

of the suppression of the incorrect action plan, defined at an abstract level in which representations of the specific values of stimulus attributes are not integrated.

2.4. EXPERIMENT 2 – Sequence effects on position only (PO) trials

2.4.1. Purpose

The main purpose of Experiment 2 was to clarify some interpretation issues pertaining to the results of Experiment 1. In Experiment 1, we tested the prediction derived from CMT that $icC^{R\neq}$ trials would be impaired relative to $icC^{R=}$ trials. This would be due to lateral inhibition in the response layer during the *n*-1 IC trial, affecting the response that should be produced in the following trial. In fact, we found no differences between the $icC^{R\neq}$ and $icC^{R=}$ trials. However, and still according to CMT, another effect of processing an *n*-1 IC trial would be the enhancement of direction information in the stimulus layer, establishing a bias that would still be present, to same extent, in the following trial. Therefore, one could hypothesize that this latter sequential effect would neutralise the first, rendering the absence of differences between $icC^{R\neq}$ and $icC^{R=}$ trials compatible with CMT's mechanisms. To clarify this possibility, we replicated Experiment 1, substituting *n* PO trials for *n* C trials. In the PO trials, the participant had to respond according to the stimulus position and, crucially, there was no direction information present. Therefore, CMT no longer provided a mechanism that might neutralise the impairment in $icC^{R\neq}$ trials, due to residual inhibition of the correct response. The processing of *n* PO trials was analysed by contrasting four conditions: cPO trials with response repetition ($cPO^{R=}$); cPO trials without response repetition ($cPO^{R\neq}$); icPO trials with response repetition ($icPO^{R=}$); and icPO trials without response repetition ($icPO^{R\neq}$). We expected that the processing of both $icPO^{R\neq}$ and $icPO^{R=}$ trials would be impaired relative to $cPO^{R\neq}$. According to the CMT, in the *n*-1 IC trials, the increased activation of the relevant stimulus information (i.e., direction) leads to a reduced activation of the irrelevant one (i.e., position). Even though PO trials do not contain direction information, it might still be conceivable that the position feature pertaining to a PO stimulus' representation would be hindered in its capacity to activate the corresponding correct response, due to lateral inhibition within the stimulus layer occurring in the previous IC arrow trial. According to the PRO, activation of the goal of suppressing an action plan associated with a predicted incorrect response would have

been necessary to obtain the best outcome in the *n*-1 IC trial. This goal should therefore be primed in the *n* PO trial, as should the criterion defining incorrectness (i.e., same-sided response-stimulus). In the *n* PO trial, this setup would initially result in inappropriately selecting for suppression the correct action plan, since in PO trials, the action plan that would provide the correct response is associated with a predicted response matching the criterion for defining incorrectness used in the previous IC trial.

For the icPO$^{R=}$ and icPO$^{R\neq}$ trial comparison, we expected, according to CMT, an impairment in icPO$^{R\neq}$ trials as an after-effect of the lateral inhibition within the response layer that occurs in the *n*-1 IC trial. The left/right response required in icPO$^{R\neq}$ trials should have been inhibited in the *n*-1 IC trial, leading to an accrued impairment in icPO$^{R\neq}$ trials relative to icPO$^{R=}$. No differences are predicted by PRO regarding the icPO$^{R\neq}$ and icPO$^{R=}$ contrast, since suppression in IC trials impacts abstract action plans ("respond according to stimulus side"), not specific (left/right) representations of motor responses.

A fourth condition, comprising cPO trials with response repetition (cPO$^{R=}$), which could not be included in Experiment 1 because it would feature full response-stimulus repetitions, was now considered in Experiment 2, since stimuli always vary across trials when using arrow-circle sequences.

As in the previous experiment, C, IC and PO trials were included in the task. The proportion of PO trials was higher (33.33 %) than in Experiment 1 in order to balance the trial types' proportion. We expected to find a spatial Stroop effect (i.e., impairment of IC trial processing relative to C trial processing), to which the PO trials should have contributed.

2.4.2. Method

The method in this experiment was the same as in Experiment 1, except for the information added bellow.

2.4.2.1. Participants

Forty participants took part in Experiment 2. Due to the presence of moderate depressive symptoms, five participants were excluded from the data analysis. Two more participants were excluded due the use of psychoactive medication. Another was excluded due to severe congenital auditory deficits. As a result, data from 32 young

adults (31 female; 18 - 24 years old, *M* = 18.8, *SD* = 1.41; 12 - 17 years of formal education, *M* = 12.8, *SD* = 1.44) were analysed in this experiment.

2.4.2.2. Materials and Procedure

The main task was composed of 675 trials that were organized into sequences. There were four critical sequences: $cPO^{R=}$, $cPO^{R\neq}$, $icPO^{R\neq}$ and $icPO^{R=}$ (for a visual representation, see Table C from the Appendix section). Non-critical sequences of trials, including sequences such as poPO, cIC and icC, were also presented in order to obtain equal proportions of PO, C and IC trials (33.33 % each). The experiment comprised two short breaks, dividing the overall duration of each participation into three parts comprising an equal number of trials and keeping the proportions of C, IC, and PO trials stable in each part (225 trials, of which 64 were critical trials; overall: 75 C trials, 75 IC trials and 75 PO trials). The overall duration of the time-on-task was 18 mins.

2.4.2.3. Data analysis

Sequence effects were analysed by comparing four conditions ($cPO^{R=}$, $cPO^{R\neq}$, $icPO^{R\neq}$ and $icPO^{R=}$). Pairwise comparisons were always performed using the Bonferroni correction. As in the previous experiment, error and post-error trials were excluded from the analysis. This excluded 7 % of the responses. The critical conditions ($icPO^{R\neq}$; $icPO^{R=}$; $cPO^{R\neq}$; and $cPO^{R=}$) were differently affected by this exclusion: 14 % of the responses were excluded in the $icPO^{R\neq}$ and $icPO^{R=}$ conditions; < 1 % were excluded in the $cPO^{R\neq}$ condition; and 2 % were excluded in the $cPO^{R=}$ condition. Anticipations and lapses of attention were also removed. This cut-off procedure excluded < 2 % of the total remaining responses with similar exclusion rates for the different conditions (±1.7 % in each condition). To assess sequence effects, we performed two separate two-way repeated measures ANOVAs with the factors *n*-1 trial's congruency (C vs IC) and *n*-1 and *n* trials' response match (response repetition vs response change), one pertaining to correct responses' RTs and the other to accuracy rates.

In addition to the sequence effect analyses, differences in the processing of the three trial types included in the critical sequences were analysed: C, IC and PO trials. We performed two separate repeated measures ANOVAs, one pertaining to correct responses' RTs and the other to accuracy rates. Trial *n*-1 responses in C-PO and IC-PO sequences without response repetition were used in these analyses as C and IC trials. Trial *n* responses (i.e., second trial responses) in C-PO sequences without response

repetition were used in these analyses as PO trials. We selected the PO trials featured in $cPO^{R\neq}$ sequences, in which they are less affected by predictable sequence effects. $cPO^{R=}$ trials may exhibit partial match deleterious sequence effects (response repetition without stimulus repetition), while all icPO trials may be affected by interference with position processing. It should be noted that a task-shift effect may still negatively affect these $cPO^{R\neq}$ trials.

2.4.3. Results

To verify that our task induced a spatial Stroop effect in this experiment, we compared the *n*-1 C and IC trials in the critical sequences. Since PO trials were also part of these sequences, being the *n* trial therein, we also included them in an overall comparison. A repeated measures ANOVA was performed to compare RTs on the three trial types. Mauchly's test indicated that the assumption of sphericity had been violated [$\chi^2(2) = 14.211, p < .001$]; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (ε =.726). The three trial types differed significantly with respect to RTs [$F(1.452, 45.016) = 84.587, p < .001, \eta^2_p = .732$]. Follow-up pairwise comparisons revealed that responses to C trials (M = 381 ms, SD = 48.1 ms) were, on average, 86 ms faster than responses to IC trials (M = 467 ms, SD = 52.9 ms) [$F(1, 31) = 147.667, p < .001, \eta^2_p = .826$], while responses to PO trials (M = 390 ms, SD = 57.4 ms) were 77 ms faster than responses to IC trials [$F(1, 31) = 71.691, p < .001, \eta^2_p = .698$]. The difference between C and PO trials' RTs was non-significant [$F(1, 31) = 3.446, p = .073$]. A second repeated measures ANOVA was performed to determine whether there were differences in accuracy between trial types. Mauchly's test indicated that the assumption of sphericity had been violated [$\chi^2(2) = 41.763, p < .001$]; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (ε = .571). Accuracy rates differed significantly across trial types [$F(1.142, 35.399) = 27.563, p < .001, \eta^2_p = .471$]. Pairwise comparisons revealed that responses to C trials (M = 99 %, SD = 2.2 %) were significantly more accurate than responses to IC trials, at 9 % in our sample (M = 90 %, SD = 9.7 %) [$F(1, 31) = 27.058, p < .001, \eta^2_p = .466$]. Responses to PO trials (M = 99 %, SD = 2 %) in our sample were 9 % more accurate than responses to IC trials [$F(1, 31) = 30.650, p < .001, \eta^2_p = .497$]. The difference between accuracy in C and PO trials was non-significant [$F(1, 31) < 1$, *ns*]. A significant spatial Stroop effect was therefore found in

respect to both RTs and accuracy, as in Experiment 1. With respect to *n* PO trials, which were affected by no particular hindrance other than task-shift, the processing effort was comparable to that required in C trials, again supporting the analogy between Experiment 1 and Experiment 2, in which *n* C trials were used. The remaining analyses refer to the analysis of sequence effects that may result from or have an impact on this spatial Stroop interference.

RTs and accuracy for each sequence are shown in Fig. 3.

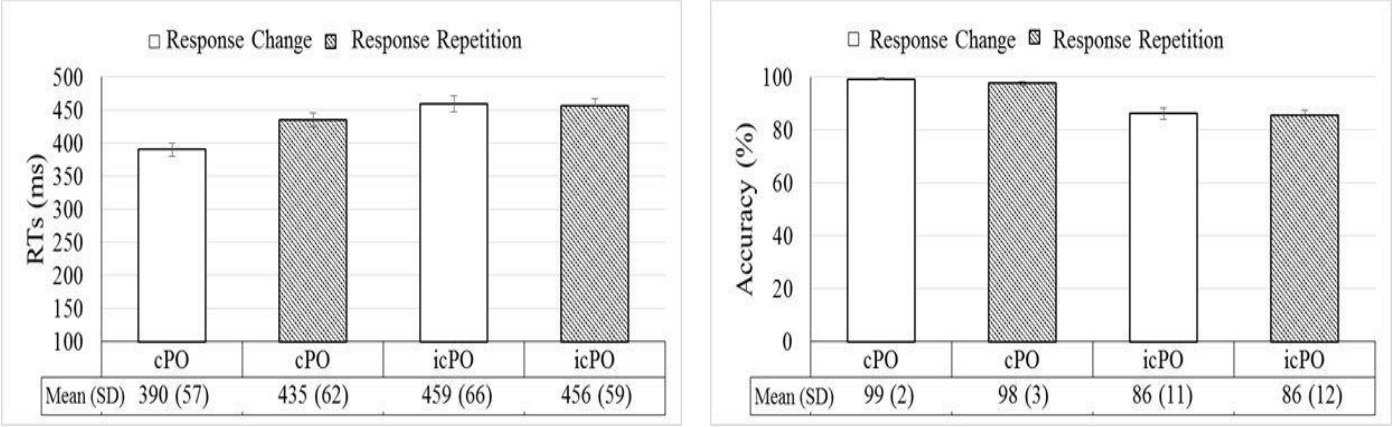

Fig. 3 - RTs and accuracy for the critical conditions: cPO trials with response change (cPO white bar); cPO trials with response repetition (cPO pattern bar); icPO trials with response change (icPO white bar); icPO trials with response repetition (icPO pattern bar). Error bars represent standard errors (SE).

A two-way repeated measures ANOVA was performed with the factors *n*-1 trial's congruency (C vs IC) and *n*-1 and *n* trials' response match (response repetition vs response change). There was a main effect of *n*-1 trial's congruency, with icPO trials (*M* = 458 ms, *SD* = 9.9 ms) being 45 ms slower that cPO trials (*M* = 413 ms, *SD* = 10.3 ms), [$F(1, 31) = 107.598$, $p < .001$, $\eta^2 p = .776$]. There was also a main effect of *n*-1 and *n* trials' response match, with response repetition trials (*M* = 446 ms, *SD* = 10.2 ms) being 21 ms slower than response change trials (*M* = 425 ms, *SD* = 10.5 ms), [$F(1, 31) = 11.265$, $p < .01$, $\eta^2 p = .267$]. There was a significant interaction between *n*-1 trial's congruency and response match, [$F(1, 31) = 34.005$, $p < .001$, $\eta^2 p = .523$]. Pairwise comparisons showed that this interaction was resolved by *n*-1 trial's congruency (C vs IC), with response repetition (*M* = 434 ms, *SD* = 61.6 ms) being slower than response change (*M* = 390 ms, *SD* = 57.4 ms) when the trial *n*-1 was congruent, [$F(1, 31) = 39.789$, $p < .001$, $\eta^2 p = .562$], and response repetition (*M* = 456

ms, *SD* = 58.9 ms) being as fast as the response change (*M* = 459 ms, *SD* = 65.7 ms) when the trial *n*-1 was incongruent, [$F(1, 31) < 1$, *ns*]. A two-way repeated measures ANOVA with the factors *n*-1 trial's congruency (C vs IC) and the *n*-1 and *n* trials' response match (response repetition vs response change) was also performed for accuracy. There was a significant main effect of *n*-1 trial's congruency, with responses to the icPO trials (*M* = 86 %, *SD* = 1.7 %) in our sample being 13 % less accurate than those to cPO trials (*M* = 98 %, *SD* = 0.4 %), [$F(1, 31) = 50.471$, $p < .001$, $\eta^2 p = .619$]. The main effect for the *n*-1 and *n* trials' response repetition was non-significant, with the performance in the response repetition trials (*M* = 91.5 %, *SD* = 1.1 %) being as accurate as in the response change trials (*M* = 92.6 %, *SD* = 1 %), [$F(1, 31) < 1$, *ns*]. The interaction between *n*-1 trial's congruency and response repetition was also non-significant, [$F(1, 31) < 1$, *ns*].

In Experiment 2, we clarified the results of Experiment 1. In Experiment 1, we tested the CMT prediction that $icC^{R\neq}$ trials would be impaired relative to $icC^{R=}$ trials, having not found differences between these two conditions. However, CMT's predicted effect with respect to response repetition might have been present, although obscured by the icC sequence effect within the stimulus layer. In fact, after processing an IC trial, the enhancement of direction information in the *n* C trial could have been powerful enough to cancel out the deleterious effect of having to produce a left/right response that had previously been inhibited. In Experiment 2, we replicated the sequence structures used in Experiment 1, but now using *n* PO trials, in which direction information is absent, instead of *n* C trials. As predicted by both PRO and CMT, the $icPO^{R\neq}$ and $icPO^{R=}$ trials were impaired relative to the $cPO^{R\neq}$ trials, repeating the pattern observed in Experiment 1 (in which the $icC^{R\neq}$ and $icC^{R=}$ trials were impaired relative to the $cC^{R\neq}$ trials). We did not find any differences between $icPO^{R\neq}$ and $icPO^{R=}$trial processing, again replicating the pattern of the results of Experiment 1 (in which no differences were found between the $icC^{R\neq}$ and $icC^{R=}$ trials). Critically, with respect to the latter contrast, the null result in Experiment 2 cannot be explained by enhancement of direction information, since PO trials do not convey such information. Thus, this result counters the CMT prediction of an impairment in $icPO^{R\neq}$ trials relative to $icPO^{R=}$ due to lateral inhibition in the response layer. The results of Experiment 2, as those of Experiment 1, favour PRO in detriment of CMT.

The analysis of the full 2 x 2 design in Experiment 2 additionally allowed us to determine that *n*-1 incongruency hinders performance in a subsequent no-conflict trial

irrespective of whether there is response repetition. Also, in the cPO vs icPO contrasts analysed, one of the trials in the critical sequences bore stimulus position repetition, while in the other, the stimulus position changed. The analysis of the full design showed that incongruency hinders performance in the subsequent trial irrespective of whether it is the cPO or the icPO trial that bears a repetition of the stimulus position. Experiment 2 further demonstrated that a sequential incongruency effect is present even when a different task and stimulus occur in the *n* trial.

2.5. EXPERIMENT 3 – Sequence effects on incongruent (IC) trials

2.5.1. Purpose

In Experiment 3, we analysed the effect of *n*-1 trials on *n* IC trials. Three different types of IC trials were considered: icIC trials without response repetition ($icIC^{R\neq}$); cIC trials with response repetition ($cIC^{R=}$); and cIC trials without response repetition ($cIC^{R\neq}$).

From CMT, we derived the prediction that $icIC^{R\neq}$ trials would be facilitated relative to both $cIC^{R=}$ and $cIC^{R\neq}$ trials. The bias set-up by the attentional units over the features represented within the stimulus layer in the *n*-1 IC trial, enhancing the arrow's direction information in detriment of its position, should still be present in the *n* IC trial, facilitating processing. According to the PRO, processing of $icIC^{R\neq}$ trials would be facilitated relative to $cIC^{R=}$ trials' processing. In the *n*-1 IC trial, the goal of suppressing the action plan associated with a predicted incorrect response was activated, as well as the criterion defining incorrectness (i.e., same-sided response-stimulus), in order to obtain the best outcome in that trial. The suppression goal and incorrectness criterion would then be primed in the *n* IC trial, facilitating the identification and suppression of the incorrect action plan in comparison to the same processes in a $cIC^{R=}$ trial. In $cIC^{R\neq}$, however, a specific facilitation effect would emerge according to PRO, the reason of which we detail below. Since there is no principled manner to derive from PRO a prediction about the relative strength of the $icIC^{R\neq}$ and $cIC^{R\neq}$ facilitation effects, we only predict the facilitation of $icIC^{R\neq}$ trials in relation to $cIC^{R=}$ trials.

We further derived from PRO the prediction that performance in $cIC^{R\neq}$ trials, in which the stimulus is presented in the same position in both trials (see Table C in the Appendix section), would be facilitated relative to performance in $cIC^{R=}$ trials. In the *n*-

1 C trial, the action plans anchored on the arrow's spatial position and on its direction are both actively processed in order to compute the corresponding response-outcome predictions. Since there is no direction and position information match, the predicted response is the same for both plans, and there is therefore no activation of the goal of identifying and suppressing the plan that should yield an incorrect response. Accordingly, in the following trial, there would be remaining activation for the plan that computes a response on the basis of stimulus position and for its instantiation to a specific spatial position, corresponding to its predicted response. Since the trial *n* is an IC trial, the goal of suppressing the action plan with a predicted incorrect response would emerge. The action plan to which the suppression goal should apply projects onto the exact same predicted response as in the previous trial, i.e., to a representation that is primed. Therefore, the criterion defining incorrectness would benefit from this priming and deliver the "incorrect" outcome prediction more promptly than in a $cIC^{R=}$ trial, in which no such priming could occur. We did not derive from CMT a specific pattern of differences regarding the comparison between the $cIC^{R\neq}$ and $cIC^{R=}$ trials. In the *n*-1 C trial position and direction, information would project onto the same response representation within the response layer. In this circumstance, no conflict would be detected and no attentional bias in favour of direction information would be established. We might speculate that even in the absence of conflict there would be strong lateral inhibition affecting the response not to be affected in a C trial. This would lead to predicting a pattern of differences between $icIC^{R\neq}$ and $cIC^{R=}$ trials opposite to that predicted by PRO. However, CMT does not elaborate upon the dynamics of excitatory and inhibitory processes in the absence of conflict.

As in Experiment 1, in addition to the C and IC trials included in critical sequences, we included PO trials in non-critical sequences in order to reduce the possibility of developing and automatizing facilitating strategies that could reduce the spatial Stroop effect. The proportion of PO trials was kept low (11 % of the total trials) in order to preserve the nature of the task.

2.5.2. Method

The method in this experiment was the same as in Experiment 1, except for the information added below.

2.5.2.1. Participants

Forty participants participated in Experiment 3. Due to the presence of moderate depressive symptoms, four participants were excluded from the data analysis. Accordingly, data from 36 young adults (31 female; 18 - 27 years old, *M* = 19.5, *SD* = 2.01; 9 - 17 years of formal education, *M* = 12.6, *SD* = 1.40) were analysed.

2.5.2.2. Materials and Procedure

The main task was composed of 648 trials, including equal proportions of C and IC trials (44.4 % each) and a low proportion of PO trials (11.1 %). There were three critical sequences: $cIC^{R=}$, $cIC^{R\neq}$, and $icIC^{R\neq}$ (see Table C in the Appendix section). As in Experiment 1, PO trials never occurred immediately before trials *n*-1 in order to minimize a possible task-switching effect directly impinging on critical sequences. The experiment comprised three short breaks, dividing the overall duration of each participation into four parts comprising an equal number of trials and maintaining the proportions of C, IC, and PO trials stable in each part (162 trials, of which 72 were critical trials; overall: 72 C trials, 72 IC trials and 18 PO trials). The overall duration of the time-on-task was 20 mins.

2.5.2.3. Data analysis

Sequence effects were analysed by comparing three conditions ($icIC^{R\neq}$, $cIC^{R\neq}$ and $cIC^{R=}$). Pairwise comparisons were performed always using the Bonferroni correction. As in previous experiments, error and post-error trials were excluded from the analysis. This excluded 21 % of the responses in the critical sequences. In the $cIC^{R\neq}$ condition, 14 % of the responses were excluded, in the $cIC^{R=}$ condition 26 % and in the $icIC^{R\neq}$ condition 21 %. Anticipations and lapses of attention were also removed. This procedure excluded < 2 % of the total remaining responses, with similar exclusion rates for the different conditions (±1.6 % in each condition). To assess sequence effects, we performed two separate one-way repeated-measures analyses of variance (ANOVAs), one pertaining to correct responses' RTs and the other to accuracy rates.

In addition to the sequence effects analyses, we analysed performance differences between C and IC trials in order to assess the spatial Stroop effect. Two paired-samples t-tests were performed, one pertaining to RTs for correct responses another for accuracy data. Responses to trials *n*-1 in C-IC and IC-IC critical sequences were used in these analyses.

2.5.3. Results

Performance in C and IC trials was compared before the analysis of the critical sequence effects. We found slower RTs for IC trials (M = 461 ms, SD = 83.6 ms) relative to C trials (M = 401 ms, SD = 89.3 ms), $t(35) = -11.101$, $p < .001$, and smaller accuracy rates for IC trials (M = 84 %, SD = 13.3 %) relative to C trials (M = 99 %, SD = 1.5 %), $t(35) = -7.035$, $p < .001$. Thus, a reliable spatial Stroop effect was found for both RTs and accuracy. The remaining analyses pertain to the examination of sequence effects that may result from or impact this spatial Stroop interference.

The RTs and the accuracy for each sequence condition are shown in Fig. 4.

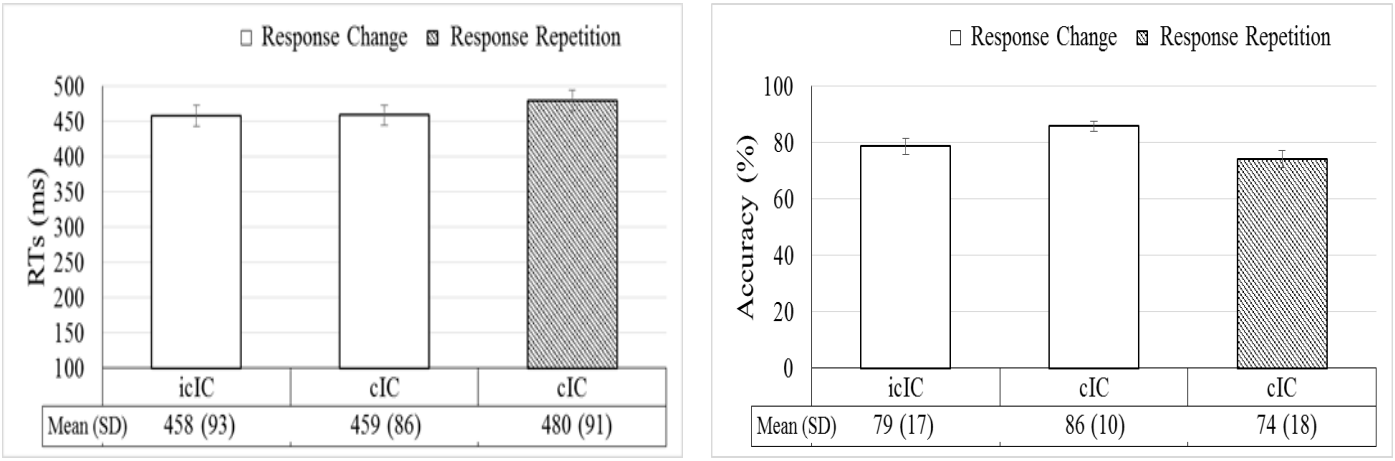

Fig. 4 - RTs and accuracy for the critical conditions: icIC trials with response change (icIC white bar); cIC trials with response change (cIC white bar); cIC trials with response repetition (cIC pattern bar). Error bars represent standard errors (SE).

A repeated measures ANOVA determined that RTs differed significantly among the three sequence conditions [$F(2, 70) = 8.164$, $p < .01$, $\eta^2_p = .189$]. Pairwise comparisons revealed that RTs in $icIC^{R\neq}$ trials (M = 458 ms, SD = 92.7 ms) and $cIC^{R=}$ trials (M = 480 ms, SD = 91.2 ms) were significantly different [$F(1, 35) = 14.228$, $p < .01$, $\eta^2_p = .290$], being 22 ms faster for $icIC^{R\neq}$ trials. $icIC^{R\neq}$ trials' RTs were as fast as in the $cIC^{R\neq}$ trials' RTs (M = 459 ms, SD = 85.6 ms) [$F(1, 35) < 1$, ns]. Responses to $cIC^{R\neq}$ trials were significantly faster than responses to $cIC^{R=}$ trials [$F(1, 35) = 10.336$, $p < .01$, $\eta^2_p = .228$], by 21 ms. A repeated measures ANOVA determined that the accuracy differed significantly among the three sequence conditions [$F(2, 70) = 26.588$, $p < .001$, $\eta^2_p = .432$]. Pairwise comparisons revealed that participants were significantly less

accurate, by 7 %, in icIC$^{R\neq}$ trials (M = 79 %, SD = 17.1 %) relative to cIC$^{R\neq}$ trials (M = 86 %, SD = 10.4 %) [$F(1, 35) = 21.030$, $p < .001$, $\eta^2_p = .375$]. Another significant difference emerged for the comparison between the icIC$^{R\neq}$ and cIC$^{R=}$ trials (M = 74 %, SD = 17.8 %), now with participants being 4 % more accurate in icIC$^{R\neq}$ trials [$F(1, 35) = 10.213$, $p < .01$, $\eta^2_p = .226$]. In cIC$^{R\neq}$ trials, the accuracy was significantly better than in cIC$^{R=}$ trials [$F(1, 35) = 40.041$, $p < .001$, $\eta^2_p = .534$], by 12 %.

The results fully support the PRO and do not support the CMT. The icIC$^{R\neq}$ trial processing was facilitated only relative to the cIC$^{R=}$ trial processing. In the cIC$^{R\neq}$ trials, there was a facilitation effect that PRO would attribute to a faster identification and suppression of an action plan associated with a predicted incorrect response. The computation of its undesirable outcome involved a specific predicted response that was primed in the n IC trial. This should have occurred because the same predicted response was generated for the same action plan in the *n*-1 C trial. As a result, responses to cIC$^{R\neq}$ trials were as fast as those to icIC$^{R\neq}$ trials.

2.6. Discussion

The main purpose of our study was to contrast predictions derived from CMT and PRO theory with respect to conflict adaptation effects in a spatial Stroop task in order to establish which of these theories best accounts for the processing of cognitive control in such a paradigm. In this task, relevant and irrelevant task-information are integrated within the same stimulus, and a prevalent response is triggered by irrelevant information. The intervention of cognitive control processes should therefore be amply reflected by performance in such a task.

Concerning our main goal, we analysed different manipulations of congruency type patterns and response repetition/stimulus position repetition in sequences of two trials within the task. These manipulations were designed to highlight contrasts between CMT and PRO in their accounts of the processing underpinnings of cognitive control. Overall, the results obtained in this set of experiments seem to be better explained by the PRO than by the CMT (see Table 1).

Table 1 - Summary of the results obtained in the three experiments concerning to the comparisons between critical sequences in each experiment. There were six comparisons in each experiment, three for RTs and three for accuracy. A plus (+) sign is used when the results were in agreement with PRO or CMT predictions; a minus (—) sign is used to mark prediction/result disagreement.

Experiment/Critical Comparisons		Comparison of Predictions and Results			
		RTs		Accuracy	
		PRO	CMT	PRO	CMT
Experiment 1	$cC^{R\neq}$ vs $icC^{R\neq}$	+	+	+	+
	$cC^{R\neq}$ vs $icC^{R=}$	+	+	+	+
	$icC^{R\neq}$ vs $icC^{R=}$	+	—	+	—
Experiment 2	$cPO^{R\neq}$ vs $icPO^{R\neq}$	+	+	+	+
	$cPO^{R\neq}$ vs $icPO^{R=}$	+	+	+	+
	$icPO^{R\neq}$ vs $icPO^{R=}$	+	—	+	—
Experiment 3	$icIC^{R\neq}$ vs $cIC^{R\neq}$	+	—	—	—
	$icIC^{R\neq}$ vs $cIC^{R=}$	+	+	+	+
	$cIC^{R\neq}$ vs $cIC^{R=}$	+	*	+	*

*As stated in the purpose section of Experiment 3: We did not derive from CMT a specific pattern of differences regarding the comparison between $cIC^{R\neq}$ and $cIC^{R=}$ trials.

In Experiment 3, we found that performance in $icIC^{R\neq}$ trials was facilitated relative to $cIC^{R=}$ trials but not relative to $cIC^{R\neq}$ trials. This was only predicted by the PRO. According to this theory, in $icIC^{R\neq}$ trials, the goal of supressing the action plan is likely to yield an incorrect response, and the criterion identifying incorrectness that was activated in the *n*-1 IC trial is primed in the *n* IC trial. This results in a facilitated identification and suppression of the action plan, which is expected to yield an incorrect response in the second trial. However, a facilitation effect also occurred in the $cIC^{R\neq}$ trials, leading to a similar processing effort relative to the $icIC^{R\neq}$ trials. In $cIC^{R\neq}$ trials, the stimulus is presented in the same position as the stimulus presented in the *n*-1 C trial. In the *n*-1 C trial, both the direction-based and the position-based action plans were processed in order to compute the respective predicted response and outcome. Since the predicted response is the same for both plans, there is no activation of the goal of identifying and suppressing the plan that should yield an incorrect response. The position-based action plan and its predicted response are therefore primed in the subsequent trial. Accordingly, in an *n* IC trial repeating the stimulus position of the previous trial, when the suppression goal and incorrectness criterion are activated, there is already an active representation of the specific predicted response for the position-based action plan. The process of matching that representation to the incorrectness criterion and the suppression of the corresponding plan will therefore be facilitated. According to CMT, $icIC^{R\neq}$ trials should have been facilitated relative to cIC trials,

regardless of the response/position repetition in the C-IC sequences. CMT predictions were also countered by the pattern of data observed in Experiments 1 and 2. The similar processing effort of the $icC^{R\neq}$ and $icC^{R=}$ trials observed in Experiment 1 and of the $icPO^{R\neq}$ and $icPO^{R=}$ trials in Experiment 2 is mainly in accordance with PRO, countering CMT predictions. If lateral inhibition between incompatible responses played a significant role in conflict resolution, we should have found an impairment in $icC^{R\neq}$ and $icPO^{R\neq}$ trial processing relative to $icC^{R=}$ and $icPO^{R=}$ trial processing, respectively. Arguably, conflict resolution involves more-abstract representations, such as the action plans and expected response-outcomes that are advocated by PRO. These representations are quite far removed from representations of motor responses and do not involve mutually inhibitory connections.

The analysis of the full congruency type (2) x response repetition (2) design in Experiment 2 further helped resolve a possible confounding factor in Experiment 1. In fact, $icC^{R\neq}$ relative to $cC^{R\neq}$ differed both in *n*-1 congruency type and in position repetition ($cC^{R\neq}$ trials on opposite sides of the screen), while $icC^{R=}$ and $cC^{R\neq}$ differed both in *n*-1 congruency type and in response repetition (the $cC^{R\neq}$ trials bearing different positions). In Experiment 2, the use of different stimuli in the *n*-1 and *n* trials allowed us to include, in addition to a $cPO^{R\neq}$ condition corresponding to $cC^{R\neq}$ in Experiment 1, a $cPO^{R=}$ condition, without the problematic full stimulus-response repetition that would have occurred in $cC^{R=}$. This new condition creates a contrast with each icPO condition that is complementary, with respect to position repetition and response repetition, to that created by $cPO^{R\neq}$. Our results enable us to establish that *n*-1 incongruency hinders performance in the following trial, irrespective of whether there is response repetition and irrespective of which *n*-1 congruency type in a cPO vs icPO contrast bears a change or repetition in stimulus-position. This conclusion is based on the main effects found for *n*-1 congruency type in both RT and accuracy analyses, taken together with the fact that the significant interaction found in the RT analysis was not resolved by *n*-1 congruency type, with icPO trials being hindered relative to cPO whether there was response repetition (with icPO bearing position repetition and cPO position change) or response change (with icPO bearing position change and cPO position repetition). Experiment 2 also added to Experiment 1 by showing that this sequential incongruency effect is quite general, impacting the trial *n* even when the task changes (from response according to direction to response according to position) and the stimuli are different (arrows and circles). This generality of the hindrance effect caused by *n*-1 incongruency is arguably

better accommodated by PRO than by CMT. This is because PRO's explanation for sequential incongruency effects relies on the activation of goals and suppression criterion impinging on abstract action plans (e.g., "respond according to stimulus position") which are in fact task-general, while CMT proposes enhancement and inhibition mechanisms that are recruited in a manner quite specific with respect to the structure of a given task's stimuli and its mapping onto the response alternatives within that task.

Even though our data seem to be better explained by PRO, there are alternative theories that could at least in part account for our results. According to some authors (Mayr et al., 2003; Nieuwenhuis et al., 2006), trial-by-trial adjustments supposedly reflecting cognitive control can be explained by associative priming. Specifically, the sequence effects could be due to the occurrence of exact stimulus-response repetitions in IC-IC and C-C sequences (benefiting processing in the second trial) and response repetitions to different stimuli in IC-C and C-IC sequences (increasing difficulty while processing the second trial). In both Mayr et al. (2003) and Nieuwenhuis et al. (2006), the sequence effects were absent in a flanker task when only sequences without exact stimulus-response repetitions or partial stimulus-response repetitions were analysed. In our experiments, we did not analyse exact stimulus-response repetitions. Concerning the conditions with and without response repetitions, the presence of associative priming effects should have been responsible for an impairment in $icC^{R=}$ trials relative to $icC^{R\neq}$ due to response repetition without stimulus repetition, a pattern we did not observe. Accordingly, our results are not explained by associative priming.

Another associative theory, the theory of event coding (TEC) (Hommel, Musseler, Aschersleben, & Prinz, 2001), argues that when we perceive an object, there is a feature-binding mechanism responsible for registering and coding the perceivable features that integrate that object (e.g., the direction and position of an arrow). This integration or binding process is not restricted to stimulus features but includes combinations of stimulus and response features. The bindings created in the trial *n*-1 affect performance in the *n* trial, explaining the sequence effects (Hommel, 2009). According to this theory, when position-response and direction-response combinations partially mismatch the combinations occurring in previous trials, as in icC trials with response repetition, processing should be impaired when compared with situations of total alternation, as icC trials without response repetition. In total alternation sequences, the features of the trial *n*-1 are completely different from the features of the *n* trial, and

therefore, there is no need for a new binding process. However, we did not find any difference between icC trials with and without response repetition, which seems to counter TEC predictions.

Associative and conflict adaptation processes may arguably both contribute to the occurrence of sequence effects (Egner, 2008). Verguts and Notebaert (2009) integrated these two processing accounts by proposing the "association by binding theory", in which cognitive control is itself seen as a binding process. After conflict detection, the cognitive control system strengthens all active connections between target stimuli and task demand units. In the following trial, the interference of irrelevant information would be reduced due to a stronger binding between the task demand unit and the input units. This theory advocates that learning of stimulus–stimulus and of stimulus–response associations are key for conflict adaptation and are therefore compatible with PRO theory.

The results of our experiments suggest the existence of an interaction between top-down processing (necessary for conflict resolution) and bottom-up processing (response and/or position repetition), in accordance with previous studies that found that both top-down and bottom-up processes contribute to the sequence effects (Egner, 2007; Notebaert et al., 2006; Notebaert & Verguts, 2007; Wuhr & Ansorge, 2005). Our observations specifically unveiled a pattern of interactions between these processing streams that mainly support PRO's account of conflict resolution, in which the intervention of top-down processing is considerably more complex than in CMT's account. This does not mean that CMT should in any manner be excluded as a valuable cognitive control theory. As noted by Funes, Lupianez, and Humphreys (2010), the mechanism (e.g., enhancement of task relevant information; inhibition of task irrelevant information; goal structures for supressing action plans and the criterion to predict response outcomes) that is in fact used by the cognitive control system to overcome conflict probably reflects task specificities. We propose that CMT is inadequate to provide a detailed account of cognitive control processes as they unfold during conflict tasks in which irrelevant and relevant information are integrated in the same stimulus and irrelevant information is linked to a prevalent response, such as the spatial Stroop task. For tasks in which conflict presents a similar type of complexity, PRO arguably provides a better account of cognitive control processing.

Future studies using techniques such as functional magnetic resonance imaging (fMRI) could better define the brain network involved in conflict processing in the

spatial Stroop task. Also, our behavioural results suggest the development of event-related potential (ERP) studies as a means to probe the fine-grained temporal course of the sequence of events leading to conflict resolution in a spatial Stroop task. This would allow testing more-detailed hypothesis regarding the information processing events that resolve response conflict when relevant and irrelevant features for determining response are integrated within the stimulus.

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3. AGE-RELATED CHANGES IN COGNITIVE CONTROL: CONFLICT RESOLUTION AND SEQUENCE EFFECTS

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3.1. Abstract

Several studies suggest that cognitive control is negatively affected by ageing. However, it is not clear to what extent this effect results from changes in the actual structure of control processes, or from changes in general cognitive function parameters, such as processing speed. To clarify this issue, we used a spatial Stroop task to study the effect of ageing upon processing of low conflict trials impacted by the cognitive control setup implemented in previous high conflict trials. In consecutive trials, we used the level of conflict in trial *n-1* to manipulate the level of control in the n^{th} trial. Performance of young (N=20; *M*=19±2.026 years old) and older adults (N=20; *M*=63.45±6.21 years old) was compared. Participants responded to the direction of an arrow, while ignoring its position. Direction and position could be congruent (C; low conflict) or incongruent (IC; high conflict). We contrasted a low control condition, two C trials (cC) without response or position repetition, and two high control conditions, with a *n*-1 IC trial followed by a *n* C trial (icC) with and without response or position repetition. The icC trials should be negatively affected by conflict resolution in the previous trial. We observed age-related general slowing and increased interference, expressed by RTs. No age-related differences emerged for the effects of conflict level in the trial *n-1* upon performance in the n^{th} trial, suggesting that the cognitive control setup triggered by conflict does not change in nature and efficiency, but merely has its implementation slowed by ageing.

Keywords: Cognitive control; Inhibition; Controlled processes; Automatic processes; Spatial Stroop; Ageing

3.2. Introduction

Cognitive control comprises a set of processes that allow information processing and behaviour to adjust to our current goals (Botvinick et al. 2001; Miller and Cohen 2001). The activation of the anterior cingulate cortex and the dorsolateral prefrontal cortex (DLPFC), has been linked to cognitive control functions in human neuroimaging studies (Liotti et al. 2000; van Veen et al. 2001; Kerns 2006; Kerns et al. 2004; Vanderhasselt et al. 2009). According to these studies, the anterior cingulate cortex is responsible for cognitive control activation through conflict detection and the DLPFC is responsible for control implementation, enabling conflict resolution. Different explanations for cognitive control recruitment and implementation have been suggested (e.g., Conflict Monitoring theory, Botvinick et al. 2001; Prediction of Response-Outcome theory, Alexander and Brown 2011), but there is a general agreement that in conflict-tasks, such as the Stroop task (Stroop 1935), processing events occurring in the trial *n*-1 affect the processing of the n^{th} trial (Gratton et al. 1992; Kerns et al. 2004; Egner 2007). These effects were first described by Gratton et al. (1992) in the Eriksen Flanker task. They found slower and less accurate responses to congruent (C) trials preceded by incongruent trials (icC) relative to C trials preceded by other C trials (cC). They also found another, weaker, sequence effect: a faster and more accurate response to an incongruent (IC) trial preceded by another IC trial (icIC) relative to the response to an IC trial preceded by a C trial (cIC). These sequence effects became known as the *Gratton effect* and were later found with other conflict tasks, such as the Stroop task (Kerns et al. 2004; Egner and Hirsch 2005; Notebaert et al. 2006; Etkin et al. 2006), and again with the Eriksen Flanker task (Ullsperger et al. 2005; Verbruggen et al. 2006). In these studies, the Gratton effect was interpreted as resulting from maintenance of the cognitive control enhancement that occurred in trial *n*-1: detection of conflict on trial *n*-1 increases the level of control in that trial, in order to resolve the conflict; this accrued level of control is then inherited by the n^{th} trial, reducing the susceptibility to conflict therein. However, other authors proposed that cognitive control implementation does not require conflict detection but is merely a consequence of priming effects. Mayr et al. (2003) and Nieuwenhuis et al. (2006) did not find the Gratton effect after controlling stimulus/response repetitions in an Eriksen Flanker task and proposed that this effect can be explained by associative stimulus-response priming effects. Another alternative

account also explained this effect in terms of a stimulus–response association or binding (Hommel et al. 2001; Hommel 2009). According to this account, in each trial stimulus and response features are associated. If the pattern of associations created in the trial *n*-1 reoccurs with some changes in the n^{th} trial, as is the case of partial S-R repetitions, reaction times (RTs) will be slower than if the pattern of association is either maintained or completely changed, as in the case of full repetitions or full alternations. In accordance with this view, slower responses would be expected to cIC and icC relative to icIC and cC trials, respectively. Responding to this challenge to the conflict detection/control implementation account of the Gratton effect, other studies found this effect even when the stimulus-response repetitions were controlled for. Such studies were conducted using the Eriksen flanker task as well as other conflict tasks, like the Stroop or the Simon task (Sturmer et al. 2002; Ullsperger et al. 2005; Wuhr and Ansorge 2005; Verbruggen et al. 2006; Notebaert and Verguts 2006). Therefore, the Gratton effect cannot be explained just by associative priming effects or stimulus-response features' binding: the intervention of top-down control, responsible for conflict detection and cognitive control implementation, is seemingly justified as the source of the effect.

In responding to conflict trials, as in all instances of cognitive control recruitment, lower processing levels have to be modulated by the top-down control signal, thereby instantiating the intended conflict-resolving effect. Several theories pertaining to conflict resolution describe such lower level processes (Alexander and Brown 2010; Pires et al, in press). For instance, Botvinick et al (2001) describe a bias in bottom-up activation flow, favouring the connexions between the task-relevant stimulus' features and, therefore, the response associated with those features. In addition, lateral inhibition among features within the stimulus and response representation layers also contributes to conflict resolution in Botvinick's account. Alexander and Brown (2011) described a process involving activation of higher level symbolic representations, namely the criteria that identifies the response-plan with the lowest expected outcome (e.g., the incorrect response in a conflict task), thereby matching and determining the suppression of that plan. It should therefore be stressed that, even though conflict resolution is firstly enabled by controlled processing, which involves noticing the conflict and using the rules defining the task at hand, the actual processing set-up that does resolve the conflict consists of automatic processes: activation flow *via* enhanced connections, lateral inhibition, matching response plans to enhanced symbolic representations of response-

suppression criteria, inhibition of response plans. These automatic processes essentially capitalize on activation enhancement and inhibition. Bringing to the foreground the involvement of such automatic processes in cognitive control could have important consequences for the explanation of sequence effects in conflict tasks. Namely, given the pattern of enhanced/inhibited connections and representations that achieve conflict resolution in the *n*-1 IC trial, the ensuing pattern of priming is likely to have a deleterious effect if the subsequent trial is a C trial. This is because the irrelevant stimulus feature(s) that in the *n*-1 trial projected onto the incorrect response, in the n^{th} C trial contributes to the correct response activation. Another hypothesis could be that the criteria that identified and tagged for suppression the action plan leading to an incorrect response in the IC trial, improperly applies to the correct response in the C trial.

It is usually assumed that the Gratton effect results from the circumstance that the top-down controlled processes triggered in the *n*-1 IC trial, that implemented therein the automatic processes that resolved conflict, are themselves still active in the *n* C trial (Blais et al. 2014; Braver 2012). However, an alternative view is possible, namely one that bridges between this "sustained control" hypothesis and the classic alternative priming account (Hommel et al. 2001; Mayr et al. 2003; Nieuwenhuis et al. 2006), that we have previously discussed. Arguably, these top-down control processes do not linger from trial to trial; instead, the automatic processes that were implemented to resolve conflict in the *n*-1 IC trial affect the subsequent trial, under the form of a particular pattern of priming. These automatic processes would create a pattern of enhanced/inhibited connections and representations that impedes appropriate processing of the *n* C trial. We can cite, as consistent with this view, the conflict adaptation effect, observed for icIC trials, consisting in a reduction of activation of the anterior cingulate cortex (ACC) and enhanced activation of the DLPFC. The DLPFC increased activation in icIC trials would result from the fact that the criteria which identified the response plan with the lowest value in the *n*-1 IC trial (following Alexander and Brown 2011), represented in DLPFC, is primed in the n^{th} IC trial. This already enhanced activation is again augmented as the response plan leading to the incorrect response immediately matches that suppression criteria. In turn, ACC function, consisting in either conflict detection (Botvinick et al. 2001) or response-outcome prediction (Alexander and Brown 2010), is rendered redundant, which is consistent with diminished ACC activation in the n^{th} IC trial.

While studying cognitive ageing, examining the presence and nature of changes in cognitive control is particularly relevant for the understanding of both the cognitive ageing process and the nature of cognitive control. One established finding in cognitive ageing research is that ageing hinders functions that involve controlled processes, but not functions that involve automatic processes (Andres et al. 2008; Collette et al. 2009; Braver 2012). With respect to the observed age-related decline in cognitive control efficiency, it should be noted that changes in general cognitive parameters, such as processing speed, may yield effects that mimic age-related changes in specific processes, such as higher level cognitive control functions (Salthouse 1996; Lee et al. 2012).

Different conflict tasks have been used to study age-related changes in cognitive control. Studies with the Eriksen Flanker Task (Wild-Wall et al. 2008; Hsieh and Fang 2012) showed a general age-related reduction in processing speed but no age differences in accuracy, probably due, according to the authors, to an increased focus on the target by older adults. Studies with the Go-Nogo task (Falkenstein et al. 2002; Vallesi et al. 2009) supported a general age-related slowing (i.e., present for both Go and the Nogo conditions) and suggested a specific change in cognitive control, namely that older adults needed more resources to suppress irrelevant information. Specific age-related deficits in cognitive control have been suggested by other authors, on the basis of observed greater Stroop interference effects (West and Alain 2000; Mayas et al. 2012), a greater stop-signal reaction time (Anguera and Gazzaley 2012) and a greater Simon effect (Bialystok et al. 2004; Proctor et al. 2005; Castel et al. 2007) in older adults. Again, it could be argued that the relevant change does not affect the control process itself (i.e., its structure and the final efficiency of its implementation), but the time-course of its implementation, reflecting age-related general slowing.

To our knowledge, only a few studies analysed age-related modulations of the Gratton effect (Yano 2011; Puccioni and Vallesi 2012). Yano (2011) compared young (N=43; 30 women; *M*=19.8, *SD*=1.5 years old) and older adults' (N=14; 5 women; *M*=69.8, *SD*=3.1 years old) performance in a nonverbal Simon task. They found general slowing in older adults resulting in a higher magnitude of the Simon effect in older adults. Subsequent analysis of the Simon effect, after controlling for the general reduction in processing speed in older adults, showed equivalent Simon effects for young and older adults. In respect to the Gratton effect no differences between the age-groups were found. For both age groups there were faster RTs for cC trials relative to

icC trials and faster RTs for icIC trials relative to cIC trials. Puccioni and Vallesi (2012) studied age-related changes in a spatial Stroop task by comparing older adults (N=17; 8 women; *M*=73 years, range 69-79 years) and young adults (N=18; 9 women; *M*=24 years, range 18-34 years). They found a similar spatial Stroop interference effect in young and older adults. The analysis of the Gratton effect showed mixed results. For both age groups there were faster RTs for cC trials relative to icC trials. Concerning the icIC vs. cIC contrast, only older adults showed faster RTs for icIC trials relative to cIC trials. Both studies converge with respect to the presence, in older adults, of general slowing and, in both age groups, of similar deleterious effects in conflict trials. Results are however divergent in respect to age related modulations of the Gratton effect: whereas Yano (2011) found no effects of age group, Puccioni and Vallesi (2012) found evidence suggesting that older adults either achieved a stronger implementation of cognitive control, and were therefore able to take more advantage of conflict-conflict sequences (icIC), or, in the control cIC trials, they are less efficient in implementing a new cognitive control set-up to resolve conflict. The second hypothesis could be taken as more likely, since the icC deleterious counterpart of the icIC benefit found for older adults does not show a corresponding increase for this age group. The discrepancies pertaining to the existence of age-related differences in the Gratton effect, and the ambiguous meaning of the results that do seem to indicate that such differences exist, strongly suggest the need for more research on this topic. In particular, there is a possibility that these discrepancies and ambiguities reflect a contamination by sequence effects other than those pertaining to the conflict level in the trial *n*-1. That may be the case of the presence of response repetition or stimulus' position repetition in a sequence, which could modulate the effect on the n^{th} trial. Other potential confounding sequence effects, such as the benefit of full S-R repetitions, could also contribute to overshadow the true effects of ageing upon conflict related sequence effects. These latter effects should therefore be examined using a design that controls for response/stimulus position repetitions as well as for complete S-R repetitions. Accordingly, only trials without complete stimulus-response repetitions were used in the spatial Stroop task that we created to assess age-related changes in cognitive control. Also, three different types of C trials were considered while operationalizing the level of control in the n^{th} trial: cC trials without position nor response repetition ($cC^{R\neq P\neq}$, low conflict, low control); icC trials without response repetition and with position repetition ($icC^{R\neq P=}$, low conflict, high control) and icC trials with response repetition and without

position repetition (icC$^{R=P\neq}$, low conflict, high control). In our task, participants must respond to the left/right direction of an arrow while ignoring its left/right position on a computer screen (Funes et al. 2007; Luo and Proctor 2013; Luo et al. 2013). We analysed the Stroop interference effect in trials *n*-1, and the effect of *n*-1 congruency type on the n^{th} C trial, distinguishing icC sequences with/without response/stimulus position repetition.

For both older and younger participants, we expected to find a spatial Stroop interference effect in *n*-1 IC trials, reflecting the time consuming process of conflict detection, the activation of the appropriate control setup to overcome the present conflict, and the implementation of the control structure coded in that setup. This implementation would consist in establishing a specific pattern of enhanced/inhibited connections and representations. With respect to age-related changes affecting the magnitude of the Stroop effect, we expected to find greater interference effects in older adults, either because the top-down implementation of a control set-up is intrinsically impaired by ageing, or because this implementation requires more time than in young adults, due to a general reduction of processing speed. Evidence relevant for deciding between these two alternatives should be obtained from the data pertaining to the interaction between age-group and sequence effects. Generally, and irrespective of age, we expected that processing of both icC$^{R\neq P=}$ and icC$^{R=P\neq}$ trials would be impaired relative to cC$^{R\neq P\neq}$ trials. Theoretically, we assumed that this impairment emerges because the enhancement/inhibition of specific connections and representations that was implemented to resolve conflict in the *n*-1 IC trial creates a particular pattern of priming that impedes appropriate processing of a following C trial. Considering that positive/negative priming are prototypical automatic processes, we should find them well preserved in older adults. Therefore, less pronounced sequence effects in older adults (as compared to younger adults) would indicate an impairment in the controlled processes that, in the *n*-1 IC trial, should have implemented control as a lower level pattern of enhancements/inhibitions, and failed to do so appropriately. Accordingly, as for the interaction between sequence effects and age-group, we should consider two contrasting scenarios and corresponding predictions, pertaining to the preservation/impairment of control implementation in a conflict trial: (i) If the process of implementing control in IC trials is preserved in older adults, or merely delayed by generalized slowing, we should observe no age-related differences in the icC x cC contrast; (ii) If the process of implementing control in IC trials is hindered in older

adults (and not merely delayed by generalized slowing) we should expect an icC vs cC cost that is inferior in older adults to that observed in young adults.

3.3. Method

3.3.1. Participants

Twenty young adults (16 female; 18-26 years old, *M*=19, *SD*=2.03; 13-17 years of formal education, *M*=13.20, *SD*=.89), and twenty older adults (16 female; 55-74 years old, *M*=63.45, *SD*=6.21; 5-17 years of formal education, *M*=11.35, *SD*=3.31) participated in the study. Young adults were undergraduate Psychology students at the University of Coimbra (Portugal) that participated for course credit while older adults were community-living volunteers. Older adults were recruited in Aposenior (a university of the third age). All participants provided written informed consent in accordance with institutional guidelines. Exclusion criteria comprised current or previous diagnosis of a psychiatric or neurologic disorder, psychoactive medication use, brain injury, and uncorrected visual or hearing impairment. Participants were screened for depressive symptoms, using a cut-off of 20 points (i.e., moderate depression symptoms) in the Beck Depression Inventory II (Beck et al. 1996) and a cut-off of 19 points (i.e., mildly depressed) in the Geriatric Depression Scale-30 (Yesavage et al. 1982). They were also screened for cognitive impairment with the Addenbrooke's Cognitive Examination Revised (Mioshi et al. 2006). Young (*M*=95.85, *SD*=2.46) and older adults (*M*=94.10, *SD*=3.13) obtained similar results regarding the total score in this cognitive screening test (range 0-100 points), $F(38)=3.875$, $p=.056$, and the total score indicated no cognitive impairment for both age groups. The estimated intelligence quotient (IQ), as measured by the TeLPI - Irregular Words Reading Test (Alves et al. 2012), a Portuguese test similar to the National Adult Reading Test (Nelson and Willison 1992), was also obtained. There were comparable results for young (*M*=117.86, *SD*=3.18) and older adults (*M*=118.06; *SD*=5.95), $F(1, 38) < 1$, *ns*. In both age groups the estimated IQ was placed well within the average range for their age and education levels.

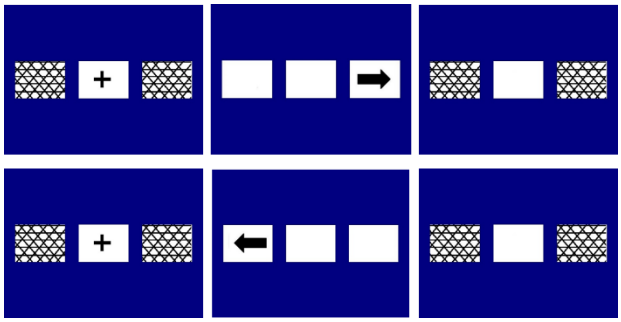
3.3.2. Materials and Procedure

Participants were tested with a computer running E-prime (Psychology Software Tools, Inc.; www.pstnet.com/products/e-prime/). They sat comfortably in front of a 17'' computer screen at a distance of 100 cm in a dimly lit room. During the task, three white boxes were horizontally displayed (at the right, middle and left of the computer screen) on a navy blue screen. The stimuli consisted of black arrows presented inside the lateral boxes. Participants were asked to maintain their fixation on the centre of the screen before the target was presented. They pressed a button held in their right/left hand, as indicated by the direction of an arrow stimulus, while ignoring its right/left position on the computer display. At the beginning of each trial, the fixation point (a cross displayed inside the box located in the centre of the screen) and two lateral boxes filled with masks were presented for 500 ms. Then, the fixation point disappeared from the central white box and the target appeared in the right or left lateral box and remained on-screen until the participant responded, with a time limit of 3000 ms. Participants' responses triggered the offset of the stimulus display, which was followed by an interval that could vary between 100 and 600 ms. During this interval, masks were displayed in the lateral boxes and the central box remained blank. Mask presentation was used to overcome afterimage effect issues (Pilling 2007). A second trial then began with the same structure as the first, starting with a fixation cross, and followed by the stimuli display. The stimulus offset of the second trial in a critical sequence was followed by a fixed interval of 1100 ms to prevent accumulated eye strain. During this interval masks were displayed in the lateral boxes and the central box remained blank. The difference in duration between interval within and between the critical sequences remained unnoticeable to participants, as confirmed during debriefing. The task comprised 664 trials that were presented in prearranged sequences of which participants were unaware, the succession of different trial types being perceived as random. The following conditions were studied in the experiment: $cC^{R\neq P\neq}$; $icC^{R\neq P=}$; and $icC^{R=P\neq}$ (see Fig 1 for a visual representation). Full stimulus-response repetitions (e.g., a C trial requiring the right response preceded by other C trials that required the same response) were not included (Mayr et al. 2003; Nieuwenhuis et al. 2006). In addition to the C and IC trials included in the critical sequences described above, we included, in non-critical sequences, position-only (PO) trials (i.e., trials in which the participant has to respond according to the position of black circles that do not convey any direction information).

In these trials participants pressed a button held in their right/left hand, as indicated by the circle's right/left position on the computer display. PO trials were introduced in order to reduce the possibility of developing facilitating strategies (e.g., focusing attention on the head of the arrow in order to systematically suppress spatial position information). These facilitating strategies are likely to reduce the spatial Stroop effect (Lu and Proctor 1995). The proportion of PO trials was kept low (11% of the total trials) in order to preserve the nature of the task. The inclusion of PO trials implied the presence of task-switching, as participants had to respond according to two instructions: respond according to the direction of an arrow and respond according to the position of a circle. To prevent a direct task-switching effect affecting the first trial (*n*-1) in a critical sequence, which could somehow affect RTs and the accuracy in the trial *n*, we controlled the type of trials *n*-2 (i.e., trials preceding *n*-1). PO trials never occurred immediately before trials *n*-1. Finally, the number and distance of PO trials appearing before critical sequences could not consistently differ between different conditions of the experiments, and a confounding variable could not therefore emerge. Other C and IC trials were combined with the PO trials in the filler sequences in order to balance C and IC proportions (44.58% each). The proportion of response types was also balanced in our task, with 50% requiring a left response and 50% requiring a right response. The experiment comprised three short breaks, dividing the overall duration of each participation into four parts. Each part was composed by an equal number of trials and the proportions of C, IC, and PO trials was kept stable in each part (166 trials, of which 72 were critical trials; overall: 74 C trials, 74 IC trials and 18 PO trials). The total time-on-task varied between 25 and 30 mins. Before engaging in the main task, participants performed 28 practice trials and were instructed to respond as quickly as possible while trying to avoid errors.

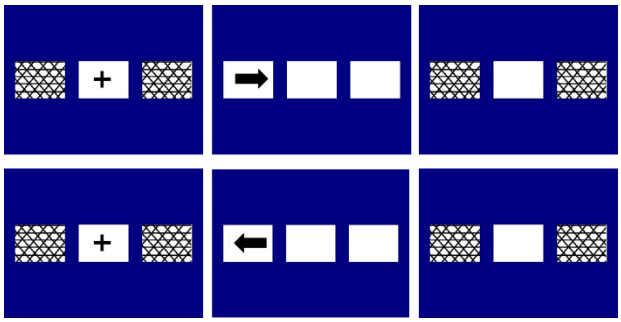
$cC^{R\neq P\neq}$

Sequence of a *n*-1 C trial and a *n* C trial in which *n*-1 and *n* trials require different responses and in which the stimulus position changed.



$icC^{R\neq P=}$

Sequence of a *n*-1 IC trial and a *n* C trial in which *n*-1 and *n* trials require different responses and in which the stimulus position was repeated.



$icC^{R=P\neq}$

Sequence of a *n*-1 IC trial and a *n* C trial in which *n*-1 and *n* trials require the same response and in which the stimulus position changed.

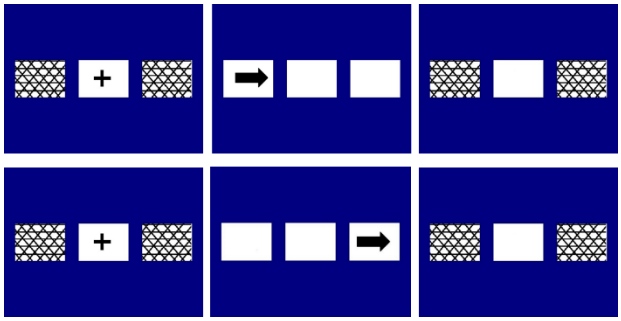


Fig 1 - Visual representation of the critical sequences under study: panels $cC^{R\neq P\neq}$, $icC^{R\neq P=}$ and $icC^{R=P\neq}$. Each sequence is composed of two trials, both represented in the corresponding panel: the first trial is shown in the upper line of the panel and the second trial in the bottom line.

3.3.3. Data analysis

Sequence effects were analysed by comparing three conditions ($cC^{R\neq P\neq}$, $icC^{R\neq P=}$ and $icC^{R=P\neq}$) in young and older adults. We analysed both RTs and accuracy results, by means of two 2 x 3 mixed analyses of variance (ANOVA), with the between-participants factor Age Group (young adults vs. older adults) and the within-participants factor Sequence Type: ($cC^{R\neq P\neq}$, low control, complete response-position mismatch vs. $icC^{R\neq P=}$, high control, position match vs. $icC^{R=P\neq}$, high control, response match). Pairwise comparisons were always performed using the Bonferroni correction. Possible confounding factors while examining sequence effects may emerge from the presence of error and post-error trials (Egner and Hirsch 2005), with faster reaction times associated to error trials (RTs; Ridderinkhof 2002) and slower RTs related with post-error trials (Rabbitt 1966). Thus, we excluded error and post-error trials from our analyses. This procedure excluded in young adults 6% of the responses. Less than one percent of the responses were excluded in the $cC^{R\neq P\neq}$ condition, while 11% were excluded in the $icC^{R\neq P=}$ as well as in the $icC^{R=P\neq}$ condition. In older adults this procedure excluded 7% of the responses. Two percent of the responses were excluded in the $cC^{R\neq P\neq}$ condition, while 10% were excluded in the $icC^{R\neq P=}$ condition and 9% were excluded in the $icC^{R=P\neq}$ condition. Anticipations (RTs less than 100 ms and RTs 3SD lower than the participant's mean for a given experimental condition) and lapses of attention (RTs more than 3SD higher than the participant's experimental condition mean) were also excluded. This cut-off procedure excluded in young adults 2% of the remaining responses with similar exclusion rates for the different conditions (2 to 3% in each condition). In respect to older adults' data, 2% of the remaining responses were excluded with similar exclusion rates for the different conditions (less than 2% in each condition).

In addition to the analyses of sequence effects, differences in the processing of C and IC trials were analysed in both young and older adults. A 2 x 2 mixed ANOVA, with the between-participants factor Age Group (young adults; older adults) and within-participants factor Congruency (Congruent; Incongruent) was conducted, for both RTs and accuracy. Trial *n*-1 responses in $cC^{R\neq P\neq}$ and $icC^{R\neq P=}$ sequences were used in these analyses as the critical C and IC trials. Trials *n*-2 were always C trials. Error and post-error trials were also excluded from the analysis. This procedure excluded in young adults less than 1% of the responses to C trials and 8% of the responses to IC trials. In

older adults this procedure excluded 1% of the responses to C trials and 11% of the responses to IC trials. Anticipations and lapses of attention were also excluded. This cut-off procedure excluded 1% of the remaining responses with similar exclusion rates for the different conditions and age groups. We used an alpha level of .05 for all statistical tests.

3.4. Results

3.4.1. Spatial Stroop effect

The C and IC trials' RTs and accuracy rates were compared before the analysis of the critical sequence effects (see Fig 2).

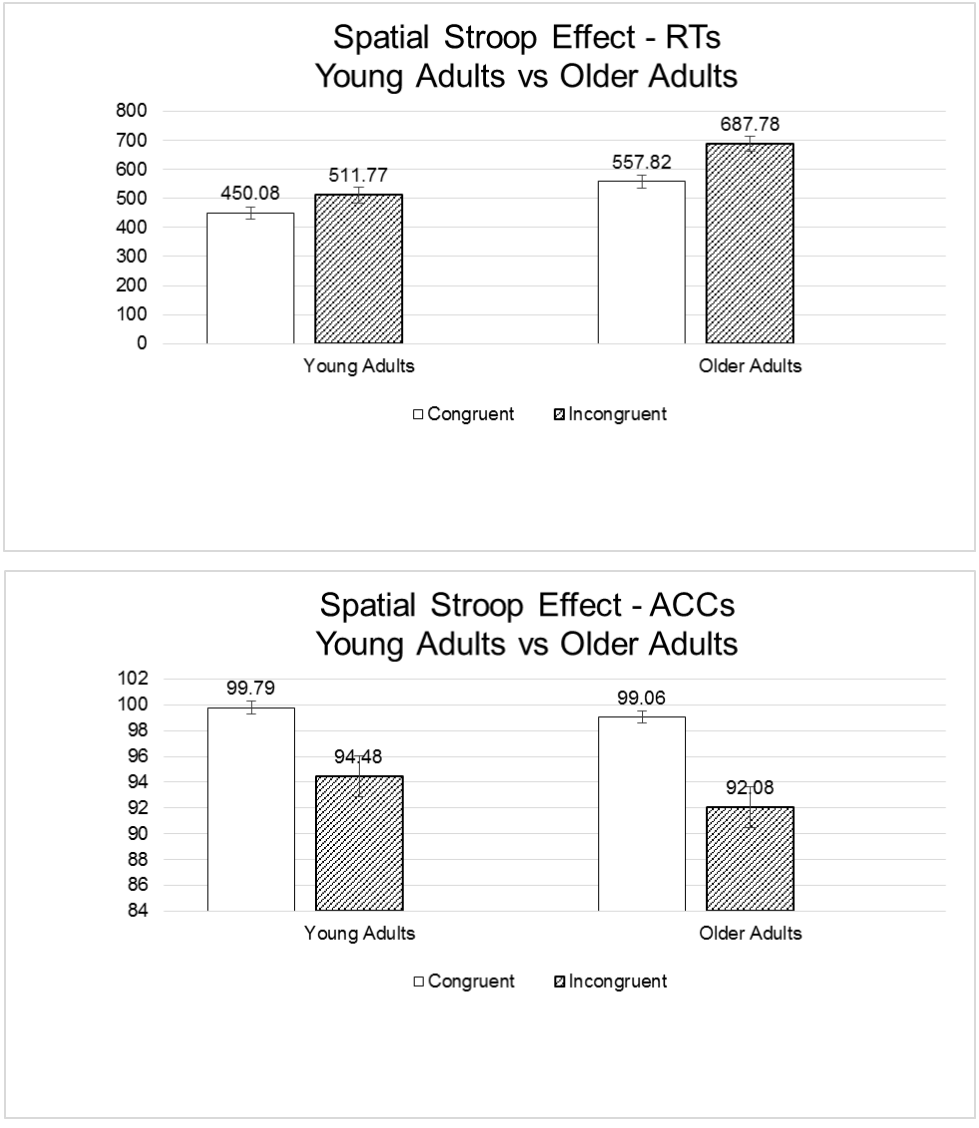


Fig 2. RTs and ACC (Mean) for young and older adults in congruent (white bar) and incongruent trials (pattern bar). Error bars represent the standard errors (SE).

A 2 x 2 mixed ANOVA, with the between-participants factor Age Group (young adults; older adults) and within-participants factor Congruency (Congruent; Incongruent) was performed for RTs. There was a main effect of age group, with young adults (M =481 ms, SD=73.72 ms) being 142 ms faster than older adults (M=623 ms, SD=150.13 ms), [F(1, 38)=18.387, p<.001, η^2p=.326]. There was also a main effect of congruency, with responses to C trials (M=504 ms, SD=107.07 ms) being 96 ms faster than responses to IC trials (M=600 ms, SD=148.74 ms), [F(1, 38)=134.090, p<.001, η^2p=.779]. There was a significant interaction between age group and congruency, [F(1, 38)=17.013, p<.001, η^2p=.309]. Inspection of follow-up univariate tests showed that this interaction resolves into the difference between the magnitude of the congruency effect in older adults [F(1, 38)=123.314, p<.001, η^2p=.764] and the magnitude of the congruency effect in young adults [F(1, 38)=27.789, p<.001, η^2p=.422], with the magnitude of the congruency effect in older adults being higher by a factor of 1.8. Another 2 x 2 mixed ANOVA, with the between-participants factor Age Group (young adults; older adults) and within-participants factor Congruency (Congruent; Incongruent), was conducted for ACC. No main effect was found for age group, with young adults (M=97 %, SD=4.07 %) being as accurate as older adults (M=96 %, SD=7.40 %), [F(1, 38)=1.556, p=.220]. There was a main effect of congruency, with responses to C trials (M=99 %, SD=2.02 %) being 6 % more accurate than responses to IC trials (M=93 %, SD=7.06 %), [F(1, 38)=33.446, p<.001, η^2p=.468]. There was no interaction between age group and congruency, [F(1, 38) < 1, *ns*]. Thus, in both age groups a reliable spatial Stroop effect was found relative to both RTs and ACC, with responses to IC trials being slower and less accurate than responses to C trials. Young and older adults differed in respect to the magnitude of the spatial Stroop effect on RTs, with a greater spatial Stroop effect in older adults due to a sharper increase of RTs in IC trials relative to C trials. Concerning ACC, There was no difference in the magnitude of this Stroop effect between young and older adults.

3.4.2. Sequence Effects

RTs and accuracy rates for each sequence condition are shown in Fig 3.

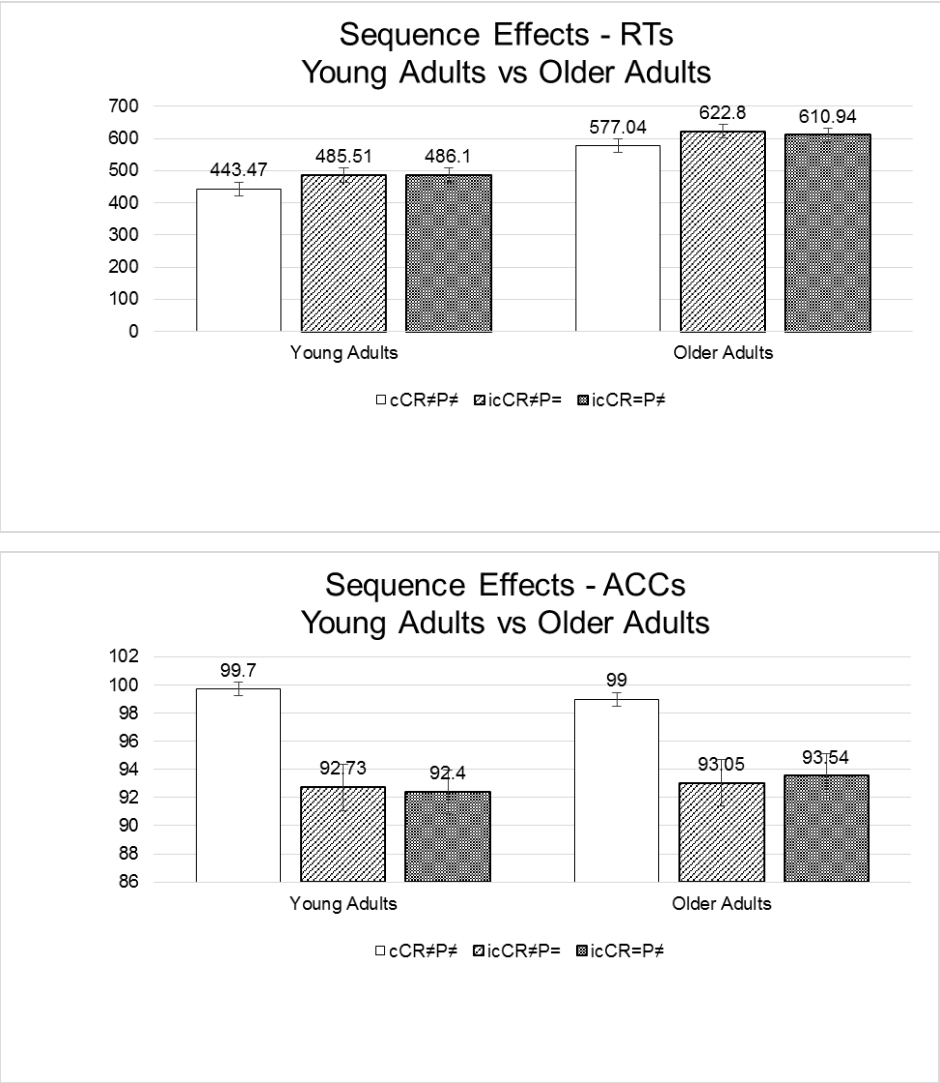


Fig 3 - RTs and ACC (Mean) for young and older adults in the three critical conditions: cC trials with response change and stimulus position change ($cC^{R\neq P\neq}$ - white bar); icC trials with response change and stimulus position repetition ($icC^{R\neq P=}$ pattern bar); icC trials with response repetition and stimulus position change ($icC^{R=P\neq}$ dark pattern bar). Error bars represent the standard errors (SE).

A 2 x 3 mixed ANOVA was performed for RTs, with the between-participants factor Age Group (young adults vs. older adults) and the within-participants factor Sequence Type: ($cC^{R\neq P\neq}$, low control, complete response-position mismatch vs. $icC^{R\neq P=}$, high control, position match vs. $icC^{R=P\neq}$, high control, response match). Mauchly's test indicated that the assumption of sphericity had been violated [$\chi^2(2) = 17.928$, $p<.001$]; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity ($\varepsilon = .723$). There was a main effect of age group, with young adults (M=472 ms, SD=71.1 ms) being 132 ms faster than older adults (M=604 ms, SD= 116.4 ms), [$F(1, 38)=20.157$, $p<.001$, $\eta^2p=.347$]. There was also a main effect of sequence type, [$F(1.445, 54.913)=25.716$, $p<.001$, $\eta^2p=.404$]. Pairwise comparisons showed that

responses to $cC^{R\neq P\neq}$ trials (*M*=510 ms, *SD*=115.4 ms) were on average 44 ms faster than responses to $icC^{R\neq P=}$ trials (*M*=554 ms, *SD*=119.2 ms), [*t*(38)=10.459, *p*<.001], and 38 ms faster than responses to $icC^{R=P\neq}$ trials (*M*=549 ms, *SD*=113.3 ms), [*t*(38)=4.811 *p*<.001]. The 6 ms difference between $icC^{R\neq P=}$ and $icC^{R=P\neq}$ trials' RTs was non-significant, [*t*(38) < 1, *ns*]. The interaction between age group and sequence type was also non-significant, [*F*(1.445, 54.913) < 1, *ns*]. A 2 x 3 mixed ANOVA, with the between-participants factor Age Group (young adults vs. older adults) and the within-participants factor Sequence Type: ($cC^{R\neq P\neq}$ vs. $icC^{R\neq P=}$ vs. $icC^{R=P\neq}$), was also performed for ACC. Mauchly's test indicated that the assumption of sphericity had been violated [$\chi^2(2) = 6.296$, *p*<.05]; therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (ε =.865). No main effect of age group was found [*F*(1, 38) < 1, *ns*]. There was a main effect of sequence type, [*F*(1.729, 65.718)=28.708, *p*<.001, $\boldsymbol{\eta}^2p$=.430]. Pairwise comparisons showed that responses to $cC^{R\neq P\neq}$ trials (*M*=99 %, *SD*=2.1 %) was 6% more accurate than response to $icC^{R\neq P=}$ trials (*M*=93 %, *SD*=7.3 %), [*t*(38)=5.814, *p*<.001], and also 6% more accurate than response to $icC^{R=P\neq}$ trials (*M*=93 %, *SD*=6.9 %), [*t*(38)=6.250, *p*<.001]. The difference between $icC^{R\neq P=}$ and $icC^{R=P\neq}$ trials' accuracy was non-significant, [*t*(38) < 1, *ns*]. The interaction between sequence type and age group was non-significant, [*F*(1.445, 54.913) < 1, *ns*]. Thus, older adults were slower but were as accurate as young adults in response to all sequence types. The comparison between the sequence types showed that the processing of $cC^{R\neq P\neq}$ trials was faster and more accurate than the processing of both $icC^{R\neq P=}$ and $icC^{R=P\neq}$. This pattern was the same in young and older adults.

3.5. Discussion

A deficit in cognitive control function is a hallmark of ageing (Braver and Barch 2002; West 2004; Lucci et al. 2013; Aschenbrenner and Balota 2015). The present study investigated whether this effect is explained by the impact of ageing upon the actual structure of cognitive control processes or if it is explained by age-related changes in general cognitive functions, such as processing speed. To clarify this issue, we compared the performance of young adults and older adults in a spatial Stroop task in which we evaluated possible age-related effects in the interference effect and in the Gratton effect.

As expected, we found a significant interference effect for both RTs and ACC (Lupiáñez and Funes 2005; Luo et al. 2010; Luo and Proctor 2013). Thus, responses to IC trials were slower and less accurate than responses to C trials, due to conflict detection and resolution in IC trials. The interference effect found in spatial Stroop tasks is usually weaker than the interference effect found in the colour-naming Stroop task and usually less than 50 ms (Hilbert et al. 2014). However, in our study the interference effect was higher than expected in both groups (i.e., 62.27 ms for young adults and 134.53 ms for older adults). The presence of PO trials, making position relevant throughout the task, probably amplified conflict in the IC trials. Concerning age-related effects, older adults were slower than young adults in both C and IC trials thus supporting the established age-related general slowing effect (Salthouse 1996). There was also an interaction between age group and congruency in respect to RTs, with a higher magnitude of the interference effect in older adults compared to young adults. However, concerning ACC there were no age differences confirming that efficiency of inhibitory processes is preserved in the elderly population. These results suggest that the top-down control process that prompts conflict resolution in IC trials is not specifically impaired by ageing but instead impacted by reduced processing speed.

In respect to the Gratton effect, we focused on the contrast between $cC^{R\neq P\neq}$ trials, a low control condition and two high control conditions, the $icC^{R\neq P=}$ trials and the $icC^{R=P\neq}$ trials. Our results replicated findings from previous studies (Botvinick et al. 2001; Notebaert et al. 2006; Notebaert and Verguts 2007; Yano 2011; Puccioni and Vallesi 2012), with increased RTs and lower ACC in icC trials (regardless of response/stimulus position repetition) relative to cC trials (without response/stimulus position repetition), implicating that the processing of a *n*-1 IC trial has a deleterious effect on the processing of a *n* C trial.

In relation to ageing effects, we found a reduced processing speed that affected older adults' performance in all conditions. Still, the pattern of sequence effects was the same in both age groups. This result indicates that the processes involved in these sequence effects are slowed-down, but their efficiency remains unchanged with ageing, an observation consistent with the view that the processes underlying conflict-related sequence effects are essentially automatic in nature (namely positive/negative priming), and therefore well preserved in the face of ageing, as suggested by Yano (2011). Furthermore, this absence of age-related differences in the icC x cC contrast also suggests that the controlled processes that occurred in the IC trial, responsible for

putting in place the pattern of priming causing the Gratton effect, were equally efficient in younger and older adults. Taken together with the observation that a greater interference effect for older adults occurs in the RT but not in the ACC data, the age invariance of the Gratton effect strongly indicates that the process of implementing control in IC trials, while delayed by generalized slowing, is well preserved in older adults.

Overall, our results support the co-existence of top-down-control and bottom-up automatic processes in the spatial Stroop task that are differently affected by ageing. Top-down controlled processes are delayed in older adults relative to young adults, and it is this delay that constitutes the substance of the increased interference effect observed in older adults.

Compliance with Ethical Standards

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Conflict of Interest: Luís Pires declares that he has no conflict of interest. José Leitão declares that he has no conflict of interest. Chiara Guerrini declares that she has no conflict of interest. Mário Simões declares that he has no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the University of Coimbra (Portugal) research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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“And now that you don't have to be perfect, you can be good.”

(John Steinbeck)

DISCUSSION

The research work presented in this thesis aimed to clarify the complex nature of EF while addressing the effects of ageing upon these functions, at two levels of analysis: the structural level (see Part I) and the processing level (see Part II). For each level we presented theoretical and empirical studies. At the structural level, the deployment of EF in different cognitive tasks was investigated in order to examine the functional dependencies within the EF system, thereby contributing to a better characterization of that system, either as a unitary system or as a "multicomponents" system, comprising several related but autonomous functions. At the processing level, inhibition and specifically its role in cognitive control was studied. Ageing studies, pertaining to both the structural and processing levels, were conducted to elucidate the nature of the age-related changes in these functions, while contributing as well to the understanding of the basic processing underpinnings of EF and cognitive control. Before discussing some key topics relating to this research, we present in a brief summary the main findings pertaining to the two levels of analysis considered in this thesis. We further present in this summary a tentative integration of these findings.

1. Main Findings: a brief summary

Part I - Structure of Executive Functions: Main findings

In the study described in section 2 of Part I, the fit of five factorial models with data gathered with nine neurocognitive tests was compared. *A priori*, and according to the theoretical grounding and standard uses of the tests, the nine tasks included in the neuropsychological test battery assessed EF, nEF pertaining to verbal abilities (VA), and processing speed (PS). A three-correlated factor model (EF, VA and PS) was the most appropriate to our data. All the tests loaded in the expected factor according to their theoretical grounding, except for the Verbal Fluency test that loaded in VA factor and not in the EF factor. Four tests loaded in the EF factor: the Stroop test, Working Memory, the Tower test and Divided Attention. The Tower test and the Divided Attention test, did not show an adequate loading. Three tests loaded in the VA factor: Verbal Fluency, Word List and the Confrontation Naming test. Two tests loaded in the PS factor: the Coding test and the Telephone Search test. EF was found to be related to

PS but surprisingly was not related to VA. This was interpreted as an indicator of the existence of a different EF system for VA that is not measured by traditional EF tests, like those loading in the EF factor. PS was related with VA suggesting that PS is indeed a relevant mediator of performance in all cognitive tests. In the study described in section 3 of Part I, performance of older adults and young adults in a comprehensive neuropsychology test battery was compared. The tests assessed of processing speed, selective and divided attention, verbal and spatial working memory, inhibition, verbal fluency (i.e., semantic, phonemic and shifting verbal fluency conditions), planning, abstraction, verbal episodic memory, confrontation naming and sentence comprehension. Older adults showed a slowing in processing speed and deficits in the measure of inhibition, the Stroop test. Older adults and young adults showed a similar performance in several measures, suggesting no age-related changes in long-term retention, recognition, confrontation naming, sentence comprehension, abstraction, verbal and spatial working memory, selective and divided attention and cognitive flexibility (i.e., verbal fluency shifting condition). In the Tower test mixed results were found. Older adults performance was worse than that of young adults in some indicators (i.e., more rules violations and more time per movement), similar to that of young adults in other indicators (i.e., total achievement score), and they achieved better results than young adults in others (i.e., needed less movements to complete the towers, being more accurate). After controlling for inhibition and processing speed, the variable "age group" was not related to most of the measures in which an age-related difference had been previously found. These findings highlight that a deficit in inhibition and a reduced processing speed can indeed account for most of the age-related changes found in this study. Taking into account the results found in the study described in section 2 of Part I, it seems that ageing affects performance in PS measures but not performance pertaining to VA and to most of the EF abilities. The exception within the EF is inhibition, as measured by the Stroop test, in which older adults showed a poorer performance than young adults. There were also other EF tests in which performance was impaired in older adults relative to young adults, but these deficits were again related to inhibition and processing speed. Deficits in inhibition can justify the increased number of rule violations in the Tower test found for older adults. The other age-related changes are in direct association with reduced processing speed (more time needed to complete the Telephone Search and the Dual Task Telephone Search tests, increased time per movement in the Tower test and reduced performance in the Coding test).

These results also contribute to a better understanding of the three-correlated factor model found in the study described in section 2 of Part I. The small sized factor loadings found for Divided Attention and for the Tower test reflect the complexity of these tasks, with both EF and nEF functions contributing to task performance. These tests depend on processes of which some are preserved and others impaired in the face of ageing. This suggests the existence of diversity among the processes needed for an adequate performance.

Part II - Processing of Executive Functions: Main Findings

In section 2 of Part II we presented a study in which three experiments were conducted to contrast two theories of cognitive control: The Conflict Monitoring Theory (CMT) and the Prediction of Response-Outcome (PRO) theory. To fulfil this aim, sequence effects were studied in a spatial Stroop task, by manipulating congruency in *n*-1 and *n* trials, as well as response repetition in the n^{th} trial. Our findings showed that both bottom-up and top-down control processes contribute to cognitive control implementation, with evidence suggesting that these top-down processes are involved in the suppression of response plans with undesirable expected outcomes. The pattern of sequence effects found across the three experiments mainly supported the PRO theory. According to this theory the existence of multiple possible responses generates a conflict situation that must be resolved. Cognitive control is implemented by identifying and suppressing the action plans associated with an unacceptable cost (e.g., an error). This leaves only the most appropriate action plan available for selection, resolving conflict. In the study described in section 3 of Part II, we examined age-related changes in cognitive control. Young and older adults' performance in a spatial Stroop task was compared. Two measures of cognitive control were used: the Stroop interference effect and sequence congruency effects. We found an increased Stroop interference effect in older adults' RT data, relative to young adults. However, with respect to accuracy rates, no differences in the Stroop interference effect were observed between age groups. Concerning sequence effects, the pattern of RTs and accuracy rates were the same in older and young adults, with cC trials being faster and more accurate than icC trials, regardless of response repetition. Our findings suggest that, while general processing speed decreases with ageing, there is substantial preservation of the effectiveness of cognitive control processes, as captured by conflict resolution and congruency sequence effects in a spatial Stroop task. This study's results also suggest a different nature for

the processing underpinnings of interference resolution and sequence effects. The processes involved in interference resolution arguably rely on controlled processes that are impaired with ageing, due to their serial nature and, therefore, strict dependency on processing speed. In turn, sequence effects probably result from automatic processes, such as the pattern of positive/negative priming that follows the enhancement of relevant information and the inhibition of irrelevant information, which, as they do not require any serial processing, should not reflect age-related cognitive slowing to a significant extent.

After this brief reminder of the main findings in the empirical studies reported in this thesis, we will proceed by discussing some key topics relating to our research. We will also present a tentative overall integration of our different findings, taking in account previous research reviewed in the theoretical studies presented in this thesis (studies described in section 1 of Part I and section 1 of Part II). Three topics are addressed: (i) unity and/or diversity of executive functions; (ii) ageing studies as a window to a better understanding of executive functions; (iii) executive functions and pathological ageing. Finally, the strengths and limits of the research presented in this thesis are discussed and implications pertaining to future research are examined.

2. Unity or/and Diversity: a single executive function or different executive functions

Our findings, in general, support a view of the EF system that emphasises the diversity and relative autonomy within this set of functions. At the structural level, only two EF were strongly linked to an EF factor (i.e. inhibition and working memory) while other EF were either poorly related or unrelated (i.e., planning and divided attention), or even more related to nEF (like memory and language) than to EF (i.e., verbal fluency). There were also distinct associations of PS to different EF, as measured by the tests in use in our study (Salthouse, 2005; Salthouse, Atkinson, & Berish, 2003). Performance in PS measures was related to performance in the Stroop test but not to performance in the Working Memory tests. The EF factor was unrelated to the VA factor comprising verbal fluency, verbal episodic memory and naming abilities. This was not expected and it can suggest the existence of independent EF systems, one linked to

linguistic/semantic processing and another, more general, related to inhibition and updating of information processed out of the scope of the lexical and syntactic systems (Abrahams et al., 2003; DeDe, Caplan, Kemtes, & Waters, 2004). The results found in the ageing study pertaining to the structural level of analysis (section 3 of Part I) also support a diverse nature of EF. Our results are in agreement with previous research (Andres, Guerrini, Phillips, & Perfect, 2008; Belleville, Rouleau, & Van der Linden, 2006; Collette & Salmon, 2014), indicating that some EF are more vulnerable to the effects of ageing than others. This further supports their diverse nature. For example, older adults showed impaired performance in the Stroop test (in comparison with young adults' performance) but not in the divided attention measure. At the processing level, there is arguably a repetition of this diversity, with the same function being implemented by different computations and courses of processing. This is illustrated by the case of inhibition. While reviewing ERP studies of inhibition (see section 1 of Part II) we found many "inhibitions" (Collette, Schmidt, Scherrer, Adam, & Salmon, 2009; Kok, 1999). For example, inhibition of irrelevant sensory information occurs before 200 ms post-stimulus while other types of inhibition, like the suppression of irrelevant word information in a Stroop task can occur as late as 800ms post-stimulus. Also, inhibition processes linked to conflict resolution are distinct across different conflict tasks (Tillman & Wiens, 2011). For example, inhibition processes necessary for conflict resolution in the Eriksen Flanker Task, in which the irrelevant information is physically apart from the relevant information (i.e., flanker on the sides, target in the middle) seem to be distinct from the ones that are needed for conflict resolution in a Stroop task, in which both relevant and irrelevant information are integrated in the same stimulus. As highlighted by Funes, Lupianez, and Humphreys (2010), different tasks may rely on different control systems. The different role proposed for inhibition in different cognitive control theories also contributes to highlight its diverse nature (see section 2 of Part II). According to the Conflict Monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001) conflict is resolved by means of lateral inhibition within the response and stimulus layers, and by attentional enhancement of the pathways connecting relevant stimulus features with the trial-appropriate response. Differently, according to the Prediction of Response-Outcome theory (Alexander & Brown, 2011) conflict is resolved by inhibition processes that occur at a more abstract level, suppressing incorrect action plan(s). This may be an indication that each of these different theoretical proposals, however general in aim, partially reflects the specific

nature of the tasks that inspired its formulation, and, therefore, of the diverse inhibitory processes recruited during task performance.

Even if our results are mainly in line with the conception of EF as essentially multiple in nature, the existence of "nuclei" of unitary EF cannot be discarded (Duncan & Owen, 2000). At the structural level, different EF tests loaded in the same factor. Other studies that used factor analysis to investigate the underlying factor structure different EF tests found the same commonality among the EF tests (Brydges, 2012; Miller, Giesbrecht, Müller, McInerney, & Kerns, 2012; Wiebe, Espy, & Charak, 2007). This suggest the presence of a large group of common mechanisms that prevail in these tasks. It remains unclear if this common mechanisms belong to a general EF system or simply reflect common nEF. At the processing level, processes that are seemingly distinct, may in fact comprise significant overlapping, which may indicate that they share, to some extent, the same stages. In a conflict task, premotor inhibition processes precede motor inhibition that is followed by evaluation processes (Lavric, Pizzagalli, & Forstmeier, 2004). This suggests the existence of executive functions responsible for selecting and sequencing subordinate processes, corresponding to a "unification" level of executive processing, at least to some extent or in some situations.

3. Ageing studies: a window into executive functions

Ageing affects selectively some executive processes while sparing others (Collette & Salmon, 2014; Verhaeghen & Cerella, 2002). The two ageing studies presented in this thesis highlight age-related changes in EF and cognitive control processing but also contribute to a better understanding of the nature of these processes (e.g., controlled vs automatic). At the structural level, we found a clear pattern indicating that older adults present impaired processing in some EF tests/measures but not in others. These support the existence of different EF. At the processing level, we found that a general processing slowing found with ageing may be the reason for age-related cognitive-control impairments, which therefore would not be specifically affected by ageing (Salthouse, 1996; Salthouse et al., 2003). For example, older adults need more time to process both incongruent trials and congruent trials and, while their RTs reflects greater impairment in incongruent than in congruent trials, the accuracy rates remain similar to

those of young adults in both types of trial. Also, no differences were found in the pattern of RTs and accuracy rates pertaining to sequence effects, despite slowed down RTs for older adults across all conditions. So, ageing does not seem to influence the effectiveness of the control system itself but the time-course of its implementation, a circumstance that would selectively impair the stages of this implementation that are serial in nature and spare those that do not requiring serial processing. This suggest, as noted by Yano (2011), that the processing underpinnings of sequence effects rely on automatic processes, which are devoid of serial structure. Taken together, these results suggest that studying age-related patterns of impaired/spared processes is a particularly appropriate strategy for probing the nature of executive functions and cognitive control processing.

4. Executive functions and pathological ageing

Our findings contribute to a better understanding of EF and cognitive control processing and have some clinical implications. As highlighted in this thesis in normal ageing there is specific deficits in executive functions rather than a general decline (Crawford et al., 2000; Lin et al., 2007). Several diseases may change the natural course of ageing. In pathological ageing conditions, like dementia associated to Alzheimer's disease or depression, it is usual to find executive deficits (Nigg, 2000). Deficits in EF have been described as one of the first deficits to emerge in dementia associated to Alzheimer's disease (AD; Perry & Hodges, 1999). A deficit in the ability to inhibit irrelevant information has been found, which impacts on the patients' ability to perform their daily lives activities (Amieva et al., 2004). So, inhibitory processes, that are an essential feature of EF, are key for a better comprehension of the cognitive changes occurring in the natural course of AD. Deficits in EF are also common in late-onset depression (defined as depression occurring among patients aged 60 years and older) (Kohler et al., 2010). Depressed older adults often experience preservative responses and deficits in initiating behaviour and in inhibiting inappropriate responses (Alexopoulos et al., 2005). A better understanding of EF and cognitive control processes may disclose important information to clarify the profile of cognitive and functional dysfunction in these disease and suggest new forms of treatment.

5. Strengths and limitations of the present research

At the structural level, our study of a multiple domain neuropsychological battery, including both tests pertaining to EF and to nEF, proved to be useful for a better understanding of EF. Since these functions cannot be studied independently from the functions that they regulate and coordinate, the study of test batteries comprising just EF tests does not suffice to better comprehend EF. At the processing level, the study of sequence effects in a spatial Stroop task while manipulating response/position repetition allowed us to tell apart two theories of cognitive control, contributing to a better understanding of the mixed results that can be found in the literature concerning sequence congruency effects (Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014; Egner, 2007; Nieuwenhuis et al., 2006; Notebaert & Verguts, 2007; Schmidt, Notebaert, & Van den Bussche, 2015; Smith, Smith, Provost, & Heathcote, 2010). The ageing studies at both levels of analysis contributed to better define the pattern of preserved/impaired functions in older adults, while also contributing for a clarification of the nature of EF as a diverse set of functions that are differently affected by ageing. Despite these positive contributions, the research presented in this thesis does have limitations that must be acknowledged. Namely, even though a better comprehension of the construct validity of the neuropsychological tests employed in the confirmatory factorial analysis study was achieved, the use of just nine measures did not allow to appropriately address all aspects of EF and their relation to nEF. Since each of the neuropsychological tests involves multiple functions (i.e., task-impurity problem), a latent-variable approach (Friedman & Miyake, 2004, 2017; Miyake et al., 2000) would be more appropriate to study the relationship between EF and other functions. At the processing level, the study of sequence effects without the inclusion of complete stimulus-response repetition can be considered a limitation, since previous studies usually examined all the possible transitions and only a posteriori assessed the presence of sequence effects without considering full repetitions. Also, a better comprehension of cognitive control processes could be achieved using a different spatial Stroop task, one that would allow the comparison between stimulus-stimulus and stimulus-response conflict resolution. Also, the use of a cross-sectional approach in the ageing studies does not allow a clear definition of age-related changes, but only the comparison of age

groups. Thus, longitudinal studies are essential for the characterization of age-related changes in EF.

6. Future Studies: What's next?

Throughout this thesis some future studies were suggested to fulfil gaps in our current understanding of EF and to overcome limitations in our own studies. In this research, we selected a battery of tests often used in clinical neuropsychology. There has been countless progress in psychological assessment, but the existing neuropsychological tests pertaining to EF assessment are still not sufficient nor adequate. Specifically, new test batteries should be developed in order to make possible an assessment of EF that takes into account the dependencies between EF and nEF tasks, and would therefore allow an appropriate differentiation of control functions and cognitive domains requiring control.

Although it is clearly the case that considerable theoretical and empirical progress has arisen in the past years regarding EF and their processing underpinnings, there are still aspects of the nature of EF that remain poorly understood. Future studies need to address the possible existence of different EF systems (e.g., the existence of a semantic executive system). Also, it will be important to examine if the age-related modulations found in controlled processes, responsible for the implementation of control, are not merely a reflection of cognitive slowing.

In our challenging environment, EF are vital to our adaptation. In this thesis we highlight processing underpinnings of EF but more research will be necessary to define their role not only in cognitive control but also in emotional regulation.

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"Act as if everything depended on you; trust as everything depended on God."

(St Ignatius of Loyola)

APPENDIX

Table A. A brief description of the neuropsychological tests

Addenbroke's Cognitive Examination Revised (ACE-R)
ACE-R is a clinical assessment instrument that was developed as a brief cognitive assessment test. ACE-R integrates Mini Mental State Examination (MMSE; the most used brief cognitive assessment test) but extend the cognitive domains assessed by it including memory, language and executive function assessment. Specifically, this test consists of 5 sub-results, each one representing one cognitive domain: attention/orientation; memory; fluency; language; and visuo-spatial capacity.
Geriatric Depression Scale 30-items (GDS-30)
This scale was specifically developed to assess depression in elderly, focusing in affective and behaviour symptoms and excluding others symptoms that can be confounded with somatic diseases or dementia.
Beck Depression Inventory II (BDI-II)
This scale measures severity of depression with 21 multiple-choice questions. Each answer is scores from 0 to 3 and highest scores indicate increase depression severity.
Irregular Words Reading Test (TeLPI)
It is an intelligence quotient (IQ) estimation test composed by 46 irregular words that must be read aloud by the participants. Each correct words' reading receives one point and each reading error receives zero points. The number of errors in the TeLPI and the number of years of formal education of the participant are used to estimate IQ.
Inventory for functional assessment in adults and older adults (IAFAI)
This inventory was developed to assess functional incapacity for both basic and instrumental daily activities (familiar and advanced). It permits the assessment of different functional domains as degree of difficulty in each everyday task, the level of assistance and identify the use of external aids (modified independence).
Coding (from Wechsler Adult Intelligence Scale - Third edition ─ WAIS-III)
In this test the examinee must copy symbols previously associated with numbers, in a predetermined matrix. There is a time limit of 2 mins. The total score is the number of correct items within the time limit, ranging from 0 to 133 points. It is commonly used as a processing speed measure.
Word List (from Wechsler Memory Scale - Third edition ─ WMS-III)
In this verbal memory test, the examiner orally presents a first word list with 12 words that must be memorized by the participant. There are four immediate recall essays. Then the participant must memorize a second (interference) word list with 12 new words that is recalled just once. Then the participant must recall again the first word list (Short Term Recall). After 25/30 mins the participant must recall again the first word list (Long Term Recall) and if the participants are not able to recall the full word list they must do a recognition test, in which they identify the 12 words belonging to the first word list

from a group of 24 words (the 12 words from the first word list and 12 new words).
Verbal Fluency – Phonemic, Semantic and Shifting Fluency (from Delis–Kaplan Executive Function System ─ D-KEFS)
This test evaluates the spontaneous production of words under restricted search conditions. In Phonemic Fluency the examinee must produce orally as many words as possible beginning with specified letter during a fix period of time (one minute). In Semantic Fluency, the examinee must produce orally as many words as possible in a certain semantic category during a fix period of time (one minute). In the Shifting Fluency task the examinee must alternate between two semantic categories (for ex., fruits and furniture) during a fix period of time (one minute).
Confrontation Naming (from Psycholinguistic Assessment of Language ─ PAL)
This task evaluates the ability to name by visual confrontation, involving recognition of the visual elements (lines, bars, dots and curves) of a figure. There are 44 items.
Sentence Comprehension (from PAL)
In this test a sentence is shown with two images. Only one of the images reflects the accurate comprehension of the sentence and the subject must choose what image will be the correct for the sentence present. There are 56 items.
Telephone Search task, Dual Task Telephone Search, Divided Attention measure (from Test of Everyday Attention ─ TEA)
The Telephone Search task is a simple search of a telephone directory page for certain symbols. The participants are instructed according to a hypothetic scenario. The participants are on a trip and have to look in the telephone directory for a number of different services (plumbers, restaurants or hotels). Beside each entry, two symbols (star, square, circle or cross) indicate certain ratings for these services, and the ones which suit the participants best are always pairs of identical symbols – i.e., two stars, two circles, two cross or two squares. When they notice these pairs of identical symbols, they have to circle them with a water-based coloured pen. The participants are asked to work as quickly, and as accurately as possible. When they finish the task, they have to make a mark in the square at the bottom right hand corner of the pages. Once they marked the box, they are not allowed to make any further marks on the sheet, and the timing is stopped. The Dual Task Telephone Search is another simple search task that is performed in combination with a second task: counting strings of tones presented on a tape recorder. The participants are instructed to perform both tasks as accurately as possible. A Divided Attention measure can be obtained by combining the scores for this and the previous task.

Digit Suppression Test (DST) *and Block Suppression Test* (BST)
These tests are commonly used as working memory measures. In the DST, the participants must repeat every second digit of a sequence of digits orally presented by the examiner, beginning with the first digit (e.g., 1-7-4 repeats 1-4; 1-5-7-8 repeats 1-7). The trial starts with a sequence of 3 digits and the length of the sequences increases until 16 digits are reached. There is a total of 28 items, two for each level. The task ends when the participant fails to correctly recall the digits of the two items of the same level (i.e., same sequence length). The BST is the spatial version of the DST, the participants must tap every second block of a sequence of blocks tapped by the examiner, beginning with the first block. The blocks are tapped by the examiner in a 1 sec pace. The task ends when the participant fails to correctly tap the blocks in the two items of the same level.
Stroop Colour-Word test
This test involves the presentation of a stimulus that has conflicting sources of information. In the Stroop condition, the participant is required to name the colour in which a word is printed when the word itself is a different colour name. It is commonly used as an inhibition measure. Other conditions can be also administered in which the participant is required to read black colour-words and name the colour ink of horizontal bars.
Tower test (from D-KEFS)
This Tower test comprises 9 towers. The participants see photographs of the towers to be built. They have a wooden board with three vertical pegs and the necessary disks to build each tower. They must follow two rules: (i) move just one disk at a time, using only one hand; (ii) never place a larger disk on a smaller disk. The towers have to be constructed using as few movements as possible and there is a time limit for each tower. It is commonly used as a planning measure.
Similarities (from WAIS-III)
This test evaluates abstract verbal reasoning. Participants have to say in what way two verbal stimulus are similar (e.g., "In what way are an orange and a banana alike?").

Table B. Pearson correlation coefficients between the neuropsychological tests. For each neuropsychological measure the correlation coefficients are shown in descending order, from the largest to the smallest. Correlation coefficients between the neuropsychological tests and age [*r*(Age)] are also shown (N=40; 18-74 years old).

Neuropsychological measures		*r*	*r(Age)*
Word List	Immediate Recall	.691** - Word List – Short Term Recall .677** - Word List - Long Term Recall .505** - Coding .484** - Stroop Total score -.462** - Telephone Search Time .436** - Word List – Retention -.403** - Dual Task Telephone Search .372* - Tower - Total Movements -.366* - Stroop Time .361* - Tower - Time per Movement .349* - Semantic Fluency .348* - Tower - Total Violations .335* - Block Suppression Test	-.470**
	Short Term Recall	.861** - Word List - Long Term Recall .691** - Word List – Immediate Recall .650** - Word List – Retention .522** - Coding .488** - Stroop Total score -.487** - Telephone Search Time .422** - Word List – Recognition -.386* - Stroop Time .349* - Semantic Fluency	-.454**
	Long Term Recall	.881** - Word List – Retention .821** - Word List – Short Term Recall .677** - Word List – Immediate Recall .561** - Stroop Total score .551** - Word List – Recognition .486** - Coding -.454** - Telephone Search Time -.362** - Stroop Time .321* - Semantic Fluency	-.394*
	Retention	.881** - Word List – Long Term Recall .656** - Word List – Short Term Recall .549** - Stroop Total score .535** - Word List – Recognition .436** - Word List – Immediate Recall -.416** - Telephone Search Time .353* - Coding	NS
	Recognition	.551** - Word List – Long Term Recall .535** - Word List – Retention .422** - Word List – Retention .413** - Stroop Total score .386* - Tower - Total Violations	NS
Verbal Fluency	Phonemic Fluency	.676** - Semantic Fluency -.389* - Tower - Movements Accuracy	NS
	Semantic Fluency	.676** - Phonemic Fluency .349* - Word List - Immediate Recall .344* - Confrontation Naming .335* - Word List – Short Term Recall .321* - Word List - Long Term Recall	NS

Shifting Fluency (%)	NS	NS
Confrontation Naming	.344* - Semantic Fluency	NS
Sentence Comprehension	.392* - Stroop Total score -.380* - Telephone Search Time .341* - Coding .313* - Digit Suppression Test	NS
Similarities	NS	NS
Block Suppression Test	-.323* - Stroop Time .590** - Digit Suppression test .392* - Stroop Total score .371* - Tower - Total Movements -.371* - Telephone Search Time -.367* - Tower - Total Violations .335* - Word List - Immediate Recall .316* - Tower - Achievement score .314* - Divided Attention .312* - Telephone Search Total	NS
Digit Suppression Test	.590** Block Suppression Test .448** - Tower - Achievement score .345* - Divided Attention -.331* - Tower - Movements Accuracy .325* Stroop Total score .313* Sentence Comprehension	NS
Coding	-.679** - Telephone Search Time .614** - Stroop Total score -.600** - Tower - Total Violations -.544 - Tower - Time per Movement -.540** - Stroop Time .522** - Word List - Short Term Recall .505** - Word List - Immediate Recall -.501** - Dual Task Telephone Search Time .486** - Word List - Long Term Recall .451** - Tower - Total Movements .406 - Telephone Search Total .353* - Word List - Retention .341* - Sentence Comprehension	.790**

Stroop	Total	.614** - Coding -.587** - Telephone Search Time .561** - Word List - Long Term Recall .549** - Word List - Retention -.544** - Stroop Time -.505** - Tower - Total Violations .488** - Word List - Short Term Recall .484** - Word List - Immediate Recall .475** - Tower - Total Movements -.465** - Tower - Time per Movement .439** - Telephone Search Total -.434** - Dual Task Telephone Search .392* - Block Suppression Test .392* - Sentence Comprehension .336* - Tower - Achievement score .325* - Digit Suppression Test	-.539**
	Time	-.544** - Stroop Total score -.540** - Coding -.416** - Tower – Total Movements -.386* - Word List - Short Term Recall .372* - Dual Task Telephone Search Time -.366* - Word List - Immediate Recall -.362* - Word List - Long Term Recall .351* - Telephone Search Time .335* - Tower – Total Violations .330* - Tower - Time per Movement -.323* - Block Suppression Test	.421**

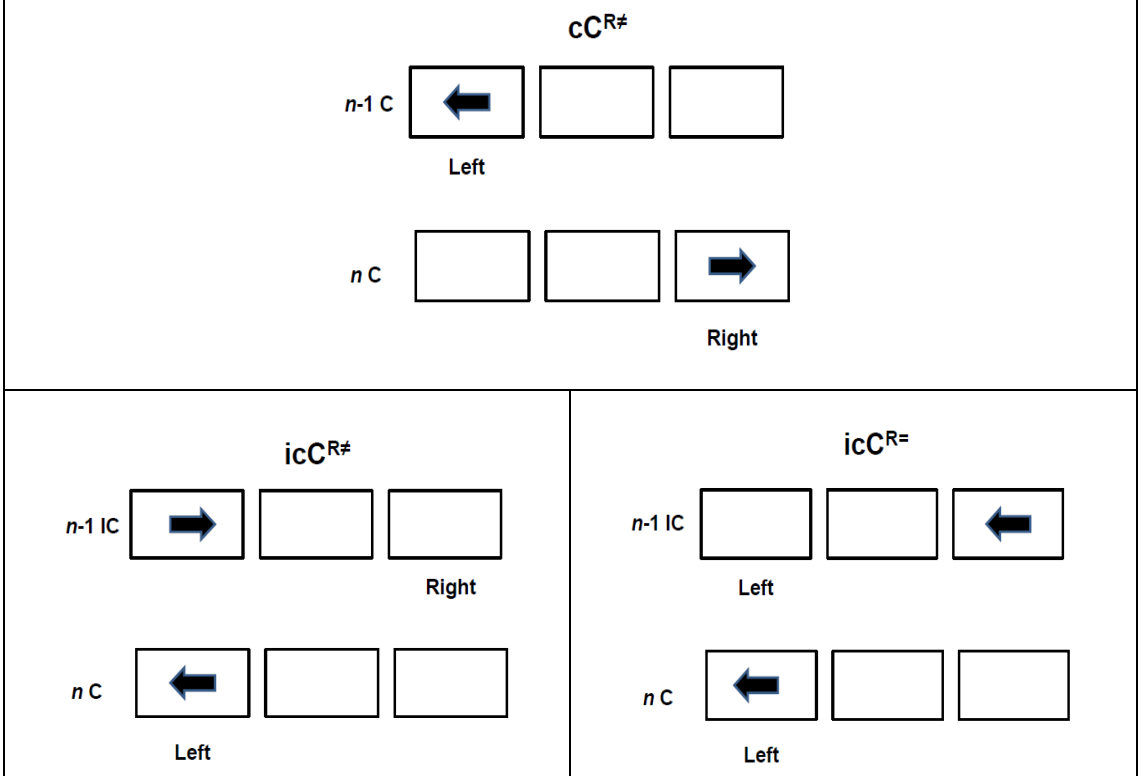
Telephone Search	Total	-.591** - Tower - Total Violations .557** - Dual Task Telephone Search Total .439** - Stroop Time .406** - Coding .312* - Block Suppression Test	NS
	Time	-.679** - Coding .669** -Dual Task Telephone Search Total -.587** - Stroop total score -.487** - Word List - Short Term Recall -.470** - Tower - Total Violations -.462** - Word List - Immediate Recall -.454** - Word List - Long Term Recall .431** - Tower - Achievement score -.416** - Word List - Retention .394* - Tower - Time per Movement -.380* - Sentence Comprehension -.371* - Block Suppression Test .351* - Stroop Time	.481**
Dual Task Telephone Search	Total	.557** - Telephone Search Total -.543** - Tower Total Violations	NS
	Time	.669** - Telephone Search Time -.501** - Coding -.434** - Stroop Total score -.403** - Word List - Immediate Recall -.382* - Tower - Total Movements .372 - Stroop Time .339* - Tower - Time per Movement	.353*
Divided Attention		.345* - Digit Suppression Test .340* - Tower - Achievement score .314* - Block Suppression Test	NS

Tower	Achievement score	.448** - Digit Suppression Test -.432** - Tower- Movements' accuracy .340* - Divided Attention .336* - Stroop Total score .316* - Block Suppression Test	NS
	Total Movements	-.643** - Tower - Total Violations -.561** - Tower - Time per Movement .504** - Tower - Movements' Accuracy .475** - Stroop Total score -.470** - Telephone Search Time .451** - Coding -.416** - Stroop Time -.382* - Dual Task Telephone Search Time .372* - Word List - immediate Recall .371* - Block Suppression test	-.544**
	Total Violations	-.643** - Tower - Total Movements .613** - Time per Movement -.600** - Coding -.591** - Telephone Search Total -.543** - Dual Task Telephone Search Total -.505** - Stroop Total score .431** - Telephone Search Time -.386* - Word List - Recognition -.367* - Block Suppression Test -.348* - Word List - Immediate Recall .335* - Stroop Time	.550**
	Movements' Accuracy	.504** - Tower - Total Movements -.432** - Tower - Achievement score -.389* - Phonemic Fluency -.341* - Tower - Time per Movement -.331* - Digit Suppression test	-.334*
	Time per Movement	.613** - Tower - Total Violations -.561** - Tower - Total Movements -.544** - Coding -.465** - Stroop Total score .394* - Telephone Search Time -.361* - Word List - Immediate Recall -.341* - Tower - Movements' Accuracy .339* - Dual Task Telephone Search Time .330* - Stroop Time	.474**

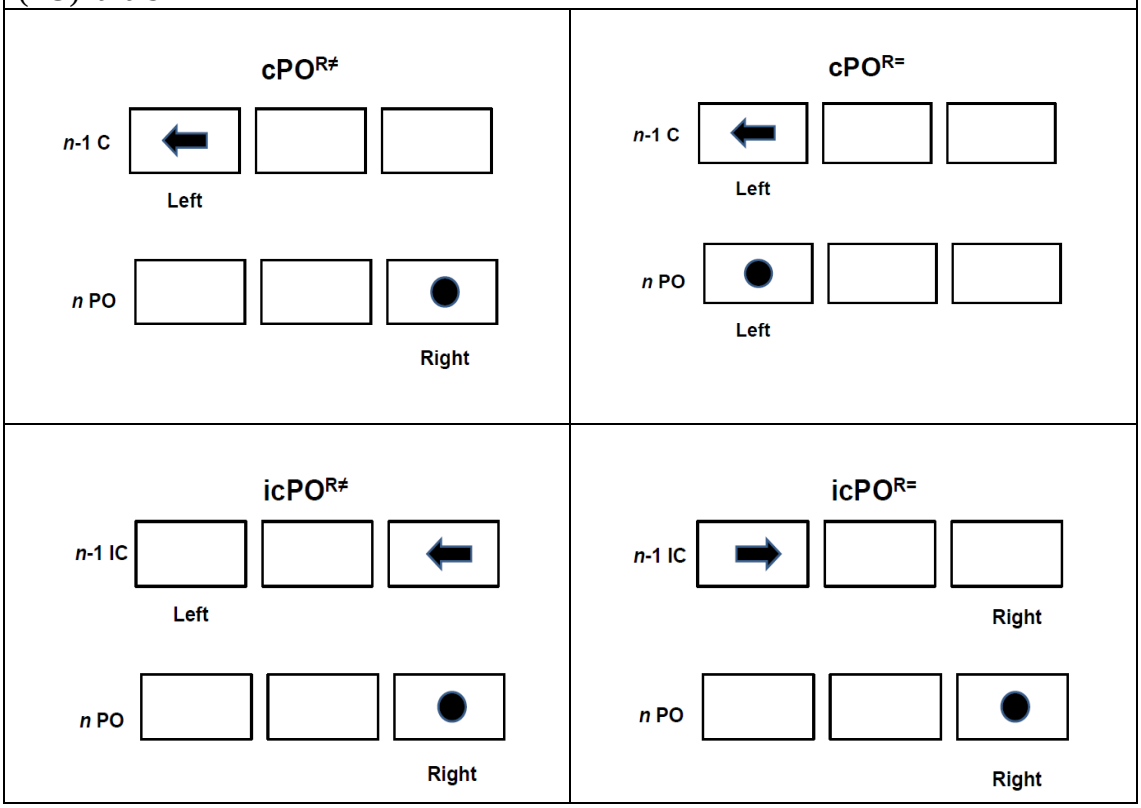
NS – Non-significant; *p<.05; **p<.01

Table C - Visual representation of the different critical sequences studied in three Experiments.

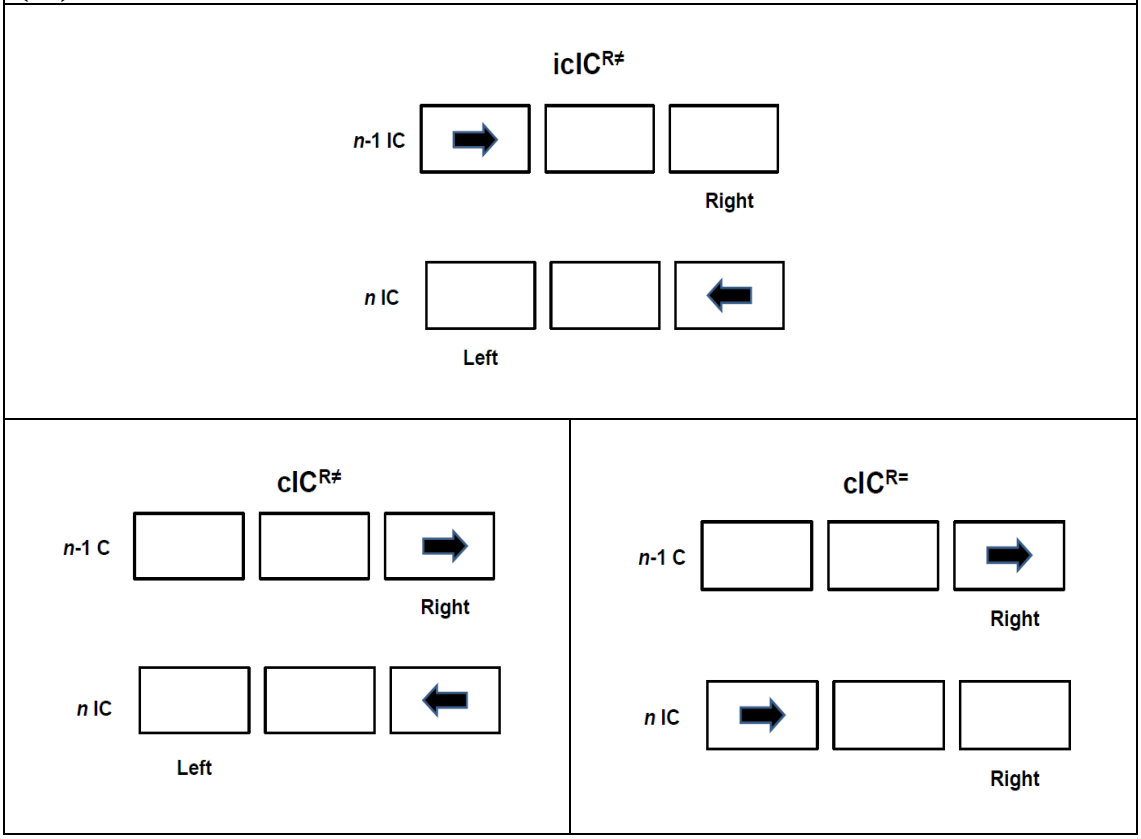
Experiment 1: Visual representation of sequence effects on current (*n*) Congruent (C) trials



Experiment 2: Visual representation of sequence effects on current (*n*) Position-Only (PO) trials



Experiment 3: Visual representation of sequence effects on current (*n*) Incongruent (IC) trials



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