COGNITIVE CONTROL:
BEYOND PRIMING,
IN AGING
AND ACROSS DOMAINS.

Candidate
Olga Puccioni

Supervisor
Dr. Antonino Vallesi

Thesis submitted for the degree of Philosophiæ Doctor
in Cognitive Neuroscience
at International School for Advanced Studies, Trieste, Italy
Academic Year: 2013/2014

A Mamma e Babbo
My nature and my nurture
Per avermi dato basi, sostegno e possibilità

Summary

Abstract

This research project aimed to address many issues related to cognitive control, such as its relationship with repetition priming, its modification in older adults and whether it can be considered a general supra-modality mechanism or rather a set of domain specific ones. The cognitive control mechanism is a top-down modulation involved in conflict resolution processes that is supposed to facilitate the discrimination between signal and noise, or targets and distractors. In the present project cognitive control was investigated through the analysis of congruency (Stroop) and sequential congruency effects with a modification of verbal and spatial Stroop paradigms that exclude the priming confound in two consecutive trials. Results revealed that both congruency and sequential congruency effects are strongly modulated by repetition priming in a verbal Stroop task, whereas a spatial Stroop is only marginally influenced.

The comparison of conflict measures and conflict-related ERPs showed that the mechanisms involved in the verbal and spatial tasks are only partially comparable.

Both tasks showed congruency effects consistent with previous findings, while sequential congruency effects are apparent in the spatial Stroop performance but are reduced in the verbal task with respect to what is reported in previous studies. In the verbal task we pointed out that cognitive control is likely to detect not the actual conflict level but rather the conflict level change in the present trial with respect to the preceding one and consequently adjust attentional resources, exerting a direct influence on performance. On the other hand, some previous studies suggested that whenever a task presents a high conflict level a proactive inhibition state is activated in order to prevent automatic responses. The results from the spatial Stroop task suggested that the attentional regulatory mechanism for spatial conflict is likely to modulate this proactive inhibition default state on the basis of the preceding trial congruency. In this domain the modulations due to preceding trial congruency and the one due to current trial congruency do not interact in determining ERP components, and this probably generates the strong conflict sequential effects seen in the behavioural performance.

Many cognitive aging theories assume a progressive decline in frontal brain areas and many authors reported an age-related deficit in conflict resolution abilities in

varied conflict-related tasks, which goes beyond the general slowing showed by older adults. We investigated the effects of normal aging on cognitive control in the verbal and spatial domains, highlighting the fact that the age-related general slowing can account for most of the difference found between younger and older adults, and that the verbal congruency effect is the only measure that suffers from a specific decline. Moreover intelligence and cognitive reserve (CR) seemed to partially account for the inter-individual variability in conflict resolution performance, especially in cognitive aging.

Finally, the hypothesis of a general, supra-domain cognitive control mechanism is discussed, since evidence reported in the present project rather supports the existence of more domain specific sub-mechanisms of cognitive control.

Chapter 1 – Introduction

1.1. Cognitive Control

Everyday several kinds of information are simultaneously processed by our brain, which has to execute its numerous functions while respecting the principle of energy efficiency. To maintain the highest possible all our cognitive skills would improve our performance on the short time, but it will not be possible during all our waking hours. In order to optimize our performance over time our central nervous system must provide a mechanism able to manage its cognitive resources appropriately.

This mechanism has been identified with the cognitive control, which, has "to coordinate thoughts and actions in relation with internal goals" (Koechlin, Ody & Kouneiher, 2003).

Cognitive control has indeed to regulate many cognitive abilities. In this thesis we focused on his role in modulating the conflict resolution related processes.

Such processes involve many aspects of selective attention, therefore in this introduction part we also provide a broad overview starting from the selective attention concept.

Selective attention is the ability to choose, among several kinds of information coming from the environment, only those that are targets of current goals, and to ignore those that are not relevant (Houghton & Tipper, 1994; Neill, 1977). Attentional processes are modulated by *'Top-down'* and *'Bottom-up'* regulations, which represent functional principles rather than anatomical systems, and in most situations they interact to optimize attentional performance (Egeth & Yantis, 1997).

Bottom-up facilitation: the repetition priming

Bottom-up attentional modulations are mainly driven by the physical characteristics of the target stimulus and its sensory context (Treisman & Gelade, 1980). Such processes underlie the subject's ability to detect targets using primarily the sensory salience of the targets themselves, as well as the ability to focus attention by recruiting 'higher' cortical areas in a bottom-up manner (e.g., from the processing of a visual target in the primary visual cortex to inferior temporal regions for object identification and to parietal regions for location) (Sarter, Givens & Bruno, 2000).

Specifically, *repetition priming* refers to facilitation in speed, accuracy, or bias, relative to an appropriate baseline, in processing a stimulus that has been already experienced previously.

Repetition priming is further dissociable into perceptual and conceptual forms (e.g., Blaxton, 1989; Roediger, Weldon, & Challis, 1989). Perceptual priming reflects implicit memory for the stimulus' *physical properties* and is reduced when there is a study-test change in stimulus form. Perceptual priming is, therefore, modality-specific (Brown, Neblett, Jones, & Mitchell, 1991; Durso & Johnson, 1979; Jacoby & Dallas, 1981; Keane, Gabrieli, Fennema, Growdon, & Corkin, 1991; Lachman & Lachman, 1980; Park & Gabrieli, 1995). For example, in a word-stem completion task, when stems are visually presented, the priming is reduced if in the study-phase words are heard (Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995; Graf, Shimamura, & Squire, 1985). Within the same modality, perceptual priming is reduced when there is a study-test change in the physical nature of the stimulus (e.g., a picture of a cat and the word *cat* are two different visual notations of the same concept). Conceptual priming, in contrast, reflects implicit memory for stimulus *meaning*. It is possible to dissociate perceptual and conceptual priming, because manipulations made on sensory modality and physical features affect the perceptual priming, but exert no effects on the conceptual one; on the contrary, the manipulation of the conceptual encoding can modulate the conceptual priming, but not the perceptual one (Gabrieli et al., 1999). Such functional dissociations between perceptual and conceptual priming, seem to reflect the existence of two kinds of implicit memory systems that belong to separate neural networks. Indeed, visual priming for words and pictures has been associated to visual regions of the occipital cortex (e.g., Blaxton et al., 1996; Blaxton et al., 1999; Buckner et al., 1995; Fleischman et al., 1995; Gabrieli et al., 1995; Keane et al., 1995; Schacter, Alpert, Savage, Rausch, & Albert, 1996; Squire et al., 1992). For what concerns other sensory modalities, the observations are much fewer with respect to the ones related to the visual system, but it is likely that auditory and tactile priming reflects plasticity in auditory and somatosensory regions, respectively. On the other hand, conceptual priming has been tied to left frontal and temporo-parietal brain regions (Blaxton et al., 1996; Demb et al., 1995; Gabrieli et al., 1996; Raichle et al., 1994; Swick & Knight, 1996).

Bottom-up interference: negative priming

When a stimulus that had to be ignored in a previous trial becomes the target of the current trial, a response slowing usually takes place. This effect is known as negative priming (NP; Lowe, 1985; Tipper, 1985; Tipper & Driver, 1988). NP is a robust and general phenomenon that has been extensively reported across a wide range of stimuli, domains and task demands (see Fox, 1995; and May, Kane, & Hasher, 1995, for reviews). NP can persist over several seconds and it can also occur after many intervening trials (DeSchepper & Treisman, 1991; May et al., 1995; Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991; Treisman, 1992), especially when distracting stimuli are repeated several times (Malley & Strayer, 1995). Two main accounts have been proposed to explain NP: selective inhibition and episodic retrieval.

The selective inhibition account (Tipper, 1985) states that when a certain feature is coded as a distractor, it gets immediately inhibited, thus reducing the neural activity of its representation. Such inhibition persists for a certain amount of time, therefore whenever in the following trial that feature becomes relevant, it is harder to re-activate its representation, leading to a slowing of the response speed. According to some authors (Tipper et al. 1991), this phenomenon is due to the fact that usually what is not relevant in a natural environment, rarely becomes important in a short time. Therefore negative priming is an adaptive mechanism.

The episodic retrieval account assumes a backward memory process (Neill, Valdes, & Terry, 1995) based on Logan's theory of automatization (Logan, 1988): he proposed that the representation of a stimulus feature automatically evokes its last presentation (episode). This representation contains multiple types of information, such as the relevance of the feature and the response associated to it, which for a distractor was in fact a non-response.

The classic Stroop paradigm is one of the most used tasks when conflict-related and inhibitory processes are investigated. Its classic version consists naming the ink colour of words that indicate colour names (e.g., "green" written in yellow) (Stroop, 1935).

The classic Stroop paradigm is indeed frequently used task to explore NP, taking advantage of the fact that distractor and target features rely on different perceptual categories, although both visually presented (i.e., one is a written word and the other

one is a colour). Nevertheless, empirical evidence has shown that NP occurs despite physical changes in stimulus features from prime to test trials, including changes from uppercase to lowercase letters (Allport et al., 1985, Lowe 1985), from pictures to words (Driver & Tipper, 1988), across sensory modalities (Driver & Baylis, 1993; Greenwald, 1972) and from word or picture to its semantic associates (Allport et al., 1985; Tipper, 1985; Yee, 1991).

It seems that when task demands involve feature comparison, NP can be associated with early perceptual features of ignored objects (DeSchepper & Treisman, 1991), whereas, when the task requires a stimulus categorization, NP can be correlated with the semantic properties of the ignored object (Tipper & Driver, 1988). Furthermore, when subjects have to directly reach for a target object, NP seems to be associated with action-centred internal representations of the non-target object rather than with its perceptual or semantic properties (Tipper et al., 1992). Considering all these lines of evidence, Tipper and colleagues (Milliken et al., 1994; Tipper et al., 1994) suggested that the processing of an object leads to the development of multiple perceptual representations relative to its different properties such as colour, location and identity. These authors suggest that the inhibition of ignored information can then be directed to any of these representational domains, depending on the current goal states. This flexibility of inhibitory mechanisms seems coherent with the finding that NP from a distractor's colour, location, or identity is modulated by the explicit goal of the task (Tipper et al., 1994). In fact when the task-goal is to indicate the *location* of a target object, the location of the ignored distractor, but not its identity, produces a NP effect. Conversely, if the task consists into *identifying* a target object, the distractor's location does not produce NP. However, it is important to note that significant NP from the identity of ignored distractors was also not observed when the task required responding to the identity of a target, contrarily to what is predicted by the episodic retrieval hypothesis. Therefore the apparent flexibility of NP effects may be due to the fact that a mismatch between prime and probe displays is more salient when such a mismatch occurs between a prime and a probe of the same level of representation. Similarly, the level of representation required to respond to the probe target is likely to provide a more salient memory cue for previously ignored information at the same level of representation.

Top-down attentional regulation: the cognitive control

Top-down attentional processes consist of knowledge-driven mechanisms aimed to boost the neuronal processing linked with the current important sensory inputs. The aim of these processes is to ease the discrimination between signal (target) and noise (distractors), and to guide the subject to focus on the locations in which relevant signals are more likely to appear (Kastner & Ungerleider, 2000). If the presentation of targets and distractors follows a regular rule, the subject becomes quickly able to calculate the probability of appearance of the target; this knowledge helps the bottom-up processes to increase attention selectively in the time window in which the target is more likely to appear.

Data from human imaging and primate single unit recording studies have supported the notion of top-down processes by demonstrating sequential activation of frontal-parietal–sensory regions, including decreases in activity in task-irrelevant sensory regions, and the modulation of neuronal activity in sensory and sensory-associational areas (Desimone & Duncan, 1995; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Gazzaley & D'Esposito, 2007; Hopfinger, Buonocore & Mangun, 2000; Kastner & Ungerleiderand, 2000; Shulman, Corbetta et al., 1997).

Activation of top-down processes is traditionally considered as a component of the frontal cortical contribution to executive functions. Such processes were previously conceptualized in the context of attention by Posner and Petersen's posterior and anterior attentional systems, which are supposed to guide the subjects' attention to target sources and to detect targets, respectively (Posner & Petersen, 1990; also see Norman & Shallice, 1986). Executive functions can be conceptualized as a set of mechanisms aimed in managing and modulating other cognitive processes for high level and complex tasks. It has been proposed that they can be subdivided in three separate but not completely independent main functions: "*Updating*", involved in working memory operations, "*inhibition*" of prepotent but not relevant information, and "*shifting*" of mental set (Hofmann, Schmeichel & Baddeley, 2012; Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000).

Top-down processes are also involved in regulating the performance on the basis of previous trials. Classic studies using choice response tasks have demonstrated that individuals are quite efficient at detecting and correcting errors (Rabbitt, 1968), as well as at adjusting levels of performance to achieve optimal RTs while guarding

against errors (Rabbitt, 1969). In addition to adjustments of cognitive control in response to errors, individuals are also quite skilful at adjusting control settings based upon the level of conflict of consecutive trials within the context of correct responding. Evidence for this is found in many stimulus-response compatibility tasks (e.g., Simon and Flanker tasks), in which there is a sequential congruency effect (i.e., a different congruency effect depending on preceding trial congruency) when some characteristic of the previous trial influences the performance on the current one.

Conflict resolution

One of the most demanding and important tasks that our attention has to achieve is to cope with conflicting incoming stimuli. The prefrontal cortex plays an important role in conflict resolution, that is, the ability to activate the processing of task-relevant information while suppressing the processing of prepotent but potentially distracting information not relevant for the current goals (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Floden, Vallesi, & Stuss, 2011; Lavie, Hirst, De Fockert, & Viding, 2004; Zysset, Muller, Lohmann, & von Cramon, 2001).

Congruency effects (i.e., higher speed and/or accuracy for congruent with respect to incongruent trials) in the spatial domain have been often explained supposing the existence of a dual-route model (De Jong, Liang, & Lauber, 1994). The target is processed through a controlled route that is relatively slow because it links a specific response to a particular stimulus feature according to the arbitrary rules of the task that the subject is performing (e.g., the colour red corresponds to a left-hand index response). The other route is automatic, therefore it is faster, and processes the available information irrespective of its relevance and pre-activates a particular response, giving rise to priming phenomena. When the correct response has been previously primed, RTs will be faster with respect to the case in which another response is required.

Sequential congruency effects

It has often been reported that in conflict tasks, such as the Stroop one, the congruency effects depend on the congruency status of the preceding trial. When the previous trial (trial *n-1*) is incongruent (e.g., GREEN written in red), the congruency effect will be reduced with respect to when the trial *n-1* was congruent (Kerns et al.,

2004). Similar effects have been observed in other conflict-related paradigm such as the Simon task (Notebaert, Soetens, & Melis, 2001; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002), the flanker task (Gratton, Coles, & Donchin, 1992), and prime–target correspondence tasks (Kunde, 2003).

A *conflict monitoring hypothesis* has been proposed by Botvinick and colleagues (Botvinick, Braver, Barch, Carter, and Cohen, 2001) in order to integrate the observed behavioural effects with the fMRI results, that showed the anterior cingulate cortex (ACC) to be highly activated by incongruent trials (Kerns et al., 2004; Pardo, Pardo, Janer, & Raichle, 1990). This increased activity for incongruent with respect to congruent trials has been interpreted as a sign of the conflict detection process (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). The conflict monitoring hypothesis suggests that a top-down control signal is generated whenever a conflict is detected by the ACC, and consequently more control is assigned to the current task. This mechanism should reinforce the internal representation of task context, trough the action of the dorsolateral prefrontal cortex (DLPFC) that seems to support the control setting. The whole process will result in the reduction of influence of the irrelevant information, facilitating target detection.

However, other evidence suggests that conflict detection might take place in the dorsolateral prefrontal cortex. Monkey lesion studies showed that a damaged DLPFC entails impaired conflict resolution behavioural results, whereas a selective lesion to ACC does not (Mansouri, Buckley, Tanaka, 2000). Moreover in the DLPFC there are some cells that get activated proportionally to the level of conflict in the current trial and other ones that are sensitive to the conflict level of the previous trial. Also human studies pointed out that DLPFC could strongly interact with ACC in conflict detection processes. Indeed patients with lateral prefrontal damage showed the same error-reletad negativity in correct and incorrect trials despite intact ACC (Gehring & Knight, 2000). Moreover, Floden and colleagues showed that increased activity in ACC corresponds to a performance worsening (Floden et al., 2011).

Several authors have claimed that there are alternative explanations for the sequential effects (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Notebaert, Gevers, Verbruggen & Liefooghe, 2006). These alternative hypotheses are based on the fact that some types of feature changes from trial *n-1* to trial *n* lead to faster RTs than other transitions because of bottom-up processes. RTs are faster when both stimulus features (colour and word in the Stroop task) are repeated, but they are

also quite fast when both features change. Conversely when only one of the features changes, RTs are slower. This phenomenon can be explained either by a binding or by a perceptual priming account. The binding approach expressed by the Theory of Event Coding (Hommel, 1998; Hommel et al., 2004; Notebaert & Soetens, 2003; Notebaert et al., 2001) states that on any given trial, the stimulus and response features are temporarily associated with each other in an *event file*, which is stored in memory. When the subsequent trial breaks this association, RTs get longer. On the other hand the priming account suggests that such a pattern of effects is due to the fact that repeating one or both features of the stimulus leads merely to repetition priming and negative priming effects described above in this paragraph. Both accounts have received empirical support (Hommel et al., 2004; Mayr et al., 2003). For example Mayr's group used a flanker task to show that by removing from the analysis trials that repeated the same target feature as the preceding one, the adaptation of the flanker effect disappears after incongruent trials. This result suggests that the adaptation of congruency effects can indeed be an artifact of repetition effects. However, other studies controlled for these repetition effects and still observed a residual interaction between the congruency of the previous trial and that of the current one. For complete alternation pairs of trials, Kerns and colleagues observed a reduced Stroop effect after incongruent trials. In addition, Wühr and Ansorge (2005) kept the repetition trials (but only the partial repetition ones) and still observed a sequential modulation of the Simon effect. In general, it seems that even when partially[1] controlling for repetition effects, top-down conflict adaptation still occurs.

General vs domain-specific account of cognitive control

Many previous studies focused on cognitive control and conflict adaptation mechanism, and many different tasks have been used, such as the classic Stroop task, the flanker task, the Simon task etc. which involve different cognitive domains (e.g. spatial, verbal). Cognitive control is usually referred to as a general supra-domain mechanism that modulates executive processes, which can be involved in processing stimuli belonging to different domains and different sensory modalities. Despite this very evident issue very few studies aimed in verifying whether the cognitive control

[1] Some of previous studies claimed to have completely excluded priming, but their task design did not really permit such control (cf. Chapter 2).

effect emerging from conflict resolution tasks is comparable across domains (Donohue, Liotti, Perez, & Woldorff, 2012; Roberts & Hall, 2008) and, to the best of our knowledge, only one study directly compare results emerging from properly matched tasks belonging to different modalities (Zoccatelli, Beltramello, Alessandrini, Pizzini & Tassinari, 2010). ERP evidence obtained from an auditory Stroop task (Donohue et al. 2012) revealed a fronto-central negative component followed by positive posterior potentials similar to the N450 and parietal SP waves found in visual Stroop tasks (e.g., Larson et al., 2009; Liotti et al., 2000; West & Alain, 2000a, 2000b). The authors suggested that the general mechanism of conflict detection processes is supra-modal, although some aspects, such as timing, may be modality-dependent. Additionally, Roberts and Hall (2008) in a neuroimaging experiment claimed that areas involved in conflict-related processes (anterior cingulate cortex, bilateral inferior frontal gyrus, parietal lobe[2] and anterior insula) result to be the same comparing visual and auditory Stroop tasks[3] performed by the same participants.

On the other hand, direct comparison of equivalent[4] verbal (colour-word) and spatial (arrow-position) Stroop tasks evidenced that, although the activation in both tasks involves the dorsolateral prefrontal cortex and the anterior cingulate cortex, such activations only partially overlap (Zoccatelli, Beltramello, Alessandrini, Pizzini & Tassinari, 2010).

[2] The intraparietal sulcus was activated by both visual and auditory conflict tasks, but anteriorly and laterally (auditory cortex) exclusively by auditory conflict, whereas posteriorly and medially (visual cortex) by visual conflict only. However these differences were not statistically significant.

[3] However, the two tasks were not perfectly comparable since the visual task involved 6 possible stimuli and 4 possible responses with respect to the 3 possible stimuli and 2 possible responses of the auditory task.

[4] The two tasks were perfectly comparable since the both involved 4 possible stimuli and 2 possible responses.

1.2. Cognitive Aging

Both naive observations and scientific studies suggest that aging is associated with decreased performance on a variety of cognitive tasks. These effects, in the absence of specific pathologies, can be collected under the umbrella definition of cognitive aging. Different accounts have been proposed for cognitive aging, with some concerning general factors, like decreased processing speed, and others assuming an increasing decline of specific cognitive processes and brain regions. In the following section the major accounts proposed in order to explain cognitive aging are shortly described.

Processing-speed theory

The processing speed theory of cognitive aging proposed by Salthouse (1996) is based on the fact that age-related declines in cognitive performance can be largely accounted for by a general processing speed decrement (Salthouse, 1991; 1996).

Despite a well documented presence of such general slowing phenomena, many studies reported residual age-related effects, which remain even after adequately controlling for differences in processing speed between younger and older adults (Keys & White, 2000; Verhaeghen, Cerella, & Basak, 2006), suggesting that a general mechanism is inadequate to entirely explain cognitive aging. It is rather more likely that multiple mechanisms may underlie age-related changes in information processing.

Frontal Lobe Hypothesis

West proposed a "frontal lobe hypothesis" (FLH) of cognitive aging (West, 1996). This hypothesis is based on two main assumptions:

A. A decline in cognitive processes supported by the prefrontal cortex should emerge at an earlier age than a decline in cognitive processes supported by non-frontal regions.

B. This decline should be greater in magnitude than that observed in cognitive processes supported by non-frontal regions.

After West's work (1996) a number of studies confirmed that the pattern of spared and impaired cognitive functions observed in the cognitive aging literature

could fit with the FLH (Dempster, 1992; Hartley, 1993; Moscovitch & Winocur, 1992). Event-related Potential (ERP) evidence also suggests that neurocognitive processes involved to perform the Stroop task that originate over the prefrontal cortex are significantly affected by the aging process (West & Alain, 2000). In that study the amplitude of ERPs associated with conflict detection was markedly attenuated in older adults, while the amplitude of ERPs associated with the controlled processing of colour information in older adults was slightly greater than that observed in younger adults. Many neuroimaging studies have also shown under-recruitment of frontal regions with aging (e.g., Grady et al., 1995; Gutchess et al., 2007; Mitchell, Raye, Johnson, & Greene, 2006; Rypma & D'Esposito, 2000; Vallesi, McIntosh & Stuss, 2009).

Greenwood (2000) argued that even taking a weaker version of the frontal aging hypothesis that simply states that the frontal lobes undergo earlier and greater decline than the other brain regions, and indeed he reported studies that have examined age-related declines on a broad range of functions and concluded that visuo-spatial abilities decline relatively early during adulthood, while verbal abilities, including verbal memory, are preserved until very late in life (Arenberg, 1978; Eisdorfer et al., 1959; Koss et al., 1991). Similar studies in primates have shown that performance in tasks involving spatial abilities declines before the one obtained in tasks involving recognition memory (Bachevalier et al. 1991; Rapp et al., 1997).

HAROLD and PASA models

Somewhat in contrast with the evidence supporting FLH, there is an extensive literature showing age-related neural over-recruitment of frontal regions (e.g., Cabeza et al., 1997, Grady, 1998, Cabeza, Anderson, Locantore, & McIntosh, 2002; Nielson, Langenecker, & Garavan, 2002; Park & Reuter-Lorenz, 2009; Vallesi et al., 2011). Several studies have revealed two consistent patterns of age-related over-recruitment in brain activity across a variety of cognitive functions. One is a more bilateral pattern of frontal recruitment in older adults, called hemispheric asymmetry reduction in older adults (HAROLD) (Cabeza, 2002). The other pattern is an age-related reduction in occipito-temporal activity coupled with an age-related increase in frontal activity, which has been called posterior-anterior shift in aging (PASA) (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008).

The HAROLD model (Cabeza, 2002) derives from the neuroimaging finding that older people do not show the pattern seen in younger people of left hemisphere involvement in encoding verbal items and right hemisphere involvement in verbal retrieval (Tulving et al., 1994). Some authors explain HAROLD patterns as due to compensatory-driven mechanisms (Cabeza, Anderson, Locantore, & McIntosh, 2002), while others explain them as due to dedifferentiation and inefficiency in prefrontal cortex and in the networks related to it in older adults (Park et al. 2001).

The PASA model originates from imaging findings such as those by Grady and colleagues (1994). In that study on face perception and locations, older adults showed weaker PET activity than younger adults in occipito-temporal regions, but greater activity in anterior regions, including the prefrontal cortex. These authors suggested that older people recruit anterior regions to compensate for sensory processing deficits in occipito-temporal regions. Madden and colleagues (Madden, 2007) showed that for senior participants the activation of frontal and parietal cortical regions was generally greater than for younger adults. When the task involved a marked top-down control, younger adults' performance was associated with a greater activation in occipital (fusiform) areas, whereas in older adults the activation was shifted in fronto-parietal regions. Reuter-Lorenz (2002) claims that, at least in the domains of working memory and episodic memory, older adults recruit different brain regions with respect to those recruited by younger adults when performing the same tasks. More specifically, older adults seem to increase the recruitment of prefrontal regions with respect to younger adults, and moreover the increased frontal activation of older adults is bilateral, whereas in younger adults it is highly lateralized. The existence of such specific age-related activation patterns suggests compensatory phenomena that can take place in order to cope with the impairment due to the aging brain (Reuter-Lorenz, 2002).

Nevertheless the nature of age-related differences in brain activation is difficult to characterize, and it may change according to the task difficulty, the strategy used and the cognitive functions required in the task (Logan et al., 2002; Nyberg, Lövdén, Riklund, Lindenberger, & Bäckman, 2012; Vallesi, McIntosh & Stuss, 2011; see Grady, 2008 for a review).

Cabeza and colleagues reported an fMRI study where they showed that the PASA pattern was found across tasks and confidence levels. This contrasts the account that assumes that this phenomenon simply reflects the difficulty of the task. Moreover, supporting the compensatory hypothesis, these authors reported that the age-related

increase in frontal activity correlated positively with performance and negatively with the occipital decrease. Additionally they showed an age-related increased correlation with parietal activity (Davis, Dennis, Madden, & Cabeza, 2008).

Cognitive Reserve

The concept of reserve has been proposed to account for the disjunction between the degree of brain damage or pathology and its clinical manifestations. For example, it is now well documented that a head injury of the same extent can exert different levels of cognitive impairment in different individuals, and that such impairments, in the face of the same therapy and rehabilitation training, can have different levels of recovery. At the same time, several studies about aging have reported that up to 25% of older adults who resulted unimpaired at neuropsychological tests turned out to fully meet the post-mortem pathologic criteria for Alzheimer's disease (Ince, 2001). This suggests that a high degree of acknowledged structural pathology does not invariably result in clinical dementia. The Cognitive Reserve (CR) theory postulates that in order to perform the same task, different individuals can use slightly different cognitive processes or neural networks; this allows some individuals to cope better than others with comparable brain damage (Stern, 2002).

The reserve construct has been classified into passive and active models (Stern, 2009). The reserve arising from brain dimension or neuronal density is called "brain reserve" (Katzman, 1993) and is an example of passive models. A bigger brain can tolerate more damage before actual deficits would occur, because the majority of functions are still supported by a sufficient neural substrate. The fact that people have different brain reserve capacity has received support from Satz's threshold model (Satz, 1993). This approach assumes that there is a critical threshold beyond which functional deficits appear.

On the other hand active models have been proposed, which suggest an active role of the brain itself in order to contrast brain damage. The Cognitive Reserve theory proposes that for the impaired brain it is possible to use pre-existing cognitive processes or to develop new compensatory ones (Stern, 2002). This implies that an individual with a greater CR can strategically cope with a wider brain lesion before the emergence of overt cognitive symptoms with respect to another patient with a lower level of CR, even if their brain reserve capacity is comparable. Thus, active models do not assume that there are fixed thresholds beyond which functional

impairment arises, but they rather state that these thresholds are different for each individual, and depend on the personal cognitive history.

Stern suggested that cognitive reserve could be subdivided into two components: neural reserve and neural compensation. Neural reserve denotes the differences in cognitive processing that usually exist among individuals in a non-pathologic brain-state. Instead the neural compensation indicates the cognitive processing adjustments that allow coping with brain pathology (Stern, 2009).

Active and passive models of reserve entail different measures. For brain reserve these measures consist in direct measures of anatomic properties such as head circumference, brain volume, synaptic count and dendritic branching. For CR it is not possible to use direct measures. Therefore, it is necessary to use other indirect indices, such as income, occupational and educational attainment and leisure activity. In order to measure the educational attainment, the degree of literacy might be a better marker with respect to the number of years of formal education (Manly, Schupf, Tang, & Stern, 2005; Manly, Touradji, Tang, & Stern, 2003). However, since it is a faster index to collect, it is more frequently used. Some authors suggest that using the IQ (or premorbid IQ) estimation might be a more appropriate measure of reserve (Albert & Teresi, 1999; Alexander et al., 1997). However, education and other life experiences have been shown to have an impact on cognitive reserve that goes beyond that one obtained from innate intelligence only. In fact several studies have demonstrated separate or synergistic effects of the lifestyle-related proxies listed above, suggesting that each of those may contribute independently to CR (Colcombe et al., 2006; Colcombe & Kramer, 2003;Evans et al., 1993; Mortel, Meyer, Herod, & Thornby, 1995; Rocca et al., 1990; Stern et al., 1994; Stern, Alexander, et al., 1995; Stern, Tang, Denaro, & Mayeux, 1995).

Recently, a questionnaire named Cognitive Reserve Index (CRI) (Nucci, Mondini & Mapelli, 2012) has been developed to quantify the CR for the Italian population.

1.3. Age-related effects on Cognitive Control

Neuroimaging studies show that the ability to successfully suppress neural activity associated with non-target information is selectively impaired in normal aging, despite a relatively spared ability to process relevant information (Gazzaley et

al., 2005; Gazzaley & D'Esposito, 2007; Vallesi, McIntosh, & Stuss, 2011). Such neuroimaging evidence supports the hypothesis that a prominent aspect of cognitive decline in aging is the impairment in preventing non-relevant material from entering working memory (e.g., Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999).

Poor performance in older adults on a variety of tasks that require suppression of non-target information is a typical finding in the literature on aging (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999; Lustig, May, & Hasher, 2001; Madden & Langley, 2003; Scialfa, Esau, & Joffe, 1998; Zeef, Sonke, Kok, Buiten, & Kenemans, 1996). Older adults are, for instance, more susceptible to proactive interference from previously relevant stimuli that subsequently become irrelevant (Ikier, Yang, & Hasher, 2008; Hasher, Chung, May, & Foong, 2002). In an event-related potentials (ERPs) study (Vallesi, Stuss, McIntosh, & Picton, 2009), young and older participants were tested on a go/nogo task while ERPs were recorded. There were two types of nogo stimuli: coloured letters which created Stroop-like conflict with go letters (high-conflict nogo), and coloured numbers which did not create conflict with the go letters (low-conflict nogo), since they belonged to a different conceptual category (numbers vs letters). Performance on the nogo numbers was at ceiling for both age-groups without any significant difference between them, but older participants showed an enhanced central nogo-P3 component, suggesting an increased need for suppression of the motor response (c.f., Roberts, Rau, Lutzenberger, & Birbaumer, 1994; Smith, Johnstone, & Barry, 2007).

Another subsequent ERP study by the same group, which used the two hands for the go response on separate blocks, showed that older individuals, but not younger controls, could not prevent a partial response preparation not only for high-conflict nogo letters, but also for low-conflict nogo numbers, as shown by the lateralized readiness potential, a measure of unimanual response preparation (Vallesi & Stuss, 2010).

Altogether, these findings suggest that older adults have difficulty in suppressing the processing (both perceptual and motor) of non-target material even when it is not similar to targets. Such a suppression deficit may have different behavioural consequences: it is possible that the performance is impaired or preserved depending on the task context or demands (Vallesi et al., 2010).

Repetition priming in non-pathological aging

The notion that priming is usually spared in normal aging is based on studies which found comparable priming magnitudes for younger and older participants on tasks such as word fragment completion (Light, Singh, & Capps, 1986), word stem completion (e.g. Dick, Kean, & Sands, 1989; Light & Singh, 1987, Experiments 1 and 2), word identification (Light & Singh, 1987, Experiment 3), picture naming (Mitchell, 1989), and category exemplar generation (Light & Albertson, 1989). In such studies significant age effects occurred for explicit retrieval of the same material, but not for priming itself. Some theories of cognitive aging tried to describe age-related differences found for explicit retrieval. However, these theories cannot explain the dissociation between explicit retrieval and priming. The environmental support hypothesis proposed by Craik (1983), for example, suggests that age effects are minimized or nullified on tasks that provide richer target information at the moment of retrieval. Indeed, comparing cued recall tasks in which the entire item is presented at test with tasks in which the test phase presents only partial information, smaller age differences have been found in the first paradigm (Craik & McDowd, 1987; Light & La Voie, 1993). Indeed La Voie and Light's review (1994) concluded that priming does decline with age, although effect sizes from priming tasks were smaller than those from explicit memory tasks. Rybash (1996) suggested that conceptual priming selectively diminishes in normal aging while perceptual priming remains relatively spared. However, in their review, Fleischman and Gabrieli reported that in 85% of the reviewed studies, there is at minimum a trend toward reduced priming in older adults compared to younger ones (Fleischman & Gabrieli, 1998).

These authors reported that priming on conceptual tasks, such as word association and category exemplar generation, also appears to be reliably unaffected by normal aging (e.g., Java, 1996; Light & Albertson, 1989; McEvoy et al., 1995; Monti et al., 1996). Using tasks in which the level of processing at encoding varies, it is possible to highlight conceptual priming deficits occurring in normal aging. It has been shown that in such tasks healthy older and younger individuals respond similarly (e.g., Chiarello & Hoyer, 1988; Friedman, Snodgrass, & Ritter, 1994; Hamberger & Friedman, 1992; Light & Singh, 1987; Experiment 3; Park & Shaw, 1992). This is consistent with minimal semantic or linguistic processing impairments on tasks that do not overload working memory (Light, 1990). Moreover, Bergerbest and colleagues

also showed that older adults have spared response time (RT) benefits in repetition priming from repeated semantic classification (Bergerbest et al., 2009).

Negative priming in non-pathological aging

Older adults may show higher distractibility and reduced negative priming (NP) relative to younger adults (Connelly, Hasher, & Zacks, 1991), both of which suggest a failure to suppress the processing of irrelevant material. Negative priming may be present in older adults when the task involves the processing of the identity of degraded stimuli (May et al., 1995) or their location (Connelly & Hasher, 1993). These results have been widely replicated (McDowd & Oseas-Kreger, 1991; Tipper et al., 1991); nonetheless other studies failed to find a relevant difference between younger and older NP (Verhaeghen and De Meersman, 1998a; Little and Hartley, 2000).

Cognitive control in non-pathological aging

Rabbitt showed that RTs for errors and error correction responses (i.e., execution of the correct response immediately following an error) can be similar in younger and older adults, while RTs for trials distant from errors are substantially slower in older than younger adults. In contrast, RTs for error detection responses (i.e., instances where individuals make a unique response indicating the commission of an error) are typically slower in older adults than in younger ones (Rabbitt, 1979). Older adults are less able than younger adults to modulate the Stroop interference effect when stimuli are mostly incongruent (West & Baylis, 1998). In contrast, in contexts where demands for control are less severe (i.e., when trials are mostly congruent) the interference effect is similar in younger and older adults. The weakened modulation of the Stroop interference effect when trials are mostly incongruent is consistent with data indicating that the performance of older adults is less sensitive to event history than that of younger adults (Rabbitt & Vyas, 1980) and that aging is associated with a decline in the functionality of the neural systems supporting adjustments of control.

Considering together the evidence supporting an age-related increase in the congruency (Stroop) effect, the FLH (West, 1996), and the conflict monitoring

hypothesis (Botvinick et al., 2001), we should expect a specific age-related cognitive control deficit, due to the decline of a general cognitive control mechanism.

However, recent evidence suggests that this view should be at least carefully examined. Indeed Verhaeghen recently reviewed a series of studies involving aging and executive control, concluding that age-related decline in cognitive control is overestimated. On the other hand general slowing can account for most of the age-related difference found in older adults with respect to younger ones in executive tasks such as inhibition of return, negative priming (although it is questionable whether inhibition of return and NP can be considered executive function), flanker, and classic Stroop (Verhaeghen, 2011). Also ERP evidence that used the inhibitory control task, where the control level is monitored, found that the age-related worsening in performance is not influenced by the control level but can rather be mostly explained by the general slowing account (Cona, Arcara, Amodio, Schiff, & Bisiacchi, 2013)

Sequential trial effects were observed in an ERP study by West and Moore (2005) reflecting a facilitation of RT for Congruent – Congruent (CC) and Incongruent – Incongruent (II) trials relative to Incongruent – Congruent (IC) and Congruent – Incongruent (CI) sequences. The magnitude of these effects was similar in younger and older adults in behavioural data. A slow wave was observed in the ERPs over the parietal scalp region that reflected reduced negativity for colour incongruent trials relative to colour congruent or word trials that was expressed in both younger and older adults. In contrast, there were age-related differences in an anterior frontal slow wave that reflected greater positivity for congruent than incongruent trials in younger adults and was absent in older adults. These findings suggest that some processes related to the adjustments of cognitive control remain stable while others change with age (West & Moore, 2005).

Preserved sequential trial effects in older adults contrast the predictions derived from the conflict monitoring theory (Botvinick et al., 2001) when considered in conjunction with theories of selective frontal lobe damage in aging (e.g., West, 1996), wherein one would expect that an age-related decline in prefrontal function leads to alterations of sequential trial effects. An alternative hypothesis is that the sequential effects arise from a form of repetition priming, which is preserved with aging, rather than from the activity of an attentional control process (Mayr et al., 2003).

1.4. The present project

In the light of all the theoretical issues described in the previous paragraphs, we noted that the unification of the cognitive control and the cognitive aging fields has some gaps. Therefore, the general aim of this PhD thesis was to investigate the conflict resolution processes and whether they undergo an age-related decline. We also wanted to explore the modulatory effect that differences in life experience could exert on this decline. Additionally, we aimed in getting insight about the unity or modularity of the cognitive control mechanism.

The theoretical framework around which our project is shaped is represented in Figure 1.

We designed our research project in order to remove some confounds that emerged in previous studies, such as:

1. Driving conclusion about congruency (Stroop) effect and sequential congruency effect without considering the previous trial congruency.

2. The priming/binding effects that arise from the presence of feature repetition in subsequent trials.

3. The imbalance between younger and older samples for what concerns education and IQ, when investigating age-related effects.

The issues listed above have been addressed singularly in many previous works. However, to the best of our knowledge, there are no studies that simultaneously controlled for all of them.

Many studies about cognitive control pointed out that, in order to investigate conflict resolution processes, it is important to take into consideration not only the congruency of current trial, but rather the congruency of the current trial and that of the previous one (Gratton et al., 1992; Kerns et al., 2004; Kunde, 2003; Notebaert et al., 2001; Stürmer et al., 2002). Considering the sequential effects emerged from the analyses of trials sequences, successive studies tried to disentangle among the different mechanisms proposed by the three main hypotheses: the priming account (e.g. Mayr et al., 2003), the Event File Coding (e.g. Hommel, 1998; Notebaert & Soetens, 2003) and the Conflict Monitoring (Botvinick et al., 2001). In order to do this, some authors manipulated feature repetitions between pairs of subsequent trials claiming to have removed the priming influence (Kerns et al., 2004; Mayr et al., 2003; Notebaert et al., 2006; Wühr & Ansorge, 2005). Actually, to the best of our

knowledge, there are no studies that completely controlled for the priming influence. Therefore, the first aim that we wanted to address in this project was to create a conflict-related task which was able to remove the priming influence coming from the trial *n-1* (at least the first order ones), in order to isolate the top-down regulation of attention in the conflict-resolution processes.

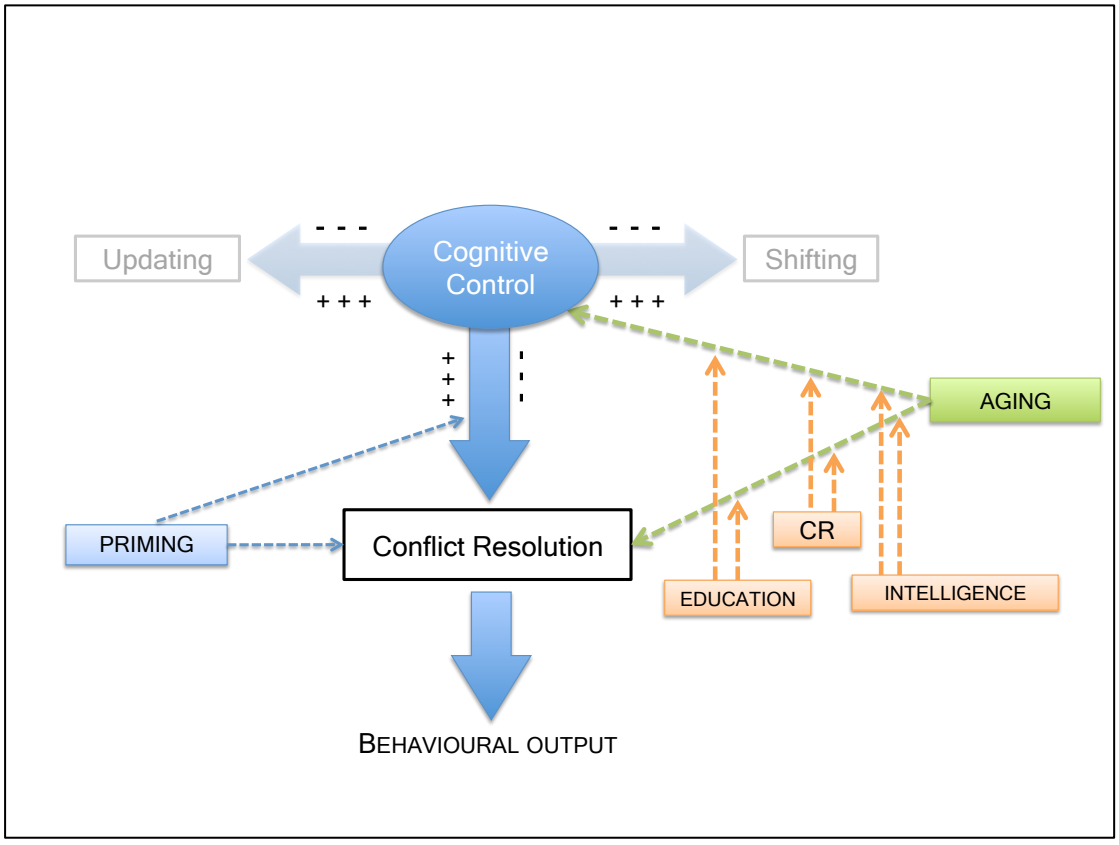

Figure 1 – Theoretical framework- Cognitive control modulates the amount of attentional resources recruited in order to carry out the conflict resolution process (+++/--- indicates the increase of decrease due to the modulation). Priming and cognitive aging could exert effects in both the cognitive control and on the conflict resolution processes. Education, intelligence and Cognitive Reserve factors could modulate the effects exerted by cognitive aging.

Moreover aging studies still provide inconclusive evidence about the cognitive aging influence on priming. Therefore, using tasks that involved a factor (priming) that is itself likely influenced by aging, in order to explore the aging effects on another process (cognitive control), would not be appropriate. Hence, the creation of a priming-free task was strongly motivated by this aim.

While many evidence showed that priming effects have a strong domain-dependence (although priming exerts an effects also cross-domains), the fact of whether the

cognitive control should be considered a general supra-modal mechanism or rather composed by domain-specific sub-mechanisms has not been adequately addressed. ,
It could be the case that there are some domain-specific control mechanisms and that these mechanisms could be differentially affected by aging. Therefore, we chose to use two types of tasks, highly comparable, which involve different domains: the verbal domain and the spatial one.

The just expressed considerations led to the creation of a priming-free colour-word Stroop task and a priming-free spatial Stroop task. Additionally, in order to explore the Cognitive Reserve influence and to account for inter-subject variability, we collected data relative to each participant's IQ, cognitive reserve, and education.

In chapter 2 we describe the methodological issues that underlie the design in the two tasks, the participant sample selection, and how the variables of interest were determined and analysed.

The two tasks were used to determine the contribution of priming and conflict adaptation in younger adults in a colour-word Stroop task (Experiment 1 and 2, Chapter 3) and in a spatial Stroop one (Experiment 5, Chapter 4). Evidence that emerged from these experiments suggested that priming and cognitive control have separable effects in the conflict resolution process. Therefore, in order to investigate cognitive control, we chose to use a priming-free version of the two tasks.

We used the two priming-free[5] Stroop tasks to behaviourally compare the verbal conflict resolution ability (Experiment 3, Chapter 3) and the spatial conflict resolution ability (Experiment 6, Chapter 4) of younger and older adults. Results from these two experiments evidenced different patterns for what concerns the conflict resolution in the two domains as well as a different impact of aging. In order to explore the neural mechanisms that gave rise to such behavioural results we decided to investigate them with an electrophysiological approach. Thus we used the priming-free Stroop tasks to obtain ERPs for a new group of younger and older adults. For the sake of clarity, experiments concerning the verbal and the spatial domain are presented separately in Chapter 3 and in Chapter 4, respectively.

In Chapter 5 we first summarized evidence obtained from the several experiments for what concerns cognitive control-related processes, then we clarify the relationship

[5] The priming contribution was excluded in two subsequent trials only. Residual priming influences caused by trials the preceded trial n-1 were not controlled for because this would have required a very high number of stimulus and response types (cf. Chapter 2).

between healthy cognitive aging and cognitive control. Afterward we discuss the existence of a general cognitive control system, as suggested by Botvinick's conflict monitoring hypothesis (Botvinick et al., 2001), with respect to the possibility of the presence of more domain-specific mechanisms.

Finally, we discuss the limits of the project as well as possible future research that would clarify the open issues. In the concluding chapter we also summarize the relevant findings emerged during the overall project and their relevance for the cognitive neuroscience community.

Chapter 2 – Methodological issues

2.1. Development of the priming-free tasks

In compatibility tasks, such as the Stroop task, it has been shown that congruency effects, measured as the accuracy or RT difference between incongruent and congruent trials, depend on the congruency of the preceding trial. When the previous trial (trial *n-1*) is incongruent, the congruency effect will be weaker than for trials in which trial *n-1* was congruent (Kerns et al., 2004).

Botvinick and colleagues (Botvinick, Braver, Barch, Carter, & Cohen, 2001) proposed a conflict-monitoring theory in order to integrate these behavioural effects with the brain imaging literature (see Chapter 1). The conflict-monitoring hypothesis states that whenever conflict is detected, top-down reconfiguration takes place and more control is allocated to the particular task at hand. The purpose of this reconfiguration is to eliminate, or at least reduce, the influence of irrelevant information in the cognitive processing of target information.

Two alternative non-strategic explanations for congruency sequential effects have subsequently been offered: one is that sequential effects are due to repetition priming (Mayr, Awh & Laurey, 2003, Nieuwenhuis et al. 2006), the other is the Theory of Event Coding (Dutzi & Hommel, 2009; Hommel 2011 Hommel, Proctor & Vu, 2004; Notebaert, Soetens & Melis, 2001). The Theory of Event Coding proposes that in each trial a link is created between stimulus and response features and that this link is momentarily memorized as an *event file*. A RT slowing takes place whenever a subsequent trial involves one of the features already associated with another one, since the event file previously created has to be dissociated. For both accounts, RT differences between certain transitions from trial *n-1* to trial *n* are solely due to feature repetitions/alternations.

The priming account suggests that the repetition of one or both features leads to performance facilitation. This means that RTs are usually shorter when both stimulus features (colour and word in the Stroop task) are repeated, but they are also relatively short when only one feature is repeated, if it maintains the same status of "target" or "distractor" as in the previous trial. Reasonably long RTs are observed instead when

both features change, whereas when the distractor becomes target, or the target becomes distractor, RTs get relatively long.

On the other hand the Event Coding approach explains sequential effects in terms of a binding process (Hommel, 1998; Hommel 2011; Hommel et al., 2004; Notebaert & Soetens, 2003; Notebaert et al., 2001) (see Chapter 1). Other studies controlled for these repetition effects and still observed a residual interaction between the congruency of the previous trial and the congruency of the current one, suggesting that when one controls for repetition effects, top-down conflict adaptation still occurs.

For example, both Kerns' and Notebaert' studies (Kerns et al., 2004; Notebaert et al., 2006) reported analyses made on complete alternation sequences to exclude the confound of the repetition effects. Both studies showed a reduced congruency (Stroop) effect after incongruent trials. However, these studies, as most of previous ones, used three possible targets/responses only (albeit sometimes combined with four distractor words), which makes it impossible to have completely repetition-free sequences. For instance, when using only three colours/responses (e.g., blue, green, red), if trial *n-1* is the word BLUE written in red and the following trial has to also be incongruent, it would mandatorily have blue or red as a word or as a colour. Thus a form of priming will always be possible. An exception in this example would be the word GREEN written in green, but it is obvious that exclusively using only this type of complete alternation sequences would imply not to have incongruent-incongruent sequences. Therefore it is clear that, in a task where stimuli are defined by two features (e.g., word and ink-colour), in order to avoid all type of repetitions in two subsequent trials, it is necessary to have at least 4 levels for each feature.

To our knowledge, there are no studies on sequential effects that used at least a four-alternative forced choice (4-AFC) Stroop task. Hence, it has not been possible to disentangle whether priming/binding factors or conflict adaptation ones determine sequential effects. To solve this problem two Stroop tasks, a classic colour-word and a spatial one, with four levels of target features and four levels of distractor features were designed. For the sake of clarity, we describe the rationale of the task design for what concerns the classic colour-word Stroop task, but the same considerations are valid for the spatial version as well.

The verbal stimuli consisted in four different words: *GIALLO* (yellow in English), *VERDE* (green), *ROSSO* (red) and *BLU* (blue), which were presented in four different ink colours: yellow, green, red, blue. The single stimuli were categorized as

congruent (C) (e.g., YELLOW coloured in yellow) and *incongruent* (I) (e.g., YELLOW coloured in blue), according to whether the word corresponded to the colour or not, respectively.

In the spatial Stroop task, stimuli were one out of four arrows (pointing to upper-right, upper-left, lower-right or lower-left) appearing in one out of four positions on the screen (upper right and left, lower right and left). Participants had to respond accordingly to the pointing direction of the arrows by pressing the corresponding button, while ignoring its position. Spatial Stroop stimuli were categorized as congruent (e.g., upper-right pointing arrow positioned in the upper right part of the screen) or incongruent (e.g., upper-right pointing arrow positioned in the upper left part of the screen).

We also categorized sequential pairs of trials in the following categories: Congruent-Congruent (CC), Congruent-Incongruent (CI), Incongruent-Congruent (IC), Incongruent-Incongruent (II), according to the congruency status of the trials *n* and *n-1*.

In addition to the previous categorization, we divided the sequential pairs of trials in: *Complete Repetition, Complete Alternation* and *Partial Repetition. Complete Repetition* trials presented the very same stimulus displayed in trial *n-1*. *Complete alternation* sequences are those in which both the colour-word (distractor) and the ink-colour (target) of trial *n* are different with respect to the colour-word and the ink-colour of trial *n-1* (e.g. trial n-1: RED printed in yellow; trial n: BLUE printed in green). *Partial Repetition* refers to pairs of trials in which one feature presented in trial *n-1* is repeated in trial *n*. They are further subdivided in five subcategories: *Target Repetition, Distractor Repetition, Target to Distractor, Negative Priming,* and *Inversion.*

In *Target Repetitions* sequences, the same target (i.e., the colour) is presented in trial *n-1* and trial *n*, but the distractors (i.e., the words) are different. In *Distractor Repetitions* sequences the target is different in trial *n-1* and trial *n* whereas the distractor is maintained. *Target to Distractor* indicates sequences in which the target of trial *n-1* becomes the distractor of trial *n*, while the distractor of trial *n-1* is different with respect to the target of trial *n*. *Negative Priming* sequences were those in which the distractor of trial *n-1* becomes the target of trial *n*, while the target of trial *n-1* is different with respect to the distractor of trial *n*. This situation usually elicits a behavioural cost known as negative priming (Tipper, 1985). *Inversion* refers to

sequences in which the target of trial *n-1* becomes the distractor of trial *n* and the distractor of trial *n-1* becomes the target of trial *n.*

With the exception of *Complete Alternations*, all the other types of sequences involve some kind of repetition, and, therefore, a certain degree of priming. *Complete Repetitions* and *Partial Repetitions* sequences, excluding *Negative Priming* ones, can be considered therefore "positive priming eliciting sequences". It is important to point out that, for simplicity, we refer to feature repetition contribution as priming, but, actually, since this paradigm does not allow separating priming from binding accounts, both explanations can be valid.

The fact that participants had to choose among 4 response alternatives versus 3 (contrary to previous studies) inevitably increased the task difficulty. However having four levels for each feature permits the use of different types of Stroop tasks. It is possible, indeed, to run a task composed of all the types of feature repetitions (as the ones used in the majority of previous studies), to display complete alternation trials only, or even to run a task using priming eliciting trials only. In all these cases it is possible to have all the four types of congruency sequences: CC, CI, IC, II.

Having 4 levels for each feature (and 4 responses) permits us to use complete alternation trials only, in order to prevent repetition, and therefore priming, in two subsequent trials. Hereafter we will refer to tasks that used complete alternations only as "priming-free" tasks. However, it is important to clarify that it is still not possible to exclude priming influence originated in trials preceding *trial n-1*. In order to completely exclude priming, it would be necessary to use many more levels for each feature, but this would dramatically increase the difficulty of the task. For this reason, we decided to avoid the latter approach.

In this project we mainly used tasks composed of complete alternation trials only, in order to reduce priming effects, at least the strongest ones coming from trials n-1. An exception is made in experiments 2 and 5, for the verbal and the spatial Stroop tasks respectively. In these control experiments all type of repetitions were displayed in order to:

a) compare the results of our 4-AFC task with previous 3-AFC tasks which did not control for repetition, in order to validate the new paradigm;

b) compare the results with those of the complete alternation only (priming-free) version.

The last point permitted us to get insights about the amount of the priming effects with respect to cognitive control in determining the congruency effect and conflict adaptation pattern shown by previous studies.

2.2. Participants

One of the aims of the present project was to explore the possible age-related cognitive decline in cognitive control mechanisms, specifically, conflict resolution processes. In order to do so, we adopted a cross-sectional approach. We therefore decided to compare samples of older adults with samples of younger adults. Since many personal characteristics could influence the variables of our interest, we were very careful in choosing the samples in order to reduce the difference between the two age-groups and in getting additional informative measures on their individual characteristics.

Initial selection criteria were that all the participants had to be native Italian-speakers, with normal or corrected-to-normal vision. Since in the colour-word Stroop task colour perception is involved, we assessed it with a computerized version of the Ishihara Color Vision Test (Ishihara, 1962). The Edinburgh Handedness Inventory (Oldfield, 1971) was used to measure participants' handedness and, with few exceptions, only right-handed individuals were selected. Older adults were also screened for dementia in order to exclude those that met the criteria on the basis of the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005).

Each volunteer could perform each of the two Stroop tasks only once, in order to avoid task repetition confounds. However, some volunteers performed one of the two tasks only, whereas others participated separately in both the verbal and the spatial experiment, or in the ERP session, where the participants were required to perform both tasks while EEG was recorded. Before taking part in each experiment, participants signed an informed consent form and at the end of the experimental session they received an economic reward proportional to the time spent for taking part in the study. The study was approved by the SISSA ethics committee.

2.3. Modulatory factors of cognitive aging

Beside the just listed criteria, some factors that could modulate age-related cognitive changes were considered to select the samples and to get important measurements for the subsequent analyses. As introduced in chapter 1, intelligence, years of education and cognitive reserve seem to be some of the most likely factors that could exert a modulatory effect on cognitive decline in aging.

Intelligence and CR might have distinct compensatory impacts on cognitive functioning (Stern, 2002, 2009). Moreover, it is necessary to be careful with data that relate intelligence and cognitive aging, since it is difficult to separate the expected beneficial effects of high IQ with respect to those of a possible compensatory strategy. It is, indeed, very difficult to disentangle between a robust set of cognitive strategies due to high intelligence that an individual can build during her lifetime, with respect to a new set of strategies built during older age in order to compensate for age-related deficits.

As Nucci and colleagues (2012) pointed out, intelligence definition and measurement are based on intellectual performance (Wechsler, 1944), whereas cognitive reserve is based on the concept of cognitive skills acquired during one's lifetime (e.g., Stern, 2002, 2009). Therefore, we decided to measure and treat cognitive reserve and intelligence separately. We moreover decided to consider years of education not only as a contribution for the CR score, but also as a separate independent predictor.

Years of Education

Biased sampling in cognitive studies is a well-known phenomena. However the majority of researchs keeps using college students as experimental participants. Apart from the general criticism that arises from an incorrect sampling selection (e.g., Heckman, 1979), this tendency is especially inappropriate when we have to compare younger and older adults. It is, in fact, clear that taking only college students and comparing them with a general sample of older adults will lead to misleading (or at least under-representative) results. Therefore, one of our concerns was to select samples of younger and older adults whose years of education were comparable in average and range.

Nowadays, in the Italian population, the majority of people between 18 and 35 years old have at least 13 years of formal education (full-time education is compulsory until 16 years of age). Therefore, it is hard to recruit volunteers that ended their educational path earlier on. On the other hand, few people over 65 years old attended university and most of them had less than 10 years of formal education. It is, therefore, clear that the restrictions we chose to apply made the participants' recruitment very long and demanding.

Intelligence

Some studies suggest a strong relationship between intelligence and a high level of cognitive functioning in aging (e.g., Alexander et al., 1997; Albert and Teresi, 1999). Therefore, intelligence is one of the preferred proxies in order to explore cognitive aging and cognitive reserve.

All of our volunteers were administered the Wechsler Adult Intelligence Scale (WAIS-r; Wechsler, 1981), or a subset of tests which allowed us to obtain a measure of total IQ (IQ), verbal IQ (VIQ), and performance IQ (PIQ), and, when they were present, to exclude possible outliers. The IQ measurement also allowed us to check whether this factor was uniformly distributed in the two age-groups.

Cognitive Reserve

The "Cognitive Reserve Index questionnaire" (CRIq; Nucci et al., 2012) is a recently developed questionnaire created to quantify the CR in the Italian population. To compute the CR index, the contribution of factors such as activities (sport, leisure, and cultural), years of education, and occupation, carried out by participants during their adult lifetime are weighted and combined in a composite score. As its authors pointed out, since there are no similar standardized instruments to measure this construct for the Italian population, it is not possible to assess concurrent validity of the CRIq (Nucci et al., 2012). Although this instrument presents some limitations, such as a modest reliability (Cronbach's $\alpha = 0.62$, 95% Confidence Intervals: 0.56–0.97), we think that it could be very useful, inasmuch it allows us to have separate measures for lifestyle-related factors, measured indeed by this test, and intelligence. This separation is useful in order to investigate which aspect could modulate more aging effects in cognition.

2.4. Data analysis

In all of the experiments run in this project, we tried to maintain the same analytical procedures in order to get comparable results.

At the participants' level, trials with RTs faster than 100 and slower than 1500 ms were excluded, as well as trials above and below 3 SD from each individual's mean. In order to avoid post-error slowing confounds (Burns, 1965), error trials and trials following an error were not considered in the RT analyses. However, in the two ERP studies we chose not to exclude post-error trials to maintain as many ERP segments as possible for the electrophysiological analyses. Consequently we run the behavioural analyses on the same set of data.

Since one of the main aims was to explore age-related effect specifically on conflict resolution, we needed to control for any age-related slowing (Salthouse and Babcock, 1991; Salthouse, 1996). Therefore we applied a logarithmic transformation to RT data in the analysis, which was intended to compare the two age-groups (Verhaeghen et al., 2005). This transformation converts proportional effects into additive ones. We thus assumed age-related slowing to be constant across conditions, allowing subsequent Analyses of Variance (ANOVAs). For the RT analysis, correct trials only were considered. RT data were analyzed with a 2x2 Analysis of Variance (ANOVA) with congruency of the current trial (C vs I) and congruency of the previous trial to compare younger and older adults across conditions in the absence of group differences in speed. Hence, significant interactions that resist logarithmic transformations can be considered as due to true condition-specific effects. On the contrary, if interactions that were significant before the logarithmic transformation are not significant any more after it, it is possible to assign the effects to general factors such as age-related slowing.

After logarithmic transformation of raw RT data, we usually ran a 2 × 2 × 2 mixed ANOVA with congruency of *trial n* and congruency of *trial n-1* as within-subjects factors and age-group as the between-subjects factor. However, we used raw RTs for the analyses conducted within each group (e.g., correlations).

Since raw accuracy data were not normally distributed (as is often the case in tasks like the one we administered), we used non-parametric tests. In particular, we used the Mann–Whitney *U* test to compare accuracy in the two age-groups across

conditions, and the Wilcoxon signed-ranks test to compare pairs of conditions within each group.

We used the accuracy Stroop effect (measured as the difference between incongruent and congruent trials), which was instead normally distributed, as a dependent variable to perform a 2 × 2 mixed ANOVA with congruency in *trial n-1* as the within-subjects factor and age-group as the between-subjects factor.

In addition to the non-parametric tests, in some experiments we applied permutation tests in order to establish whether interactions exist. Indeed the statistical error of assuming that an interaction exists solely based on the presence of a simple effect in one group but not in the other group is well known in the literature (see Nieuwenhuis, Forstmann & Wagenmakers, 2011). The permutation approach we applied is the one suggested by Manly (Manly, 2007), which implies an unrestricted permutation of observations. We permuted all the factors randomly among all the participants and compared each F value of our real data with the distribution of the F values of the samples obtained from the permutations.

We also conducted exploratory correlation analyses between behavioural data regarding RT and accuracy with the volunteers' individual measures of age, CR, intelligence and years of education. In Experiments 4 and 8 also the ERP amplitude was used to explore the correlation among electrophysiological measurements, behavioural data and individual measures. Since these analyses were run separately for each age-group, we did not use logarithmic transformations but rather raw data. It is, however, important to point out that the correlational analyses made have to be considered as exploratory, since corrections for multiple comparisons were not applied.

Chapter 3 – Cognitive Control in the Verbal domain

In this chapter we explore Cognitive Control in the verbal domain. We firstly wanted to investigate the contribution of priming/binding mechanisms in a classic Colour-Word Stroop task with 4 alternative-forced choices and moreover to disentangle it from the effect of conflict adaptation. Once we obtained the confirmation that priming exerts an effect above and beyond that of conflict adaptation, we explored conflict adaptation phenomena and its age-related differences using a task with minimized priming effects (see chapter 2). Finally, we used the ERP technique paired with our priming-free task to gain electrophysiological evidence of age-related differences in cognitive control processes.

3.1. Disentangling priming and conflict adaptation in the Colour-word Stroop task

As explained in Chapter 2, to the best of our knowledge, there are no studies on sequential effects that used a four-alternative forced choice (4-AFC) Stroop task. Therefore, it has not been possible to disentangle whether priming/binding factors or conflict adaptation determine sequential effect, since a 3-AFC task does not allow for completely priming-free pairs of subsequent trials. To solve this problem, a colour-word Stroop task with four colours/responses and four words was designed in order to have priming-free sequences, at least for each pair of subsequent trials, while higher order sequential effects were still potentially present. Since previous studies used different paradigms (e.g., 3-choice Stroop task), results derived from these paradigms would not be directly comparable to ours. Thus, it would not be possible to establish whether differences between this study and previous ones are due to the increased difficulty of having four different alternatives or to the use of a priming-free context. To circumvent this problem, we ran a second experiment, which was composed of all the possible sequences, like in previous studies, but which employed four colours and four words, like the first experiment. If sequential congruency effects are (partially or totally) due to high-level conflict adaptation

mechanisms, they should occur even in a context of complete alternations (Experiment 1). On the other hand, if they are due to perceptual or mnemonic priming mechanisms or to binding processes, they should exclusively emerge when feature repetitions are present (Experiment 2).

Hereafter, we will refer to the contribution of feature repetition as priming, but, actually, since our design does not allow separating priming from binding accounts (see Chapter 1), these two possible explanations could be equally valid here.

3. 1. 1. Priming-free colour-word Stroop task – Experiment 1

Methods

Participants

Sixteen young adults (mean age = 24.6 years, range 18–34; 8 female, mean formal education = 13.8 years) participated in this study. All participants were native Italian-speakers, with normal or corrected-to-normal vision and normal colour perception, as assessed with a computerized version of the Ishihara Color Vision Test (Ishihara, 1962). All participants were right-handed, as measured with the Edinburgh Handedness Inventory (Oldfield, 1971). Participants signed an informed consent form and received 15€ for taking part in the study.

Design and stimuli

Participants were tested individually in a dimly lit room, sitting at a distance of about 50 cm from the computer display. The stimuli were presented against a light-grey background and consisted in four different words: GIALLO (yellow), VERDE (green), ROSSO (red) and BLU (blue), which were presented in four different ink colours: yellow, green, red, blue.

The task was a classical colour-word Stroop task in which participants were required to identify the ink colour and to ignore the word by pressing one out of four keys on a computer keyboard labeled with coloured stickers. They were asked to use the index and the middle finger of both hands for responses, and to respond as fast and accurately as possible. The colour-to-key mapping ("yellow,

green, red, blue" from left to right vs from right to left) was counterbalanced across participants (see Figure 2).

The single stimuli were categorized as congruent (C) (e.g., YELLOW printed in yellow) and incongruent (I) (e.g., YELLOW printed in blue), according to whether the word corresponded to the colour or not, respectively. Complete alternation sequences only were used, which means that in *trial n* both the colour-word (distractor) and the ink-colour (target) were different with respect to both the colour-word and the ink-colour of *trial n - 1* (e.g., *trial n - 1*: RED printed in yellow; *trial n*: BLUE printed in green). We also categorized sequential pairs of trials in the following categories: congruent–congruent (CC), congruent–incongruent, (CI), incongruent–congruent (IC), incongruent–incongruent (II), according to the congruency status of the *trials n - 1* and *n*.

At the beginning of the session, a training phase was presented to make sure that participants understood and were familiarized with the task. The training phase included 16 trials with all the possible word-colour combinations, namely 4 congruent and 12 incongruent trials. Each stimulus remained on the screen until a response was given. Then, a feedback about accuracy and speed appeared. If the response was correct and within 2,000 ms from trial onset, the feedback message in Italian was ‘‘Bene!’’ (in English: Good). Whenever the response was incorrect, or correct but occurred later then 2,000 ms from stimulus onset, the feedback messages was ‘‘Sbagliato’’ (‘‘Wrong’’) or ‘‘Corretto, ma cerca di essere più veloce...’’ (‘‘Correct, but try to be faster...’’), respectively. After an inter-trial-interval (ITI) of 500 ms, the next stimulus appeared. The training phase was repeated if the participant did not reach the proportion of 10 correct trials out of 16.

The test phase was divided in three blocks, each one subdivided in two sub-blocks composed of 64 stimuli arranged in order to have at least 15 trials for each sequence (CC, CI, II, IC), and at least 30 congruent trials, in order to avoid any contextual influence from unequal frequencies of occurrence of different congruency conditions (Gratton et al., 1992). For each test trial, the stimulus appeared in the center of the screen for 500 ms, followed by a blank of 2,000 ms whose offset marked the response deadline (2,500 ms). An extra blank screen varying randomly and continuously between 250 and 700 ms was presented before the onset of the next trial.

Data analysis

Trials with RTs beyond the 100–1,500 ms range were excluded (<0.07% of the total). Moreover, for each individual, trials above and below 3 SD from the mean RT within this range were also excluded. For the RT analysis we also excluded trials following an error, to avoid the confound of post-error slowing (Burns, 1965).

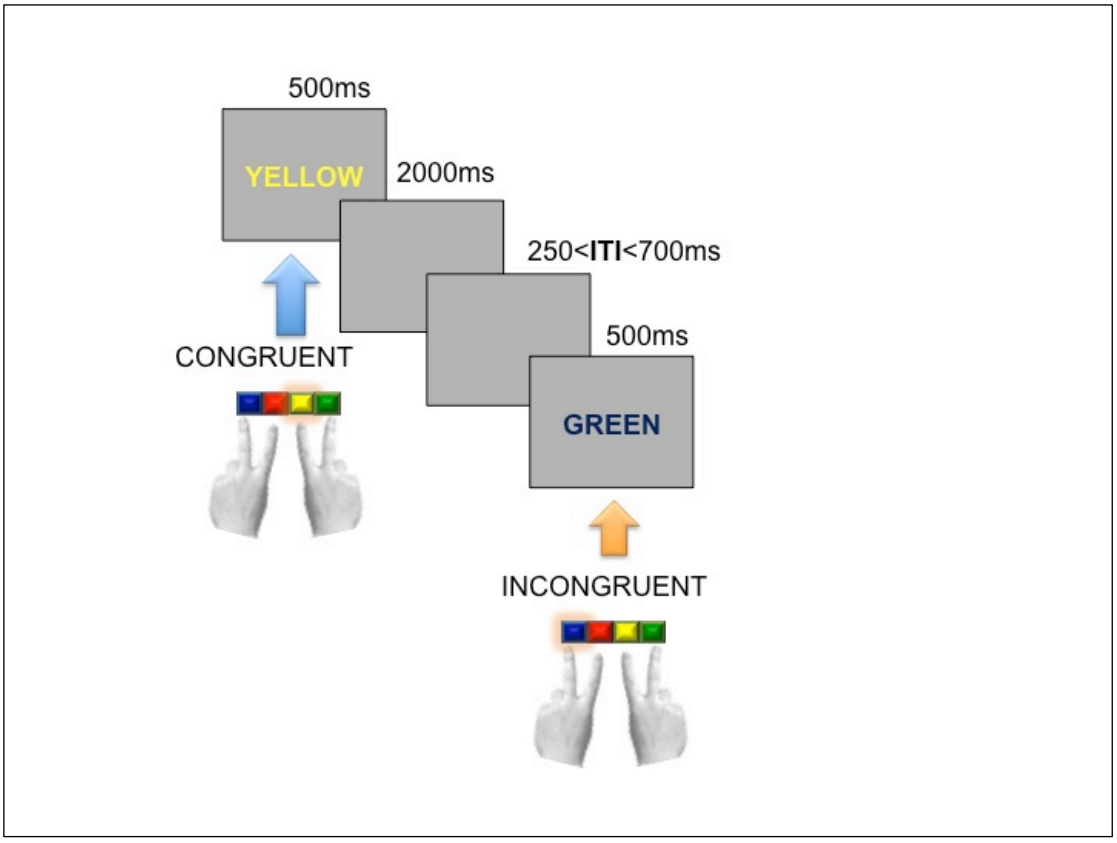

Figure 2- **Experimental design**. During the colour-word Stroop task each stimulus was presented for 500 ms, followed by a blank screen lasting 2000 ms. Before the onset of the subsequent stimulus, an Inter-Trial-Interval (ITI) varying randomly and continuously between 250 and 700 ms was presented. Stroop stimuli were divided in Congruent and Incongruent trials based on whether the ink-colour and the word corresponded or not. Participants were asked to respond by pressing one out of four response buttons displayed as shown in the panel. In the picture two Stroop trials are represented.

For the RT analysis, correct trials only were considered. RT data were analyzed with a 2x2 ANOVA with congruency of the current trial (C vs I) and congruency of the previous trial (C vs I) as within-subjects factors (Figure 3a). Since error data were not normally distributed, a non-parametric Wilcoxon test was used to compare pairs of conditions.

Results

Response times

RTs are reported in Figure 3a. The main effect of current trial congruency was significant [$F(1,14) = 31.04$, $p < .001$], indicating that responses to congruent stimuli were shorter than those to the incongruent ones with a Stroop effect of 32 ms. Neither the main effect of preceding trial congruency [$F(1,14) = 0.05$, $p = .83$] nor the interaction [$F(1,14) = 0.55$, $p = .47$] between these factors were significant.

Accuracy

The accuracy Stroop effect in the current trial was significant when the previous trial was congruent [CI vs CC; Wilcoxon's T = 18, Z = 2.38, $p = .017$] but not when it was incongruent [II vs IC; Wilcoxon's T = 58, Z = 0.11, $p = .9$]. Moreover, error rate in incongruent trials was reduced when preceded by a congruent vs incongruent trial [CI vs II; Wilcoxon's T = 25, Z = 2.22, $p = .03$, Figure 3b]. Conversely, incongruent trials preceded by an incongruent trial (II) showed the same accuracy level as congruent trials preceded by either a congruent (CC) [Wilcoxon's T = 65, Z = 0.15, $p = .88$] or by an incongruent trial (IC) [Wilcoxon's T (16) = 58, Z = 0.11, $p = .91$]. Finally, congruent trials' accuracy was not modulated by *trial n-1* congruency [CC vs IC; Wilcoxon's T = 53, Z = 0.77, $p = .44$] as shown in Figure 3b.

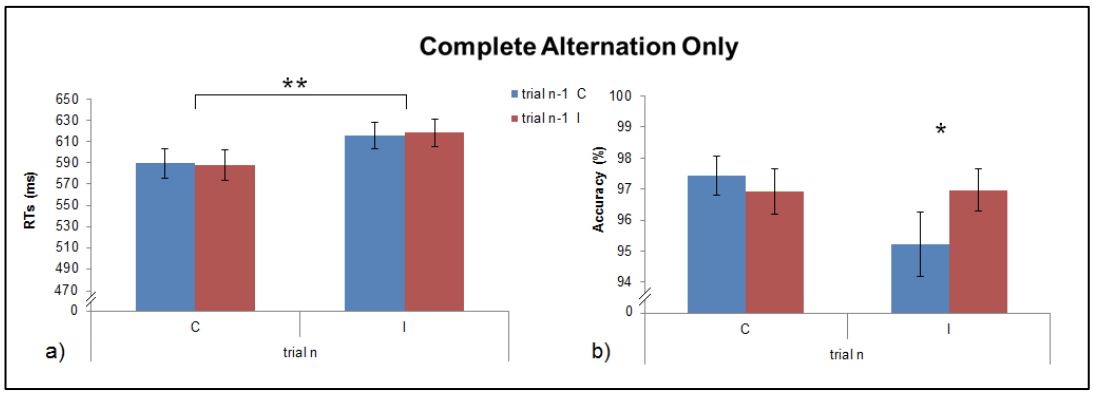

Figure 3. Response times (a) and accuracy (b) in Experiment 1 as a function of current (*n*) and preceding (*n-1*) trial congruency. Error bars represent the standard error of the mean.

Discussion

RTs in Experiment 1 showed the presence of a Stroop effect but no conflict adaptation effects, while a conflict adaptation effect was present for accuracy. Accuracy results showed that without first level priming, the Stroop effect is nullified when the preceding trial is incongruent. This means that II sequences are performed as well as IC and CC ones, but there is no advantage for CC sequences with respect to IC. This seems to be in contrast with other studies (Notebaert et al., 2006; Notebaert & Verguts, 2007; West & Moore, 2005). These previous studies showed a consistent conflict adaptation effect in RTs and the modulation of preceding trials was present also for congruent current trials, making CC responses faster than IC ones. Such differences could be essentially due to two reasons. One possibility for the absence of conflict adaptation effects in RTs is that previous studies did not use complete alternation trials, and the effect was mainly driven by partial feature repetitions, as suggested by Mayr and colleagues (2003). Notebaert and associates (2006) showed a significant interaction between previous and current congruency in the complete alternation trial analysis, although this interaction was stronger in the feature repetition trials analysis. However, as we already mentioned, these trials were not strictly priming-free, due to the presence of sequences such as: GREEN in red in *trial n - 1* and RED in green in *trial n*, which could give rise to residual carry over effects.

Another possibility for the discrepancy between the present study and previous ones is that the difficulty was higher in the present 4-choice RT task than in previous Stroop tasks with fewer responses and relevant colours. Four target-colours were used here in order to have complete alternation sequences. Despite participants having to choose among four-alternative (Vs 3) choices in the present experiment, shorter mean RTs were observed here (608 ms) than in previous studies (e.g., Notebaert et al., 2006: approximately 650 ms; West and Moore, 2005: about 795 ms). It is therefore likely that our sample of participants stressed speed over accuracy, which in turn might have caused the shift of conflict adaptation effect from speed to accuracy level. Unfortunately, the accuracy results are not fully reported in some previous studies, and we cannot establish whether sequential effects were also present in the accuracy data of these studies that used fewer alternative choices.

3. 1. 2. Classic colour-word Stroop task - Experiment 2

Experiment 1 revealed no RT conflict adaptation effect in a priming-free 4-AFC Stroop task. Most of the previous studies about conflict adaptation consistently showed the presence of this effect (Notebaert et al., 2006; Notebaert & Verguts, 2007; West & Moore, 2005) but they did not exclusively use complete alternation sequences. At the same time, we found a partial conflict adaptation effect in the accuracy level that was selective for incongruent current trials. Such a discrepancy between our results and previous ones deserved further investigation to rule out the possibility that the differences are due to methodological issues such as the use of a 4-choice Stroop task vs 3- or 2-choice versions and not to the use of a priming-free paradigm. We therefore ran a second experiment in which all the possible sequences were presented (like in some previous studies) but now using four-alternative choices, and then analyzed separately the conflict adaptation depending on the type of feature repetition/alternation.

Methods

Participants

Sixteen young adults (mean age = 25.9 years, range 22–30; 9 females, mean formal education = 19.4 years) participated in this study. All participants were native Italian-speakers, with normal or corrected-to-normal vision and normal colour perception as assessed with Ishihara Color Vision Test. All participants were right-handed as assessed with the Edinburgh Handedness Inventory. Participants signed an informed consent form and received 15 € for taking part in the study.

Design and stimuli

The material and design of Experiment 2 were identical to those of Experiment 1, with the exception that not only complete alternations, but all the possible sequences of trials were presented. The final amount of trials and the task structure are the same of Experiment 1: three blocks, each one subdivided in two sub-blocks composed of 64 stimuli.

In addition to the previous categorization, we divided the sequential pairs of trials into: *Complete Repetition, Complete Alternation* and *Partial Repetition*. Moreover we subdivided *Partial Repetition* sequences into five subcategories: *Target Repetition, Distractor Repetition, Target to Distractor, Negative Priming,* and *Inversion* (see also Chapter 2).

In Target Repetition sequences, the target (i.e., the colour) was the same in *trial n - 1* and *trial n*, but the distractors (i.e., the words) were different. In Distractor Repetition sequences the target was different in *trial n - 1* and *trial n* while the distractor was the same word. Target to Distractor indicates sequences in which the target of *trial n - 1* became the distractor of *trial n*, while the distractor of *trial n - 1* was different with respect to the target of *trial n*. Negative Priming sequences were those in which the distractor of *trial n - 1* became the target of *trial n*, while the target of *trial n - 1* was different with respect to the distractor of *trial n.* This situation usually elicits a behavioural cost known as negative priming (Tipper & Cranston, 1985). Inversion refers to sequences in which the target of *trial n - 1* became the distractor of *trial n* and the distractor of *trial n - 1* became the target of *trial n*. All of the different types of trials and sequences were presented randomly.

Data analysis

Trials with RTs beyond the 100–1,500 ms range were excluded (<0.04% of the total). For each participant, trials above and below 3 SD from their mean RT were excluded. Moreover, we excluded trials following an error from RT analysis, to avoid the confound of post-error slowing (Burns, 1965).

Since accuracy data were not normally distributed, a Wilcoxon test was used to analyze them. For the RT analysis, we considered correct trials only. RTs on correct trials were submitted to a 2x2 ANOVA with congruency of the current trial and congruency of the previous trial as within-subjects factors.

We ran four different analyses in order to separate various aspects of priming on sequential effects. First, we analyzed all trials together, which included all possible sequences, to verify that these results are comparable to the ones of previous studies. Second, only complete alternation sequences were taken into account to reveal the strength and the type of sequential effects in the absence of priming. Complementary to the latter, the third analysis involved all the

sequences presenting some kind of repetition (i.e., complete and partial repetitions). Since repetition sequences are composed by pairs of trials involving both positive (i.e., Complete Repetition, Target Repetition, Distractor Repetition) and negative priming (i.e., Inversion, Distractor to Target), a fourth analysis focused on sequences supposed to elicit positive priming only (i.e., Complete Repetitions, Target Repetition and Distractor Repetition). This specifically highlighted the contribution of repetition priming on sequential effects.

Results

All sequences

The first analysis was run including all the possible sequences, as it is typical in previous literature.

Response times

The mean RTs are shown in Figure 4a. The main effect of current trial congruency was significant [$F(1,15) = 85.98$, $p < .001$], indicating that responses for congruent trials were faster compared to those for incongruent trials, with a Stroop effect of 45 ms. The main effect of preceding trial was not significant [$F(1,15) = 0.39$, $p = .54$]. The interaction between the congruency on *trial n* and the congruency on *trial n - 1* resulted significant [$F(1,15) = 23.06$, $p < .001$]. Tukey's HSD post-hoc test revealed that congruent trial responses were influenced by the preceding trial congruency [$p = .005$], being faster when *trial n - 1* was congruent (CC) than when it was incongruent (IC). RTs on incongruent current trials, did not significantly depend on *trial n - 1* congruency, although this effect was very close to the significance level [II vs CI, $p = .06$].

Accuracy

Incongruent trials had a lower number of errors when preceded by another incongruent trial than by a congruent one [CI vs II, Wilcoxon's T = 16, Z = 2.06, $p = .039$]. Responses to incongruent trials preceded by an incongruent trial (II) showed the same accuracy as congruent trials preceded by either a congruent (CC) [Wilcoxon's T = 32, Z = 0.94, $p = .34$] or an incongruent trial (IC) [Wilcoxon's T = 30.5, Z = 0.17, $p = .86$]. Accuracy on congruent trials was not modulated by congruency on preceding trials [CC vs IC, Wilcoxon's T = 30, Z = 1.08, $p = .27$], as shown in Figure 4b.

Complete alternations only

Among all the possible sequences, complete alternation pairs of trials only were included in this analysis, like in Experiment 1. This means that both the colour-word (distractor) and the ink-colour (target) of the *trial n* were different with respect to the colour-word and the ink-colour of *trial n-1*.

Response times

The results are comparable to those of Experiment 1. Figure 4c shows that the main effect of current trial congruency was significant [$F(1,15) = 65.68$, $p < .001$], indicating that responses for congruent trials were faster compared to the incongruent trial ones and showing a Stroop effect of 50 ms. Neither the main effect of preceding trial congruency [$F(1,15) = 1.13$, $p = .30$], nor the interaction [$F(1,15) = 0.95$, $p = .34$] were significant.

Accuracy

Although accuracy showed the same trend as in Experiment 1, namely it was reduced in incongruent trials when a congruent (Vs incongruent) trial preceded it (Figure 4d), the difference between the CI and other conditions (i.e., II, CC and IC) did not reach significance here [Wilcoxon's T = 16, Z = 1.17, $p = .24$; Wilcoxon's T = 26, Z = 0.15, $p = .87$; Wilcoxon's T = 22, Z = 1.29, $p = .19$, respectively]. Thus, response accuracy was similar across all conditions.

Repetitions only

Only pairs of trials presenting complete or partial feature repetitions were considered here. Those were the pairs of trials in which the colour-word (distractor) and/or the ink-colour (target) were present in *trial n - 1* as target or distractor. More specifically, this analysis included: Target Repetition (e.g., *trial n - 1*: GREEN in red; *trial n*: BLUE in red), Distractor Repetition (e.g., *trial n - 1*: GREEN in red; *trial n*: GREEN in blue), Target to Distractor (e.g., *trial n - 1*: GREEN in red; *trial n*: RED in blue), Negative Priming (e.g., *trial n - 1*: GREEN in red; *trial n*: BLUE in green), and Inversion (e.g., *trial n - 1*: GREEN in blue; *trial n*: BLUE in green).

Response times

Both the main effects of current trial congruency [$F(1,15) = 95.82$, $p < .001$; Stroop effect: 50 ms] and the preceding trial congruency [$F(1,15) = 31.03$, $p < .001$] were significant. The interaction between current trial congruency and the preceding trial congruency was also significant [$F(1,15) = 16.61$, $p < .001$]. Tukey's test showed that RTs on incongruent trials were not affected by the preceding trial congruency [II vs CI, $p = .70$], while RTs on congruent trials were shorter when preceded by a congruent trial than by an incongruent one [CC vs IC, $p < .01$].

Accuracy

Accuracy was not modulated by any congruency condition [for all, ps > 0.11].

Positive priming sequences

Since repetitions elicit different types of phenomena that could facilitate or, on the contrary, impair conflict resolution, only sequences thought to elicit positive priming were included in this analysis, that is, complete repetitions, target repetition and distractor repetition sequences.

Response times

The main effects of current trial congruency [$F(1,15) = 52.72$, $p < .001$; Stroop effect: 40 ms] and of the preceding trial congruency [$F(1,15) = 13.79$, $p < .002$] were significant (Figure 4e). The current by preceding congruency interaction was also significant [$F(1,15) = 26.32$, $p < .001$]. RTs on incongruent trials were not modulated by the preceding trial congruency [II vs CI, Tukey's $p = .42$], while RTs on congruent trials were shorter when preceded by a congruent trial than by an incongruent one [CC vs IC, Tukey's $p < .001$].

Accuracy

The accuracy level did not change across conditions [for all, ps > 0.09; Figure 4f].

Global analysis

In order to definitely check that the exclusion of priming in Experiment 1 was the critical factor for the occurrence of sequential effects, a direct comparison of RTs between Experiment 1 and Experiment 2 was made.

RTs on correct trials were submitted to a 2x2x2 ANOVA with Experiment (1 vs 2) as between-subjects factor and congruency of the current trial and congruency of the previous trial as within-subjects factors. Both the main effects of current trial congruency [$F(1,30) = 105.3, p < .001$] and the interaction between current and previous trial congruency were significant [$F(1,30) = 4.6, p < .04$]. Furthermore, the experiment by current by preceding congruency three-way interaction was significant [$F(1,30) = 11.3, p < .002$], supporting the fact that the presence of priming sequences modulates sequential effects.

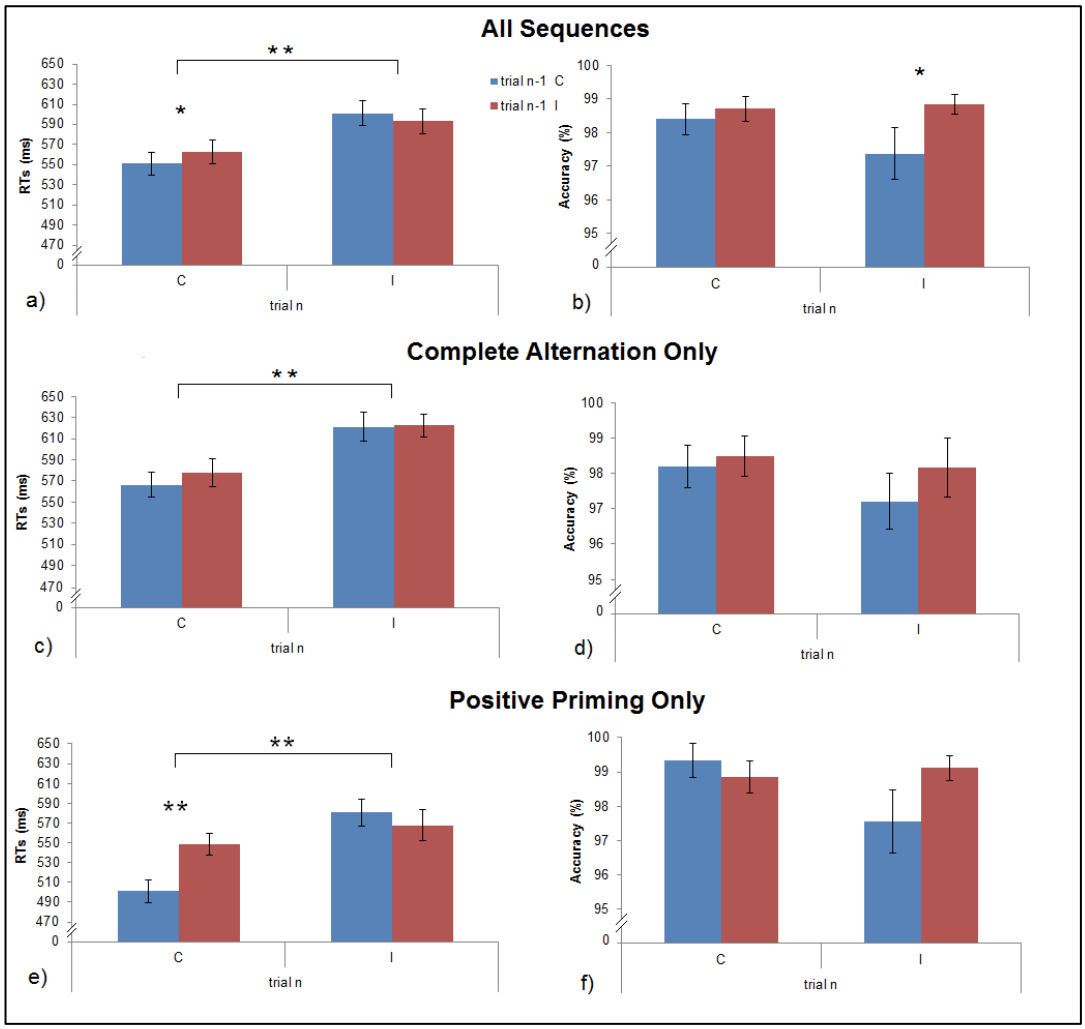

Figure 4 - Response times in ms (a, c, e) and accuracy (b, d, f) in Experiment 2 as a function of current (*n*) and previous (*n - 1*) trial congruency. Error bars represent the standard error of the mean. (a, b) - All the different types of sequences were included in the graphs. (c, d) - Complete alternation sequences only were included in the plotted data. (e, f) - Sequences involving positive priming only were included in the plotted data.

Discussion

In the second experiment, RT results concerning all possible sequences corroborate previous findings with a few exceptions. Using this 4-choice RT paradigm, the post-hoc analysis showed facilitation for CC with respect to IC sequences but not for II with respect to CI, unlike in previous literature. Notebaert and associates (2006) reported a significant interaction between previous and current trial congruency but did not report post-hoc comparisons. It has to be considered again that we used a paradigm with four colour-words and four colour responses, while previous paradigms usually had three or four colour-words and three colour responses. In our paradigm, sequences with incongruent current trials have about 44% of repetitions with respect to 50% average repetition sequences of Notebaert and colleagues' paradigm. The opposite happens for negative priming eliciting sequences: 31% with respect to 28%. If sequential effects are mainly driven by priming effects (both positive and negative), these subtle differences in the relative percentage of sequence types can partially explain why our results do not perfectly coincide with previous ones.

Results from Experiment 1 suggested that, in priming-free conditions such as complete alternation sequences, RTs of current trials are not influenced by previous trial congruency. The analysis focusing on complete alternations in Experiment 2 confirmed that when first-order priming contributions are prevented, RTs do not show conflict adaptation of the Stroop effect.

Priming conditions, that is repetitions and positive priming eliciting sequences, showed the typical RT conflict adaptation effects, with a significant interaction between current and previous congruency due to shorter RTs on CC than IC sequences, and on II than CI sequences.

When considering the Stroop effect with respect to feature repetitions, it emerges that the presence of priming reduces the average RTs but increases the Stroop effect. In priming sequences with a congruent *trial n - 1*, the Stroop effect was greater than in priming-free conditions. This probably occurs because priming facilitates current congruent trials with respect to incongruent ones, provided that conflict has not been experienced in the preceding trial. On the contrary, if conflict has been experienced in *trial n - 1*, the performance is not

modulated by priming, and the Stroop effect is similar for every feature repetition condition.

In the analysis concerning accuracy, the Stroop effect disappeared with incongruent preceding trials. Such a pattern was observed in every feature repetition condition, although it did not always reach significance. Some related previous works do not report accuracy results. Among the exceptions, Mayr et al. (2003) reported the error percentage in a classical flanker task, comparing the performance with and without complete repetition sequences. Their results for the condition with complete repetitions are comparable with ours, with an increased error rate limited to CI sequences.

General discussion of Experiments 1 and 2

Classic conflict adaptation effects have usually been described as reduced congruency effects (e.g., Stroop effect) whenever the preceding trial is incongruent and thus elicits conflict between relevant and irrelevant features. Previous studies also showed this phenomenon as a behavioural facilitation of CC with respect to IC sequences and a facilitation of II with respect to CI sequences.

The present study aimed at separating feature repetition from conflict adaptation contributions in order to clarify the origin of sequential effects in a Stroop task with four colour-words and four colour responses. First, a priming-free classic Stroop task was used in Experiment 1 to understand whether genuine conflict adaptation effects still occur. Then, a control Stroop task was used in Experiment 2 with no constraints on sequential repetitions and alternations.

It is necessary to point out that our study was not designed to disentangle perceptual priming contributions from binding ones. Future studies should be designed in order to disentangle if contributions from feature repetitions on sequential effects are due to priming processes, or can be better explained by binding mechanisms.

The results show two different patterns related to the congruency of the present trial. Whenever the present trial is congruent (absence of conflict) the sequential effects are exclusively due to priming, since they disappeared in the priming-free conditions and increased when considering priming sequences only (i.e., partial and complete repetitions) with respect to non-priming sequences

(complete alternations). Thus, sequential effects related to current congruent trials could not reflect conflict adaptation.

By contrast, in priming-free conditions, when the present trial is incongruent (presence of conflict), and the previous trial was also incongruent (just experienced conflict), the effect of Stroop interference disappears for accuracy with respect to when the previous trial was congruent. Such a tendency is present in all the other feature repetition conditions, although it does not always reach significance. The presence of sequential effects in a priming-free condition, for incongruent trials only, supports the idea that cognitive control can modulate the performance only if the current trial leads to a conflict.

In conclusion, the findings arising from this first study demonstrate that whenever target and distracting information are not in conflict, like in congruent trials, facilitation due to repetition priming occurs, while experiencing a trial with conflicting features increases cognitive control, above and beyond priming- or binding-related effects, probably to cope better with a possible subsequent situation in which a new conflict has to be solved.

3.2. Cognitive Control in the verbal domain and its age-related modifications: behavioural evidence – Experiment 3

In the previous section we reported a study where, in a sample of younger individuals, we observed that sequential effects concerning congruent *trials n* were exclusively due to priming, whereas conflict adaptation effects were actually present in incongruent *trials n*. Specifically, the accuracy-Stroop effect was present when *trial n-1* was congruent, but it disappeared when *trial n-1* was incongruent. These results support the hypothesis that priming (or binding) exerts its modulation, separately with respect to the cognitive control one, to determine conflict resolution and conflict adaptation.

Thus, in the present study, we used the priming-free version of our 4-AFC Colour-word Stroop paradigm to explore aging effects on verbal conflict resolution and conflict adaptation, above and beyond possible confounding effects of priming-related processes. More specifically, we used the Stroop effect

(i.e., the difference between incongruent and congruent trials for RTs and accuracy) as a measure of conflict resolution, and the effect of the preceding trial's congruency on the Stroop effect (i.e., the difference between incongruent and congruent trials *n-1* on the Stroop effect calculated in *trial n*) as a measure of conflict adaptation.

Considering the results from the previously mentioned studies (e.g., Davidson et al., 2003; Mayas et al., 2011; West & Alain, 2000; Ludwig et al., 2010; Verhaeghen & De Meersman, 1998), we predicted an age-related decline both for conflict-resolution ability and for conflict adaptation. We also aimed at verifying the hypothesis of a compensatory role of cognitive reserve (CR) and intelligence in coping with the age-related decline on specific cognitive processes underlying performance of the Stroop task. We expected that older adults with higher levels of CR and intelligence might better countervail the age-related impairment in verbal conflict resolution.

Methods

Participants

Twenty-three older adults (mean age = 71 years, range 65-79; 12 females) and 22 younger controls (mean age = 24 years, range 18-34; 10 females) participated in this study. All participants but one in each group were right-handed, as measured with the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were native Italian speakers, with normal or corrected-to-normal vision and normal colour perception controlled through the use of the Ishihara Color Vision Test (Ishihara, 1962).

None of the older adults met the criteria for dementia (Mini Mental State Examination score range: 28–30/30, Folstein, Folstein, & McHugh, 1975, Montreal Cognitive Assessment score range: 26 –30/30, Nasreddine et al., 2005). Six of them reported the use of regular medications for cardiovascular disease. Two additional older participants were excluded, one because of colour perception deficits and the other because of excessively slow responses (> 3 *SD* from the group mean). Two extra younger adults were also excluded because of low intelligence scores (IQ =72) and low accuracy rate (86%, - 2.9 *SD*).

The two age-groups had on average attained the same years of formal education (younger, range: 9–18, *M* =13.4 years; older, range: 6–18, *M* =12.1

year, [$t(43) = -1.28$, $p = .2$]. The data from 16 of the 22 younger participants of this study has already been reported in Experiment 1. Participants signed an informed consent form and received €15 for taking part in the study.

Experimental Material and Design

The task design is the same described in Experiment 1, presenting complete alternation only sequences. This implies that the colour word (distractor) and the ink colour (target) on *trial n* were different from the colour word and the ink colour on *trial n-1* (e.g., RED in yellow, followed by BLUE in green).

During the intervals between Stroop blocks, the WAIS–R subtests were administered in a randomized order. Nine subtests of the WAIS–R (Wechsler, 1981) were administered to the participants to calculate verbal and performance IQs (VIQ and PIQ): block design, arithmetic, vocabulary, similarities, comprehension, digit span, digit symbol, object assembly, and picture completion. Participants were administered some of the WAIS–R subtests during the intervals between the first and second Stroop blocks, and between the second and third ones (randomized order). The remaining WAIS–R subtests were administered in a second session, run on a different day, when the same participants performed a different experimental task. Six participants (4 younger and 2 older) were not available for the second WAIS session.

After the last Stroop block, the CRIq (Nucci et al., 2011) was administered to the older participants only. This questionnaire was developed to quantify CR for the Italian population. The CR index is computed by weighting the contribution of factors, such as years of education, occupation, and activities (sport, leisure, cultural), that had been carried out during the entire adult lifetime. The items used in the CRIq show good reliability ($\alpha = .62$, 95% CI: 0.56– 0.97). However, concurrent validation of the CRIq cannot be assessed, because there are no similar standardized instruments to measure this construct for the Italian population.

Results

Response Times

Trials with RTs slower than 100 and faster than 1500 ms were excluded (1.33%). For each participant, trials above and below 3 *SD* from their mean RT

were also excluded (1.15% of the total). Error trials and trials following an error were not considered in the RT analysis to avoid post-error slowing confounds (Burns, 1965).

RT data were analyzed with a 2x2x2 mixed ANOVA with congruency of *trial n* and congruency of *trial n-1* as within-subjects factors, and age-group as the between-subjects factor. To compare the RTs of the two age-groups, a logarithmic transformation of raw data was applied to partially control for age-related slowing (Verhaeghen & De Meersman, 1998). The age main effect was significant [$F(1, 43) = 70.6$, $p < .001$], indicating that older adults responded more slowly than younger controls (mean RT: 863 ms and 611 ms, respectively).

The interaction between group and *trial n* congruency was significant [$F(1, 43) = 20$, $p < .001$], supporting the well-known increase of the Stroop effect (i.e., the difference between incongruent and congruent trials) in older adults (89 ms) with respect to younger adults (30 ms) (Figure 5a). A significant interaction that resists a logarithmic transformation cannot simply be explained as due to general factors (i.e., age-related slowing); it needs to be interpreted as due to condition-specific effects. No other effect was significant. In particular, neither of the two groups showed a significant main effect of *trial n-1* congruency: younger, *t* test $p = .27$; older, $p = .09$, or an interaction between *trial n* and *trial n-1* congruency: younger, $p = .51$; older, $p = .08$. We then conducted Pearson's correlation analyses between the RTs and measures of CR and intelligence. Since these analyses were run separately for each group, we used raw RTs instead of a logarithmic transformation. As specified in the methods section, IQ measures of six participants were missing. Those participants were excluded from the analyses involving correlations with intelligence. Younger adults' overall mean RTs were inversely correlated with VIQ [$r(16) = -.48$, $p < .045$] and PIQ [$r(16) = -.52$, $p = .027$]. Older adults showed a negative correlation between overall mean RTs and VIQ [$r(19) = -.49$, $p = .026$], PIQ [$r(19) = -.55$, $p = .01$], years of education [$r(19) = -.63$, $p = .002$], and, more generally CRIq [$r(19) = -.45$, $p = .042$]. In older adults, the RT Stroop effect was inversely correlated with VIQ [$r(19) = -.55$, $p = .01$] and only as a tendency with PIQ [$r(19) = -.40$, $p = .071$]. Younger adults' Stroop effect was not modulated by intelligence measures [VIQ: $p = .518$; PIQ: $p = .989$; see Figure 6].

Moreover, an ANCOVA was run with the raw RT-Stroop effect as dependent variable, and group, VIQ, PIQ, and education as predictors. This analysis revealed that the interaction between group and VIQ was significant [$F(1, 31) = 4.55$, $p = .041$], whereas interactions between group and PIQ and between group and education were not significant [for both, ps > .76].

Accuracy

Since the raw accuracy data were not normally distributed we used non-parametric tests. In particular, we used a Mann–Whitney *U* test to compare accuracy in the two age-groups across conditions, and a Wilcoxon signed-ranks test to compare pairs of conditions within each group. Younger and older adults showed a comparable level of general accuracy [96% and 97%, respectively; Mann–Whitney $U = 185$, $Z = -1.53$, $p = .12$]. The accuracy difference between incongruent and congruent trials (i.e., the Stroop effect) was not significant in either age-group [younger: Wilcoxon's $T = 1.13$, $p = .27$; older: Wilcoxon's $T = 1.63$, $p = .12$].

We then used the accuracy-Stroop effect, which was normally distributed, as a dependent variable for the subsequent 2x2 mixed ANOVA with congruency in *trial n-1* as a within-subjects factor, and age-group as a between-subjects factor. *Trial n-1* congruency significantly modulated the Stroop effect on *trial n* [$F(1, 43) = 8.87$, $p < .005$; see Figure 5b]. This means that the accuracy-Stroop effect was present after a congruent trial (a CI sequence), but it disappeared after an incongruent one (an II sequence). However, neither the main effect of age-group [$F(1, 43) = 0.002$, $p = .97$], nor the interaction between *trial n-1* congruency and age-group [$F(1, 43) = .40$, $p = .53$], were significant, indicating that such sequential Stroop effects are not different in older people. Noteworthy is that the analysis carried out on the Stroop effect did not assess the impact of *trial n-1* on repeated congruency.

Thus, a Wilcoxon signed-ranks test was used to directly compare CC and IC sequences. No significant difference, however, was found in either age-group, although there was a tendency for the older group to show higher accuracy for CC with respect to IC sequences [$p = .052$; younger: $p = .57$].

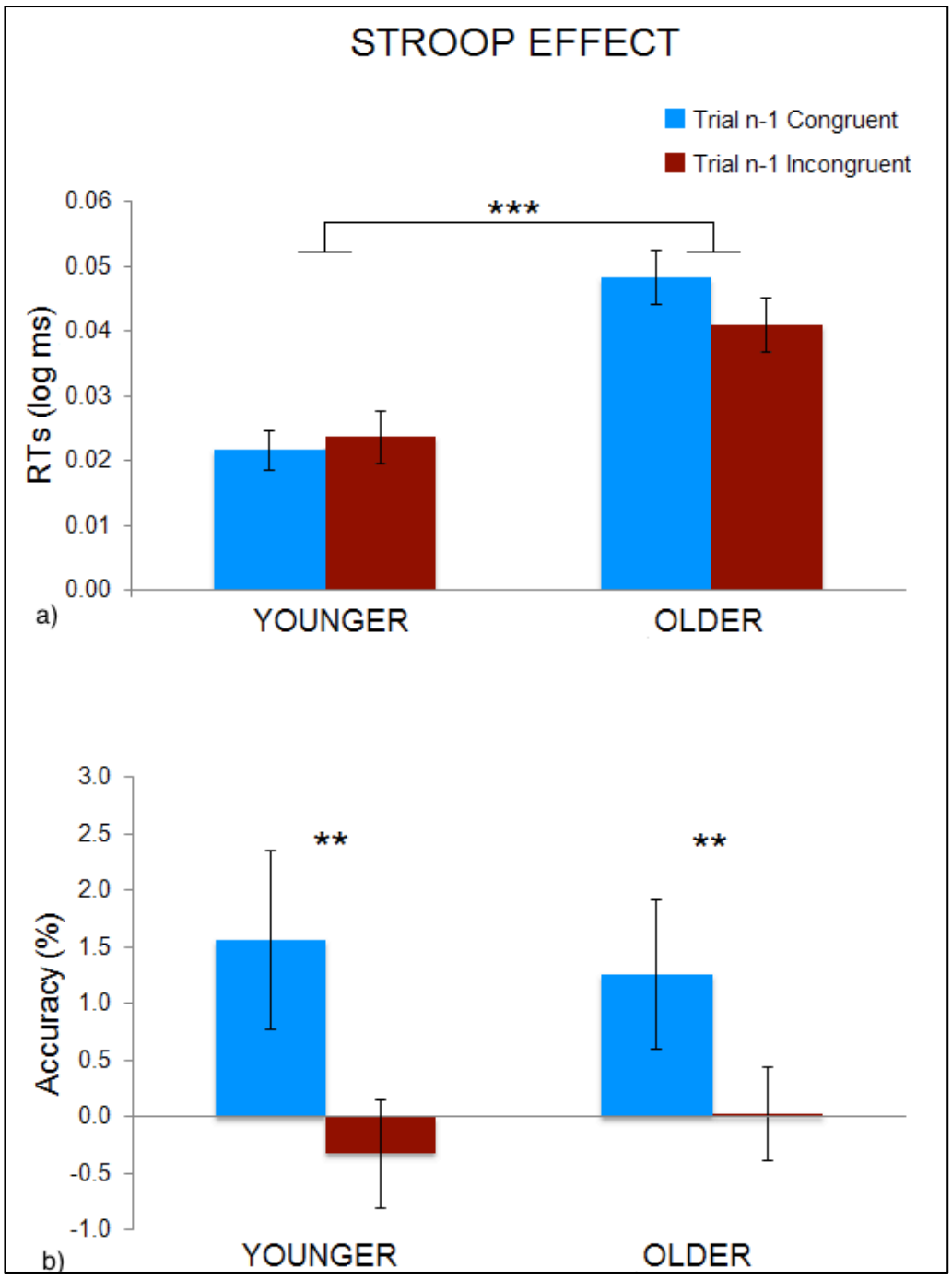

Figure 5 - RT-Stroop effect (Panel a) and accuracy-Stroop effect (Panel b) as a function of previous-trial *(n-1)* congruency, in younger and older adults. Error bars represent the standard error of the mean.

Discussion

The goal of this study was multifaceted. First, it investigated age-related differences in two fundamental cognitive abilities: conflict resolution and conflict adaptation. We considered the Stroop effect as a measure of conflict

resolution, and the modulation of the Stroop effect by the congruency of the preceding trial on the Stroop effect as a measure of conflict adaptation.

A sub-goal was to study conflict adaptation in a more genuine context, one in which priming effects were controlled for. To that purpose, the Stroop task was designed so as to exclude sequences with partial and complete feature repetitions. This prevented first-order positive and negative priming from affecting performance. Finally, we also assessed the compensatory role of factors such as CR and intelligence on specific cognitive processes underlying performance of the Stroop task. In the following paragraphs, we shall present and discuss how the different aspects of the findings relate to each of these goals.

We replicated the typical findings of cognitive aging studies as far as speed is concerned: older adults were slower than younger ones, even if the accuracy level was comparable in the two age-groups. Older adults sacrificed speed for accuracy (e.g., Rabbitt, 1979; Salthouse, 1985).

The fact that they were slower but not less accurate with respect to younger adults supports the general slowing theory (Salthouse & Babcock, 1991; Salthouse, 1996). However, this theoretical framework cannot easily explain the greater Stroop effect found in older adults by the current and previous studies (e.g., MacLeod, 1991; West & Alain, 2000; West & Moore, 2005). To avoid the confound of absolute RT slowing, we transformed the data logarithmically (see Verhaeghen & De Meersman, 1998), and still observed a significant increase of the RT-Stroop effect in older adults, suggesting that aging also affects the specific process of conflict resolution.

A large part of the literature about conflict resolution has shown the presence of sequential effects, namely, a facilitation that takes place whenever the preceding trial has the same type of congruency as the current one (Botvinick et al., 2001; Mayr et al., 2003; West & Moore, 2005). It is still a matter of debate whether such effects are due to conflict adaptation or originate from priming influence. By using a paradigm that reduced priming effects, we found that sequential effects were still partially present. In particular, sequential effects relative to congruent trials disappeared, suggesting that they are likely due to priming or binding phenomena rather than to pure conflict adaptation. On the contrary, although conflict adaptation effects were absent for RT data, accuracy

results clearly showed that the Stroop effect is nullified after incongruent preceding trials.

This finding confirmed the results of Experiment 1 and it is consistent with theories of conflict adaptation (Botvinick et al., 2001), since it demonstrates that experiencing a trial with conflicting features enhances conflict resolution in a subsequent trial in which a new conflict has to be solved above and beyond priming-related effects. Nevertheless, conflict adaptation was spared by aging in our dataset.

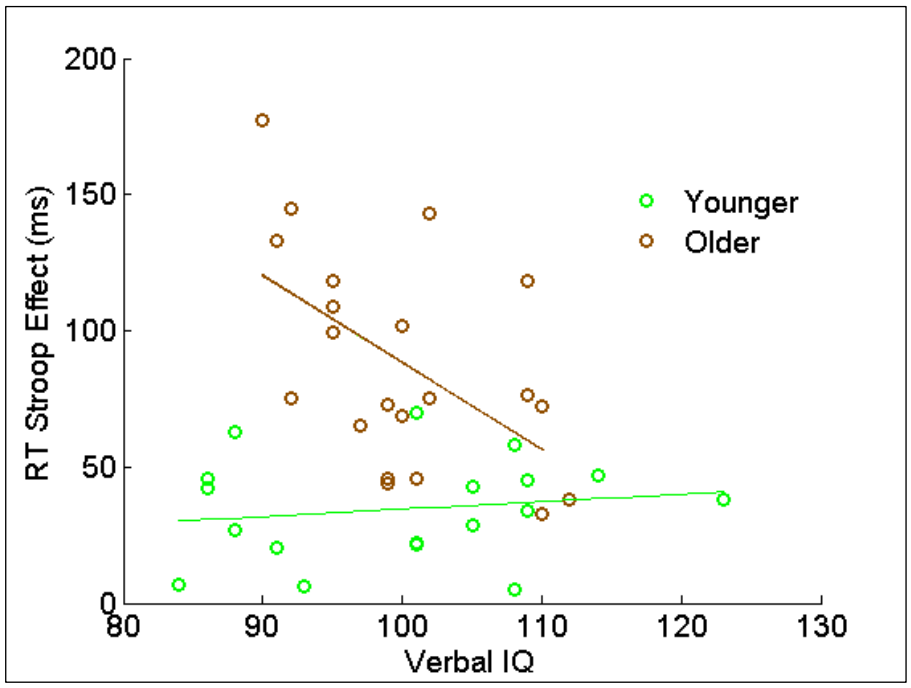

Figure 6 - RT-Stroop effect as a function of verbal intelligence in younger and older adults. Error bars represent the standard error of the mean.

This introduces a possible discrepancy between the assumptions of the conflict-monitoring theory (Botvinick et al., 2001) and West's frontal-lobe-damage hypothesis of aging (West, 1996; West & Bell, 1997). Botvinick and colleagues' (2001) theory suggests that the anterior cingulate is an important node for conflict monitoring, and sends signals to the lateral prefrontal cortex for conflict resolution, resulting in conflict adaptation at the behavioural level. In view of the selective frontal-lobe-damage hypothesis of cognitive aging (West, 1996), we should then expect a strong impact of aging on conflict adaptation.

However, our results show that this is not the case. Unfortunately, our behavioural study was not designed to draw anatomical interpretations. Future neuroimaging work should address this issue by keeping conflict-independent factors such as priming under experimental control.

We also correlated different aspects of Stroop-task performance with putative modulatory variables, such as verbal and performance intelligence, education, and CR. In both age-groups, RTs were inversely correlated with verbal and performance IQ measures. This result indirectly corroborates a recent study by Van Ravenzwaaij and colleagues (Van Ravenzwaaij, Brown, & Wagenmakers, 2011), which shows a strong relation between general intelligence and individual differences in "drift rate", that is, the speed of the information accumulation process in Ratcliff's diffusion model (1979). Our correlational data suggest that specifically older adults also took advantage of years of formal education and CR to maintain an adequate speed level. It is likely that education exerts an effect in older adults only, because younger adults are already at their optimal level of functioning and do not have to compensate for intervening age-related deficits (Springer, McIntosh, Winocur, & Grady, 2005). A possible issue is that CR was measured here in older adults only. Thus, it is impossible to know from the present study whether lifestyle and CR start influencing performance already from young adulthood.

As far as the Stroop effect is concerned, no influence of any of the modulatory variables considered here was observed in the younger group. Older adults, instead, showed an inverse relationship between verbal intelligence and the Stroop effect, a correlation that significantly differed from the null correlation in younger adults (see ANCOVA results). The fact that verbal intelligence was associated with the size of the verbal Stroop effect in older adults suggests that the mechanism underlying compensation for conflict resolution in the classic Stroop task is a domain-specific one. In particular, older adults can cope better with the age-related impairment in a verbal conflict resolution if they have higher verbal skills.

Thus, our results show age-related differences both generally in absolute speed measures, and more specifically in conflict resolution. These results are best explained by combining theories that appeal to general slowing accounts of cognitive aging (e.g., Salthouse, 1996) with theories that propose more specific

age-related deficits in cognitive inhibition (e.g., Gazzaley et al., 2005; Gazzaley & D'Esposito, 2007; Hasher & Zacks, 1988). Accordingly, age-related problems in these different aspects of cognitive functioning can be compensated for by partially different factors. In particular, whereas CR (measured here by considering the joint contribution of years of education, occupation and usual activities) was associated with the maintenance of an adequate level of performance speed, verbal intelligence was additionally associated with less marked problems in verbal conflict resolution (Stroop effect).

The present study raises new questions that should be addressed in future investigations. Since intelligence and CR were not experimentally modulated, it is impossible to infer causal relations between these independent variables and reduced deficits in conflict resolution. Future studies adopting a longitudinal design would be useful to understand whether intelligence and CR measures have a predictive value in determining which individuals will preserve cognitive functions, underlying general speed, conflict resolution, and conflict adaptation during aging. Moreover, it would be important to clarify whether the factors that exert a compensatory influence in cognitive aging are determined genetically and during the course of the entire life or, instead, may also derive from appropriate training during senescence.

Exploring these possibilities would imply experimental manipulation and, as a consequence, the opportunity to draw causal inferences. In fact, issues similar to these have already started to be addressed by other groups. Habeck and colleagues demonstrated that younger adults already show individual differences in network efficiency, which can be explained by CR (Habeck et al., 2003; but also see Stern, 2009). Moreover, there is evidence suggesting that CR does not have a compensatory role in aging, but simply reflects the presence of preexisting differences in cognitive functioning (Tucker-Drob, Johnson, & Jones, 2009). On the other hand, there is a growing body of research that demonstrates how specific cognitive and physical training interventions could improve cognitive abilities usually prone to aging, such as executive functions (e.g., Colcombe & Kramer, 2003; Ball et al., 2002; Smith et al., 2009). It is therefore clear that more specific investigation is still needed.

In conclusion, the present study shows that, beyond general slowing, cognitive aging exerts a reduction in the ability of verbal conflict resolution, as

shown by an increased Stroop effect, whereas conflict adaptation is preserved. We also showed that different factors play a compensatory role in reducing the detrimental effects of cognitive aging. The years of formal education and CR in general are associated with a less severe age-related general performance slowing. Moreover, possessing high intelligence skills in the verbal domain countervails age-related impairment in verbal conflict resolution.

3.3. Cognitive Control in the verbal domain and its age-related modifications: electrophysiological evidence - Experiment 4

In the previous experiment we showed that normally aging people are prone to the well-known general slowing effects, but, additionally, they suffer from a specific conflict resolution deficit in the verbal domain as expressed by an increase of the Stroop effect. On the other hand, the study showed that both these age related impairments are reduced proportionally to some specific personal factors. Specifically, the increase of Stroop effect is reduced in older individuals with a high verbal IQ scores and people with higher cognitive reserve and years of formal education resulted as the ones who are less affected by general slowing.

There is quite a small number of cognitive control studies that used the ERP technique to investigate the mechanisms that underlie conflict resolution in deeper detail than allowed by behavioural measures alone, and even fewer electrophysiological studies have been carried out in order to explore conflict resolution in normal aging. Most of the previous studies evidenced two main conflict-related components. A fronto-central negativity (N450), more negative for incongruent with respect to congruent trials, and a parietal sustained potential (SP) more positive for incongruent stimuli with respect to congruent ones. Evidence for age-related effects is controversial: some authors found an attenuation of the conflict-related components in older adults (West & Alain, 2000a; West, 2004; West and Moore, 2005; West & Schwarb, 2006), whereas other authors found such modulation increased in older adults (Mager et al., 2007).

Moreover none of the existing studies simultaneously considered the conflict adaptation phenomena and the priming confounds. We therefore decided to collect data from two new samples of younger and older adults and to record the electroencephalogram while participants were performing the priming-free verbal Stroop task. To couple the priming-free classic Stroop task with the ERP technique permitted us to address new questions with respect to the previous behavioural experiment. Indeed ERP evidence would uncover the temporal evolution of verbal conflict-related processes and their neural correlates with respect to the various sequential conditions. Moreover EEG could clarify the origin of the age-related increase of Stroop effect found in Experiment 3. Indeed the ERP component analyses could evidence whether older adults' conflict-related evoked potentials are only time-delayed in older adults or whether they present dissimilar patterns with respect to younger adults.

In the following section we summarize previous studies that investigated cognitive control and age-related cognitive control modifications with the ERPs, and afterwards we report our ERP study.

Cognitive Control ERP studies

Using a modified version of the colour-word Stroop task, Rebai and colleagues (1997) first reported a modulation that reflects the sensitivity to current trial congruency. It consisted of an enhanced midline fronto-central negativity between 350 and 450 ms for incongruent stimuli. Subsequently, West and Alain (1999) confirmed this finding using a classic version of the Stroop task. The same authors later varied the proportion of congruent and incongruent trials across different blocks in a colour-word Stroop task (West & Alain, 2000b). Beside the increased amplitude for N450 in incongruent with respect to congruent trials, which was greater when trials were mostly congruent in comparison to when trials were mostly incongruent, they also reported a sustained increased positivity for incongruent trials relative to congruent ones over the temporo-parietal scalp region between 600 ms and 800 ms. West and Alain (1999) suggested that, on incongruent trials, colour and word information activate competing representations in a conceptual level processing system. To cope with this conflict, a signal is generated that leads to the suppression of

activation in the system connected to the non-relevant information, marked by the increased negativity of N450 for incongruent with respect to congruent trials. This increases the reliance on information from a perceptual level colour processing system to guide a response. In contrast, on congruent trials, information from the conceptual level system is thought to be the primary source of information utilized to guide a response.

Subsequently, Liotti and colleagues (Liotti, Woldorff, Perez, Mayberg, 2000) used a classic Stroop paradigm with 4 colours and 4 words. Half of the trials were congruent and half incongruent. Additionally to the N450, in the 600-800 time-window a late positive complex of increased positivity was found for incongruent trials in the temporo-parietal sites. Using high-density ERPs, Liotti and colleagues could show that the N450 negativity has a different scalp distribution in a verbal compared to a manual Stroop version, suggesting that response-related processes modulate this negativity. A dipole source analysis made on ERP data supports the presence of two independent generators in the ACC correlated with the interference-related negativity. This supports previous PET and fMRI findings, which showed that ACC activity correlates with interference (e.g., Kerns et al., 2004; Pardo et al., 1990).

More recently, Larson and associates (Larson, Kaufman & Perlstein, 2009) used a classic Stroop with 3 colours. Trials presented were 70% incongruent and 30% congruent. In this study the previous trial congruency was controlled for. However the priming was only partially controlled for. The authors confirmed the presence of a fronto-medial, negative peak between 350 and 500 ms, sensitive to current trial congruency only. Such N450 showed that incongruent trials are more negative than congruent ones (confirming Perlstein, 2006; West, 2003; West, 2004; and West & Alain, 2000) and this modulation correlates with Stroop interference. They also showed that the parietal conflict Sustained Potential (SP) between 650 and 800 ms was modulated both by current and previous trial congruency. However the SP amplitude did not correlate with behavioural measures, suggesting that this late conflict adaptation modulation is not predictive of behavioural conflict adaptation effects. The authors suggested that the first modulation, the N450, could reflect a more automatic process of conflict monitoring, whereas the SP marks a top-down controlled process which reflects a signal for the level of conflict. Therefore consistent neurophysiological

findings are an increased negativity in the range of 350–650 ms in response to incongruent versus congruent stimuli and a sustained positive potential (SP) in temporo-parietal regions between 600 ms and 800 ms, which is more pronounced for incongruent trials.

Age-related Cognitive Control modification ERP studies

Some work has been carried out in order to explore the electrophysiological modifications that conflict resolution processes encounter during healthy aging, but, to the best of our knowledge, none of the few previous studies tried to control for repetition priming and sequential congruency effects in its task design at the same time. In 2000, West and Alain observed 4 different ERP modulations: a) an N500 phasic negativity for incongruent stimuli in the midline fronto-central electrodes; b) a reduced positivity in the left parietal region, paired with a bilateral frontal reduced negativity for incongruent trials; c) a negative fronto-central slow wave for incongruent trials; d) an enhanced positivity for incongruent stimuli over the left temporo-parietal region. The amplitude of N500 and positivity in the left parietal and frontal modulation were attenuated in older adults (West & Alain, 2000a). Successively, West and Moore (2005) used a 4-AFC Stroop task where the relevant dimension was the colour (as for the classic Stroop) or the word and it was cued to check the switching cost. They reported two sustained modulations in the ERPs reflecting the congruency of current trials. The first one was a modulation over central-parietal scalp regions, with increased positivity for incongruent with respect to congruent trials. The second one occurred over the frontal scalp region, with reduced positivity for incongruent with respect to congruent trials. The first modulation was present in both younger and older adults, whereas the second one was absent in the older group. Again, West (2004) reported that the N450 has a reversed polarity over lateral-frontal and frontopolar regions. They confirmed the presence of an SP in parietal regions, which was more pronounced for incongruent with respect to congruent trials. In older adults the SP was reduced and frontally shifted. West's group kept investigating aging effects on conflict-related electrophysiology using a different task with respect to the Stroop paradigm. They used a counting task (West & Schwarb 2006) and confirmed the presence of an N450 component in

the central electrodes and a later sustained potential which were more pronounced for incongruent trials than for congruent ones. In older adults both modulations appeared attenuated as in their preceding studies (West, 2004; West & Alain, 2000a; West & Moore, 2005)

Mager and colleagues (Mager et al., 2007) used a Stroop task with two response buttons only and explicitly asked younger and older participants whether each trial was congruent or incongruent. They reported the presence of a fronto-central negativity between 350 and 650 ms increased for incongruent trials. However, contrarily to what was reported by West's studies, such a modulation was increased in latency and amplitude in middle-age adults. Moreover they reported a parietal and left lateralized N800 with reduced negativity for incongruent trials. The late negative component was delayed and reduced in middle-age participants. The authors suggested that the fronto-central negativity reflects a conflict detection mechanism, whereas the late potential could reflect a more intense processing for incongruent trials versus congruent ones reflecting the activation of the left temporoparietal cortex, involved in word meaning (see also Liotti et al., 2000).

Despite the evidence apparently showing some contradictions, the fact emerges that those experiments in which the participant was asked to solve the conflict, that is identifying the color and ignoring the word, consistently showed a delay and a voltage decrease in ERP conflict-related markers in older adults. On the other hand evidence of a voltage increase was shown in designs where participants had just to identify the presence of conflict. Therefore the results actually belong to a different mechanism and cannot really be considered as in conflict.

It is clear that previous studies evidenced the N450 frontal negativity and the parietal SP as key factors for conflict related processes, at least in a verbal Stroop task. Hence, in Experiment 4 the electrophysiological analyses have focused on the two TWs (400-500 ms and 600-800 ms from the stimulus onset) that previous studies have identified as those where conflict-related components take place.

Methods

Participants

After the approval of the SISSA ethical committee, participants were recruited from the local community in Trieste, Italy. Each participant was informed about the structure of the task and the EEG recording procedure by the experimenter and signed an informed consent form. Volunteers received 25 € for taking part in the study.

Twenty younger controls (mean age = 26 years, range 18-35; 11 females) and 20 older adults (mean age = 73 years, range 66-82; 10 females) took part in this study. Inclusion criteria were: being right-handed, native Italian speaker, with normal or corrected-to-normal vision and normal colour perception, and absence of cognitive decline or dementia for the older adults. The two age-groups were matched for years of formal education (younger, range: 6-20, M = 13.3 years; older, range: 5-20, M = 13.4 years, [$t(38) = -0.11$, $p = .91$]). Seven older adults reported the use of regular medications for cardiovascular disease.

Four additional participants were initially involved in the experiment but were later excluded from the analyses (one belonging to the older group and 3 to the younger one): two because of excessively long response times (RTs) and two because of a very low accuracy rate (> 3 SD from their respective group mean).

Procedure and task

Participants were tested individually in a silent room, and took part in two experimental sessions on two different days.

The first session consisted of a battery of several tests. Initially participants received an informed consent form, which described the general aims of the experiment and the EEG recording procedure that they would undergo in the subsequent session. The test battery was formed of the Edinburgh Handedness Inventory (*Oldfield, 1971)*, for checking handedness, the Ishihara Color Vision Test (Ishihara, 1962), for the colour blindness screening, the Cognitive Reserve Index questionnaire (CRIq; Nucci et al., 2012) and the Wechsler Adult Intelligence Scale revised (WAIS-r), in order to quantify cognitive reserve and Intelligence Quotient (IQ), respectively. The CRIq was selected because it had been validated on the Italian population and its score summarizes the

contribution of several characterizing aspects of an adult individual's life: years of education, years and type of employment, physical, leisure and cultural activities (Nucci et al., 2012). Although it is clear that they interact together, we chose to treat IQ and cognitive reserve as different factors because we were interested in understanding which aspects could be more influential in modulating the negative effects of cognitive aging. The CRI score of the older sample ranged from 98 to 159, with an average score of 130 ± 15 SD.

Older participants only were also administered the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) to screen them for mild cognitive impairment or dementia and exclude those who scored under 26. This session lasted approximately 1.5 hours.

The second session took place a few days after (3 to 10 days) the first one. During the EEG cap preparation, each participant received instructions on how to avoid producing artifacts during the EEG recording, for instance by relaxing, and by reducing as much as possible unnecessary eye movements and blinks. Participants were seated at a distance of about 50 cm from the computer LCD monitor and were instructed to maintain their gaze on a fixation cross shown in the middle of the screen. Participants were asked to use the index and middle fingers of both hands to give a response as fast and accurately as possible by pressing one of the four colour-labeled buttons: blue, green, yellow or red (see Figure 2).

The task completed is the same described in our previous verbal behavioural studies, Experiments 1, 2 and 3 (described in the *Methods* section of Experiment 1 – paragraph 3.1.1), and similarly to Experiments 1 and 3, only complete alternation sequences were used. In addition, two single-feature tasks were administered in a counterbalanced order one block of each at the beginning and one block of each at the end of the experimental session: Colour Naming and Black Words. Three classic colour-word Stroop blocks were run between these baseline tasks. An instruction page preceded the presentation of each task. In each condition, the stimuli were presented against a light-gray background and a fixation cross was displayed in the middle of the screen. In the Colour Naming condition, four coloured Xs (each arm 2.5 cm) appeared in the center of the screen. During the Black Words task, a word referring to one of four colours (i.e., blue, green, yellow or red) appeared. In both tasks, participants were asked

to indicate the colour of the stimulus by pressing the corresponding colour-labeled button (i.e., blue, green, yellow or red). Each block of the single-feature tasks was composed of 32 test trials, preceded by 2 training trials.

Participants that took part in this experiment were also administered a spatial version of the Stroop task. The structure of the two Stroop tasks was the same and their presentation order was counterbalanced across participants. The whole session lasted approximately two hours.

EEG recording and analysis

Scalp voltage was recorded from 128 scalp sites using a Biosemi™ ActiveTwo EEG system with sintered Ag-AgCl electrodes (of a modified 10/20 system headcap) (Figure 7). Recording voltages were referenced online to mastoid electrodes and EEG signal was continuously sampled at 256 Hz. Four surface electrodes were used in order to record horizontal and vertical electro-oculographic (EOG) signals, placing the electrodes on right and left external canthi and infra-orbital ridges of each participant. Four extra electrodes were positioned on the mastoid and the peri-auricular area of each side of each participant's head. Electrodes were adjusted in order to maintain the offset of each electrode below 40 mV.

For each participant, 7 separate EEG data files were recorded: 2 Colour Naming, 2 Black Words and 3 Verbal Stroop blocks. For each of them EEG signal was pre-processed using EEGLab v12.0.0.0b (Delorme & Makeig, 2004). All electrodes were re-referenced offline to the average-reference. A 0.1 Hz high-pass filter was applied to the EEG signal in order to reduce very slow drifts of the EEG signal. Then, a 20 Hz low-pass filter was applied to remove high-frequency noise, such as that derived from muscular activity or the line noise derived from external electrical devices. All files belonging to a single participant were then merged and the signal was visually inspected to also exclude excessively noisy portions. Noisy electrodes, selected through an automatic procedure implemented in EEGLab, were interpolated. Continuous EEG signal was divided in epochs, starting 200 ms before the stimulus onset and ending 2600 ms after it and baseline-corrected considering the time windows from -200 ms to 0 ms with respect to the stimulus onset.

An automatic procedure was applied to reject epochs, setting the threshold to -/+ 1000 µV and allowing a maximum of 5% of rejections per iteration. The EEG signal was then analyzed using EEGLab Independent Component Analysis (ICA) in order to exclude independent components that clearly reflected artifacts such as blinks, horizontal eye movements and residual bad electrodes.

Error trials were removed and correct ones were sorted with respect to 6 different conditions: Black Words, Colour Naming, CC, CI, IC and II Stroop sequences.

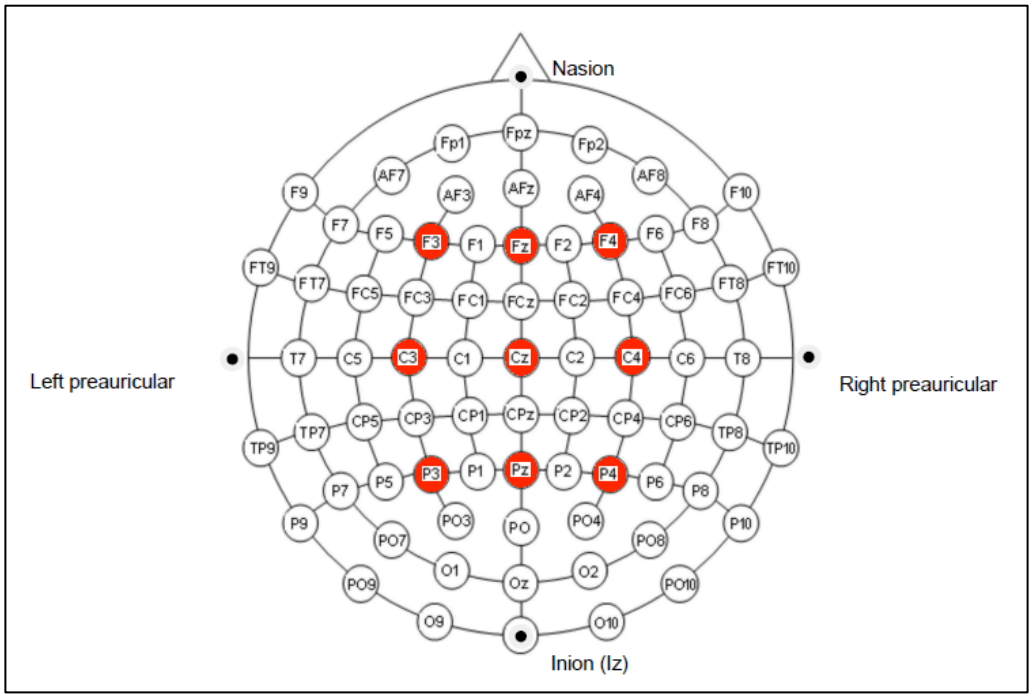

Figure 7 - Electrode distribution on the scalp. The 9 electrodes selected for statistical analysis are marked in red.

Results

Behavioural results

The RT analysis was performed using correct trials with RTs included between 100 ms and 1500 ms only (3.95% of total trials were removed). Outlier trials (0.69% of the remaining trials) (i.e., above and below 3 *SD* from each participants mean RT) were also excluded.

As suggested by Verhaeghen and De Meersman (1998), raw RT data were logarithmically transformed in order to compare the two age-groups and reduce the confound associated with age-related slowing.

The analysis of single feature tasks revealed that younger adults were systematically faster with respect to older adults both in Colour Naming [younger = 589 ms; older = 795 ms, t-test*:* t (38) = -5.29, $p < .001$] and Black Words [younger = 602 ms; older = 804 ms, t-test*:* t (38) = -6.29, $p < .001$]. The two age-groups reached the same level of accuracy in both the Colour Naming [younger = 95.7%; older = 95.5%, Mann–Whitney $U = 197.5$, $Z = 0.06$, $p = .95$] and Black Words [younger = 95.4%; older = 96.3%, Mann–Whitney $U = 178$, $Z = -0.59$, $p = .55$].

The comparison among single feature conditions and Stroop ones showed that in younger adults the presence of two incongruent features exerts RT interference with respect to both Colour Naming [CN = 589 ms; Incongruent trials = 753 ms,

Table 1 - Mean RTs (ms) and accuracy (%) with respect to conditions and age-groups. SD in parentheses.

		CC	IC	CI	II	Colour Naming	Black Words
Younger	RTs	643 (127)	657 (148)	751 (155)	753 (155)	589 (61)	602 (59)
	Accuracy	95.5 (4.7)	96.0 (3.8)	91.5 (6.2)	93.1 (5.5)	95.7 (3.8)	95.4 (5.7)
Older	RTs	820 (171)	830 (170)	953 (159)	952 (155)	795 (162)	804 (130)
	Accuracy	97.2 (3.6)	96.6 (4.2)	93.4 (6.0)	93.6 (5.2)	95.5 (4.4)	96.3 (4.2)

t-test*: t* (19) = -4.36, *p* < .001] and Black Words [BW = 603 ms; Incongruent trials = 753 ms, t-test*: t* (19) = -3.79, *p* = .001]. The same effect was shown by older adults as well [CN = 795 ms; Incongruent trials = 956 ms, t-test*: t* (19) = -5.30, *p* < .001] and Black Words [BW = 804 ms; Incongruent trials = 956 ms, t-test*: t* (19) = -6.16, *p* < .001]. Congruent trials were not statistically different from single feature conditions in either age-group [all *p*s > .14]. This suggests that the presence of two congruent types of information exerts neither facilitation nor interference on RTs.

In order to analyze our data, we used a 2x2x2 mixed ANOVA with age-group (Younger vs Older) as the between-subjects factor and congruency of the current and preceding trials (for both, Congruent vs Incongruent) as within-subjects factors.

In the 2x2x2 ANOVA, as expected, both age-group and *trial n* main effects were significant. Younger adults responded more rapidly than older ones [*F*(1, 38) = 16.4, *p* < .001; mean RT 701 ms and 886 ms, respectively] and responses to congruent trials were faster than ones to incongruent trials [*F*(1, 38) = 203.5 , *p* < .001; mean RT 739 ms and 854 ms, respectively]. *Trial n-1* congruency [*F*(1, 38) = 2.8, *p* = .1] and all interactions among factors were not significant [all *ps* > .09]. The absence of a significant interaction between age-group and *trial n* suggests that aging does not specifically affect the Stroop effect, whereas the lack of significance for *trial n-1* congruency effect and the related interactions suggests that the preceding trial congruency *per se* does not influence the present trial conflict resolution at the behavioural level.

We computed a 2x2 ANOVA analyses also on the Stroop effect, that is, the RT difference between incongruent and congruent trials. Again, the main effects of age-group, *trial n-1* congruency, and their interaction were not significant [*F*(1, 38) = 0.082 , *p* = .776; *F*(1, 38) = 2.78, *p* = .1; *F*(1, 38) < 0.01 , *p* = .99], confirming the results of the analyses on RTs (Figure 8a).

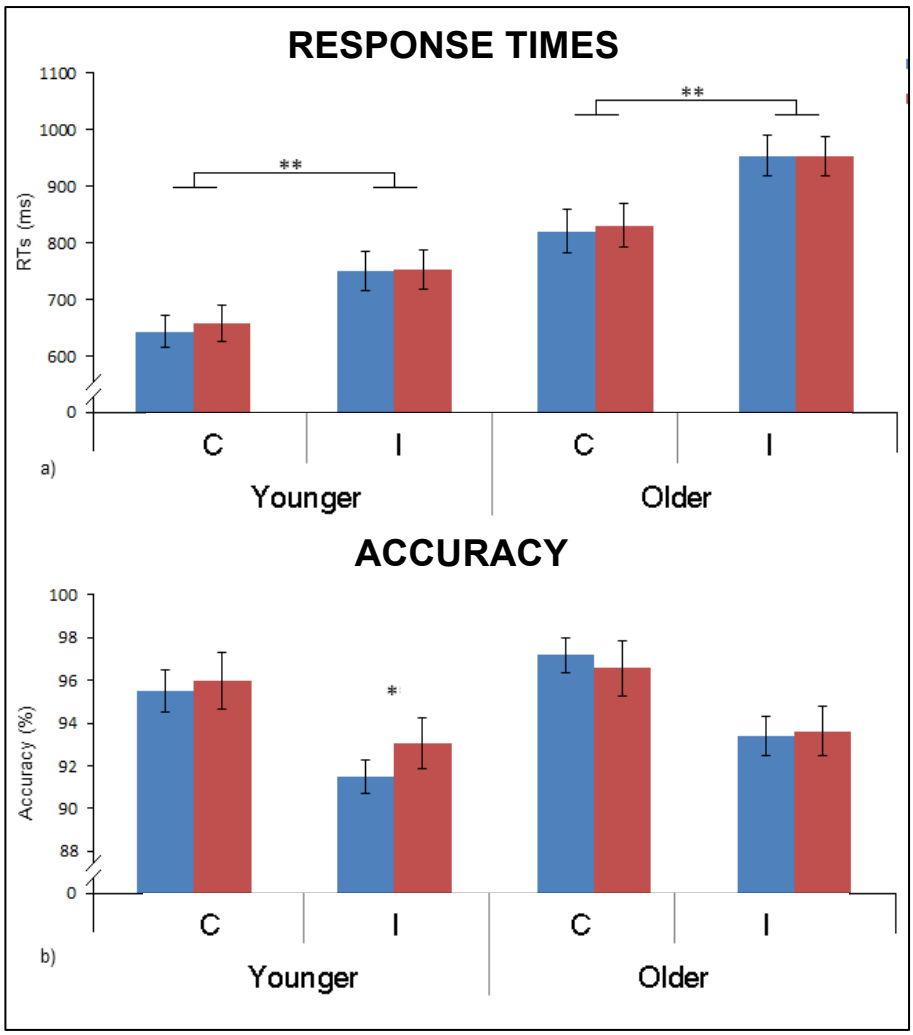

Figure 8 - Response times in ms a) and accuracy in percentage b) of Experiment 4 as a function of previous (n - 1) and current (n) trial congruency. Error bars represent the standard error of the mean.

Accuracy data were not normally distributed. Therefore it was not possible to apply a parametric test such as an ANOVA.

The accuracy comparisons between single feature conditions and Stroop ones showed that in younger adults the presence of two incongruent features exerts interference with respect to both Colour Naming [CN = 95.5%; Incongruent trials = 92.2%, Wilcoxon's $T = 15$, $Z = 3.07$, $p = .002$] and Black Words [BW = 95.4%; Incongruent trials = 92.2%, Wilcoxon's $T = 40$, $Z = 2.42$, $p = .015$]. Older adults instead showed interference on incongruent trials with respect to Black Words [BW = 96.3%; Incongruent trials = 93.1%, Wilcoxon's $T = 27$, $Z = 2.55$, $p = .011$] and facilitation on CC trials with respect to Colour Naming [CN = 95.6%; CC trials = 97.2%, Wilcoxon's $T = 45$, $Z = 2.01$, $p = .044$]. All the

other conditions in both age-groups did not statistically differ from the single feature conditions [all *p*s > .08].

To directly compare the two age-groups a Mann–Whitney *U* test was used: the two age-groups reached the same level of accuracy, 94.9% (older) and 93.9% (younger) [Mann–Whitney $U = 177.5$, $Z = -0.60$, $p = .54$]. We then verified that *trial n* congruency had a significant effect on accuracy (i.e., accuracy Stroop). A Wilcoxon signed-rank test was used to compare congruent and incongruent trials *n*, separately in the two age-groups. In both age-groups the effect of *trial n* was significant [younger group, Wilcoxon's $T = 16$, $Z = 3.02$, $p = .002$; older: Wilcoxon's $T = 21$, $Z = 2.97$, $p = .003$].

Wilcoxon signed-rank tests were used also to compare pairs of conditions within each group in order to compare CC vs CI and CI vs II conditions. These comparisons revealed that in younger adults II and CI trials are different (as shown in Experiments 1 and 2) (Wilcoxon's $T = 49.5$, $Z = 2.07$, $p = .04$), whereas in older adults they are not significantly different ($p = .72$). In both age-groups CC vs IC comparisons were non-significant (*p*s> 0.18).

We then analyzed the accuracy Stroop effect (i.e., the difference in accuracy between incongruent and congruent trials) in a 2 × 2 mixed ANOVA with congruency in *trial n-1* as a within-subjects factor and age-group as the between-subjects factor. The main effect of group [$F(1, 38) < 0.001$, $p = .95$], the main effect of *trial n-1* congruency [$F(1, 38) = 2.60$, $p = .115$] and the interaction between age-group and *trial n-1* congruency [$F(1, 36) = 0.04$ $p = .84$] were non-significant (Figure 8b).

Since parametric analyses are less powerful, in order to double check, we also performed the analysis on accuracy by means of a series of permutation tests (cf., Chapter 2). We calculated the 2x2x2 mixed model ANOVA to obtain the F statistics of the factors Group, *trial n* and *trial n-1* and their interactions.

We then applied Manly's permutation approach (Manly, 2007), which implies an unrestricted permutation of observations. We therefore permuted all three factors randomly among all participants and compared each F value of our real data with the distribution of F values of the samples obtained from the permutations. The Group effect was not significant (N = 1000 permutations, F =

2.17, p = .34), confirming that older and younger adults reached the same level of accuracy.

The effect of *trial n* was significant (N = 1000 permutations, F = 18.6, p < .001), denoting the presence of a strong Stroop effect. The effect of *trial n-1* was not significant (N = 1000 permutations, F = 0.29, p = .592) suggesting that congruency of preceding trial does not exert an effect on the current one. None of the interactions resulted significant (all *p*s> 0.45).

Correlation analysis of behavioural data

Younger adults' accuracy in the Stroop task correlated with performance IQ [r(20) = 0.58, p = .007]. Colour Naming task accuracy correlated with verbal IQ [r(20) = 0.49, p = .029] and with years of education [r(20) = 0.55, p = .012].

Older adults showed a negative correlation between CRI and RTs [r(20) = −0.47, p = .034], supporting the hypothesis that CR could counteract the general slowing effect due do aging. Older adults' age correlated with the amount of interference (i.e., the difference between the Stroop trials' RT and Colour Naming task RT) in all four conditions [CC: r(20) = 0.47, p = .035; IC: r(20) = 0.46, p = .044; CI: r(20) = 0.47, p = .037; II: r(20) = 0.46, p = .040], suggesting that the older one is, the higher the interference that arises from having 2 features vs one is.

It is important to point out that all of the correlations we calculated are not corrected for multiple comparisons. Therefore they have to be considered as exploratory analyses.

Electrophysiological data

After the rejection procedures, we obtained an average of 292 ± 31 (range: 173–328) trials for younger adults and 298 ± 14 (range: 236–338) trials for older ones.

Current trial congruent waveforms contained an average (±SD) of 146 ± 14 trials per subject (range: 94–162) in the younger group and 153 ± 16 trials per subject (range: 108–174) in the older one. Incongruent current trial waveforms contained an average of 145 ± 18 trials per subject (range: 79–167) in the younger group and 145 ± 18 trials per subject (range: 112–176) in the older one. When broken down to examine potential conflict adaptation effects, the number

of trials retained in the younger adults group was: CC trials 73 ± 8 (range: 46–83), CI trials 72 ± 10 (range: 40–87), IC trials 73 ± 8 (range: 48–87), and II trials 73 ± 9 (range: 39–80). Whereas in the older adults group was: CC trials 77 ± 8 (range: 59–88), CI trials 72 ± 9 (range: 57–88), IC trials 76 ± 10 (range: 49–88), and II trials 73 ± 10 (range: 52–89).

Both on the basis of results of earlier studies (e.g., West & Alain, 2000a, 2000b; Larson et al., 2009; Liotti et al., 2000) and of visual inspection of the waveforms, we decided to run statistical analyses in two latency time windows (TW): one between 400 and 500 ms and the other between 600 and 800 ms from the stimulus onset. We selected 9 electrodes from the 10/20 system spatially distributed in a 3 by 3 matrix: P3, Pz, P4, C3, Cz, C4, F3, Fz, F4 (See Figures 9 and 10).

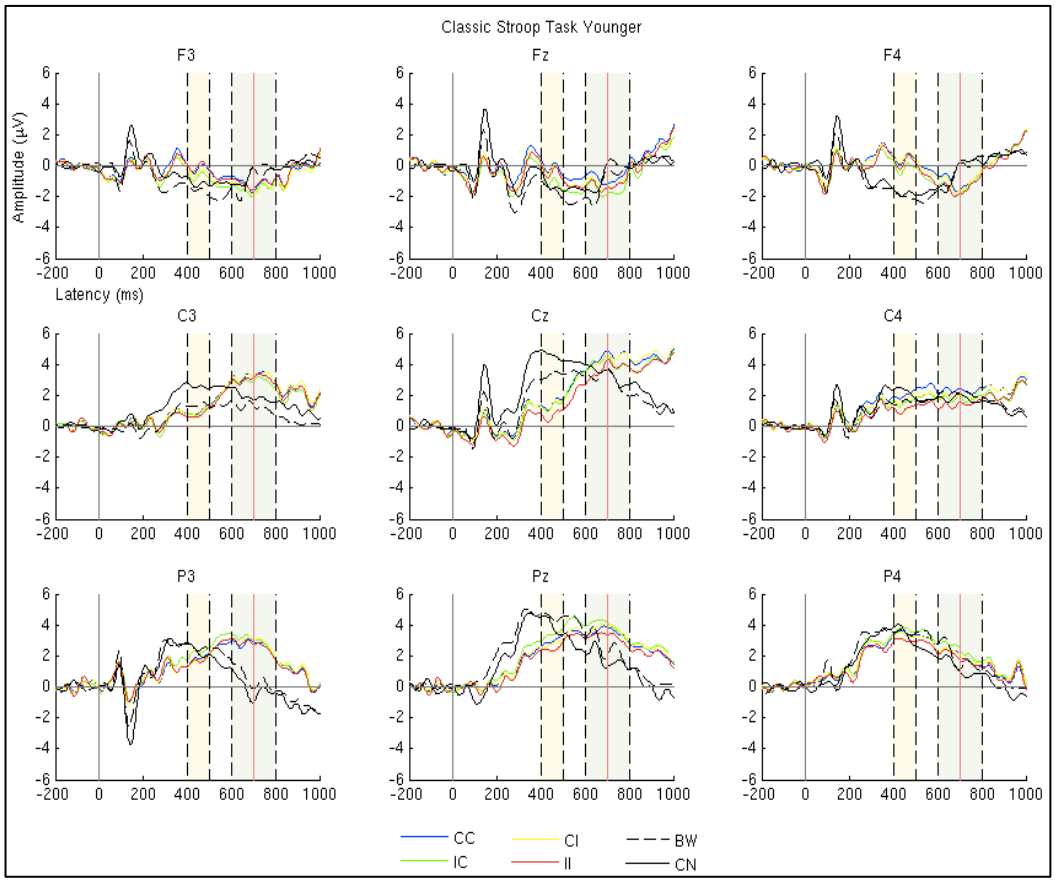

Figure 9 - Grand average ERP waveforms of stimulus-locked Stroop trials (CC – Congruent-Congruent, IC – Incongruent-Congruent, CI – Congruent-Incongruent, II – Incongruent - Incongruent) and single feature trials (BW – Black words; CN – Colour Naming) recorded in younger adults. The 9 electrodes selected for the analyses are displayed. The two colour-shaded areas indicate the analyzed time windows. The red vertical line indicates the average RT of the group.

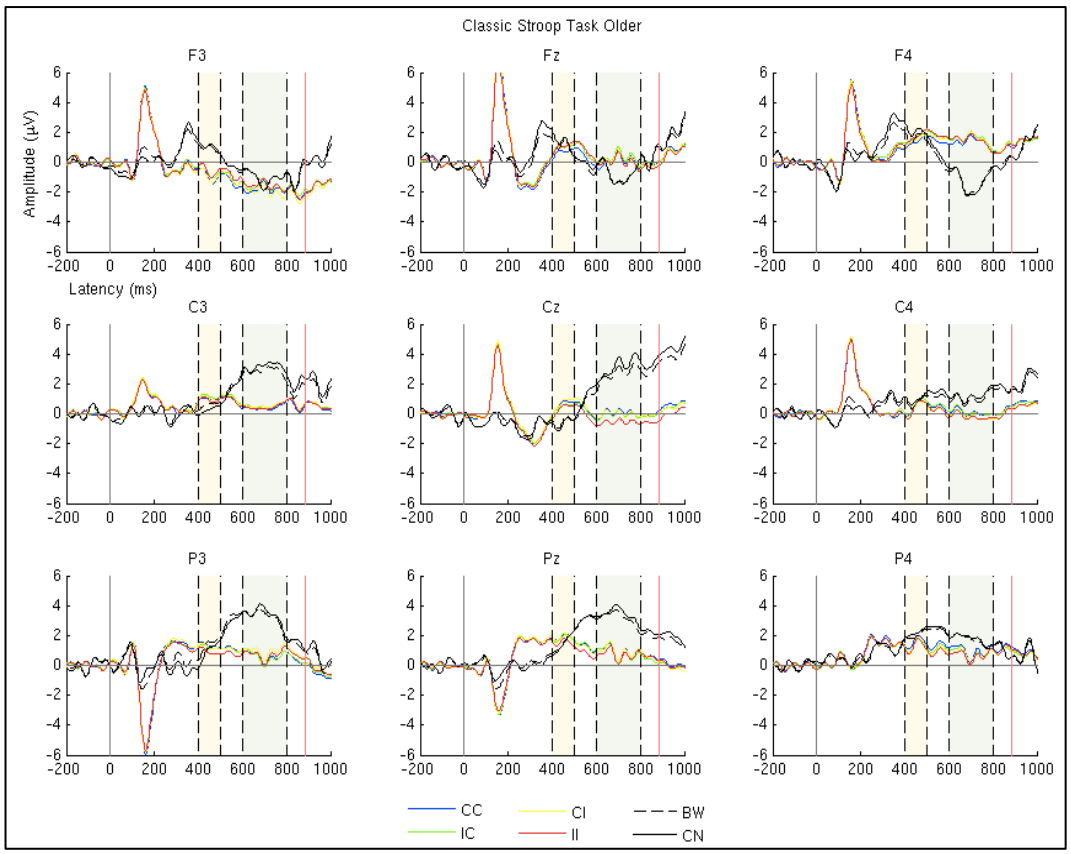

Figure 10 - Grand average ERP waveforms of stimulus-locked Stroop trials (CC – Congruent Congruent, IC – Incongruent-Congruent, CI – Congruent-Incongruent, II – Incongruent - Incongruent) and single feature trials (BW – Black words; CN – Colour Naming) recorded in older adults. The 9 electrodes selected for the analyses are displayed. The two colour-shaded areas indicate the analyzed time windows. The red vertical line indicates the average RT of the group.
.

The analyses were based on the mean amplitude in the windows specified above, relative to a 200 ms baseline preceding the stimulus presentation. The Greenhouse-Geisser correction was applied when evaluating effects with more than one degree of freedom in the numerator (Greenhouse & Geisser, 1959). The adjusted degrees of freedom and *p*-values are reported.

400-500 Time Window

In order to analyze our data, we first ran a 2x2x2x3x3 mixed ANOVA with age-group (Group: Younger vs Older) as the between-subjects factor and 4 within-subjects factors: congruency of *trial n* (Trial *n*: Congruent vs Incongruent), congruency of *trial n-1* (Trial *n-1*: Congruent vs Incongruent), scalp position (Scalp: Frontal vs Central vs Parietal), side position (Side: Left vs Midline vs Right). This first ANOVA revealed a significant 5 way interaction

Group X Trial *n* X Trial *n-1* X Scalp X Side [$F(4, 152) = 2.83, p = .032$]. Once verified that the age factor interacts with the other ones, we decided to go on with the analysis separately for younger and older adults. Figure 15 reports a schema of the significant effects in the 9 selected electrodes.

Younger adults

We ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed that the 4-way interaction was significant [$F(4, 76) = 6.29, p = .001$]. To better understand the sources of this complex interaction, we therefore ran three separate Trial *n* X Trial *n-1* X Side ANOVAs, one for each scalp region: frontal, central and parietal.

In frontal electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 6.49, p = .005$]. Hence we explored each electrode (F3, Fz, F4) with a Trial *n* X Trial *n-1* ANOVA. In all frontal electrodes congruency of *trial n* and congruency of *trial n-1* interacted [F3: $F(1, 19) = 29.07, p < .001$ (see Figures 11 and 16); Fz: $F(1, 19) = 25.72, p < .001$; F4: $F(1, 19) = 6.54, p = .019$], but this interaction was much stronger in F3 and reduced in F4. Indeed planned comparisons confirmed that the *trial n* and *trial n-1 congruency* interaction was greater in F3 with respect to Fz and F4 [$F = 25.71, p < .001$]

In central electrodes the 3-way interaction was not significant [$F(2, 38) = 2.93, p = .07$], but all the 2-way interactions were significant: Trial *n* X Trial *n-1* [$F(2, 19) = 8.95, p = .007$]; Trial *n* X Side [$F(2, 38) = 3.68, p = .035$]; Trial *n-1* X Side [$F(2, 38) = 9.69, p = .001$].

We decided to explore the Trial *n* X Trial *n-1* interaction. Hence we averaged the voltage of the three central electrodes (C3, Cz, C4) and subsequently ran a Trial *n* X Trial *n-1* ANOVA. In central sites congruency of *trial n* and congruency of *trial n-1* interacted [$F(1, 19) = 8.95, p = .007$].

In parietal electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 4.99, p = .015$]. Hence we explored each electrode (P3, Pz, P4) with a Trial *n* X Trial *n-1* ANOVA. In all parietal electrodes congruency of *trial n* and congruency of *trial n-1* interacted [P3: $F(1, 19) = 15.33, p < .001$; Pz: $F(1, 19) = 26.05, p < .001$; P4: $F(1, 19) = 19.37, p < .001$], but such an interaction was stronger in Pz (Figures 11 and 16).

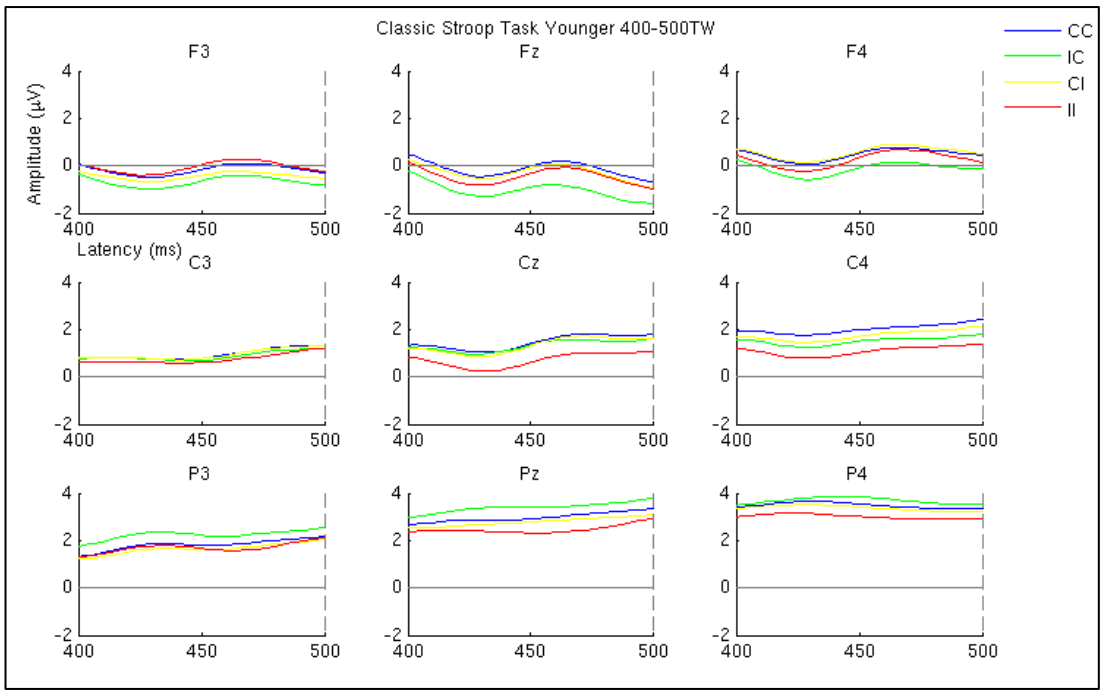

Figure 11 - Grand average ERP waveforms of stimulus-locked Stroop trials (CC, IC, CI, II) recorded in younger adults (the 400-500 ms time window only is shown). The 9 electrodes selected for the analyses are displayed.

Correlations

In younger adults the *trial n* by *trial n-1* congruency interaction was present in all of the examined electrodes. Indeed this modulation correlated with behavioural data for many aspects. In order to investigate this relationship we calculated the mean voltage difference between CI and CC waves, and between II and IC waves.

The CI-CC difference reflects the modulation caused by *trial n* congruency when the preceding trial was congruent. The CI-CC difference correlated with:

a) Years of education in F3 [r(20) = 0.59, p = .006], F4 [r(20) = 0.49, p = .027];

b) RT Stroop effect in Fz [r(20) =- 0.49, p = .026];

c) Accuracy Stroop effect in F4 [r(20) = -0.5, p = .026];

The II-IC difference reflects the modulation caused by *trial n* congruency when the preceding trial was incongruent. The II-IC difference correlated with:

a) Years of education in F4 [r(20) = 0.45, p = .044];

b) RT Stroop effect in F3 [r(20) =- 0.47, p = .035];

c) IQ in F4 [r(20) = 0.66, p = .001].

Older adults

We ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed that the 4-way interaction was significant [$F(4, 76) = 3.02$, $p = .035$]. We therefore ran three separate Trial *n* X Trial *n-1* X Side ANOVAs, one for each scalp region: frontal, central and parietal.

In frontal electrodes the interactions were all non-significant [all *p*s> 0.11] whereas the main effects of *trial n-1* congruency [$F(1, 19) = 19.35$, $p < .001$] (see Figures 12 and 17) and side [$F(2, 38) = 66.61$, $p < .001$] were significant.

In central electrodes the Trial *n* X Trial *n-1* X Side interaction was not significant [$F(2, 38) = 2.44$, $p = .11$], but the Trial *n-1* X Side interaction was significant [$F(2, 38) = 6.89$, $p = .005$]. We therefore averaged the two *trial n* conditions in order to perform a Trial *n-1* X Side ANOVA on the three central electrodes (C3, Cz, C4).

Trial n-1 congruency interacted with the side factor $F(2, 19) = 5.54$, $p = .018$]. Hence we ran three one-way ANOVAs in order to check the effect of *trial n-1* congruency on each of the three levels of the side factor: left, midline, right (i.e., C3, Cz, C4). *Trial n-1* congruency had a significant effect only in Cz [$F(1, 19) = 5.54$, $p = .018$]. Indeed we also ran a 2x2 Trial *n* X Trial *n-1* ANOVA on Cz and we verified that the only significant effect is the one due to *trial n-1* congruency [$F(1, 19) = 14.01$, $p < .001$].

In parietal electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 9.33$, $p < .001$]. Hence we explored each electrode (P3, Pz, P4) with a Trial *n* X Trial *n-1* ANOVA. In P3 congruency of *trial n* and congruency of *trial n-1* interacted [$F(1, 19) = 5.9$, $p = .025$]. In Pz only the main effect of *trial n-1* congruency was significant [$F(1, 19) = 8.81$, $p = .008$]. In P4 the interaction was present as a trend [$F(1, 19) = 4.24$, $p = .054$] (Figures 12 and 17).

Correlations

In older adults the *trial n* by *trial n-1* congruency interaction was present only in P3, whereas in the other electrodes the *trial n-1* effect was mainly present. As before, we calculated the modulations caused by *trial n* congruency when the preceding trial was congruent (CI-CC) and by *trial n* congruency when the preceding trial was incongruent (II-IC), but these modulation in P3 did not show

any significant correlation with performance. Similarly, the *trial n-1* modulation did not show any significant correlation with performance.

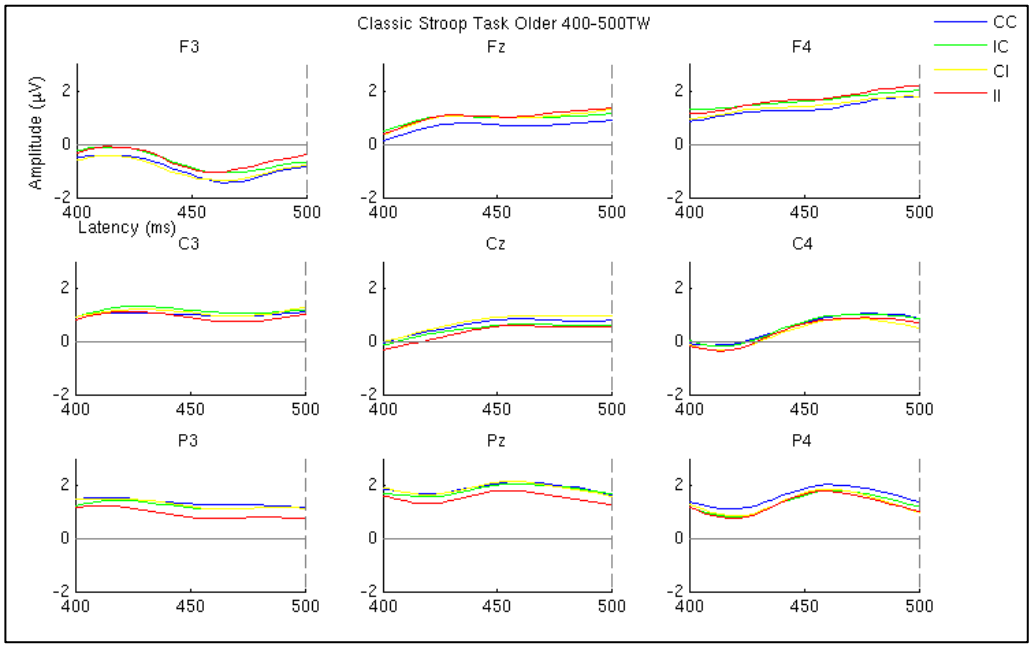

Figure 12 - Grand average ERP waveforms of stimulus-locked Stroop trials (CC, IC, CI, II) recorded in older adults in the 400-500 ms TW (zoomed in). The 9 electrodes selected for the analyses are displayed. Note that, in order to make the waveforms clearer, the y scales relative to frontal electrodes are different with respect to those relative to central and parietal electrodes.

600-800 Time Window

Following the same rationale used for the analysis of the 400-500 TW, we first ran a 2x2x2x3x3 mixed ANOVA with age-group as the between-subjects factor and congruency of *trial n*, congruency of *trial n-1*, scalp and side as within-subjects factors.

This ANOVA revealed a significant 5-way interaction [$F(4, 152) = 2.68, p = .046$]. We therefore ran separate analyses for younger and older adults in order to break down this complex interaction and facilitate the interpretation of the results. Figure 15 reports a schema of the significant effects in the 9 selected electrodes.

Younger adults

We ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed that the 4 way interaction was significant [$F(4, 76) = 4.87$, $p = .005$]. We therefore ran three separate Trial *n* X Trial *n-1* X Side ANOVAs, one for each scalp region.

In frontal electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 4.56$, $p = .024$]. Therefore, we explored each electrode (F3, Fz, F4) with a Trial *n* X Trial *n-1* ANOVA. Both in F3 and in Fz the congruency of *trial n* and congruency of *trial n-1* interacted [F3: $F(1, 19) = 8.40$, $p = .009$ (see Figures 13 and 16); Fz: $F(1, 19) = 10.38$, $p = .004$] whereas in F4 only the main effect of congruency of *trial n-1* was significant [$F(1, 19) = 39.03$, $p < .001$].

In central electrodes the Trial *n* X Trial *n-1* X Side interaction was not significant [$F(2, 38) = 1.91$, $p = .17$], and only the Trial *n* X Side interaction was significant [$F(2, 38) = 11.16$, $p < .001$]. Hence we averaged the voltage of CC and IC trials and of CI and II trials of the central electrodes and ran a Trial *n* X Side ANOVA. Congruency of *trial n* and side factors interacted [$F(2, 42) = 8.77$, $p = .002$]. Therefore we ran three separate one-way ANOVAs in order to verify the effect of *trial n* congruency in C3, Cz and C4 electrodes. The congruency of *trial n* had a significant effect in Cz and C4 [$F(1, 19) = 4.74$, $p = .041$ and $F(1, 19) = 6.11$, $p = .022$], respectively], whereas it was not significant in C3 [$F(1, 19) = 2.32$, $p = .143$].

In parietal electrodes the Trial *n* X Trial *n-1* X Side interaction was only a tendency [$F(2, 38) = 2.91$, $p = .07$], but the two-way interactions Trial *n* X Trial *n-1* and Trial *n* X Side were significant [$F(1, 19) = 22.15$, $p < .001$ and $F(2, 38) = 7.53$, $p = .004$, respectively].

We decided to explore the Trial *n* X Trial *n-1* interaction. Therefore we averaged the voltage of the three parietal electrodes (P3, Pz, P4) and subsequently ran a Trial *n* X Trial *n-1* ANOVA. In parietal sites congruency of *trial n* and congruency of *trial n-1* interacted [$F(1, 19) = 22.73$, $p < .001$] (Figure 13, see also Figure 16).

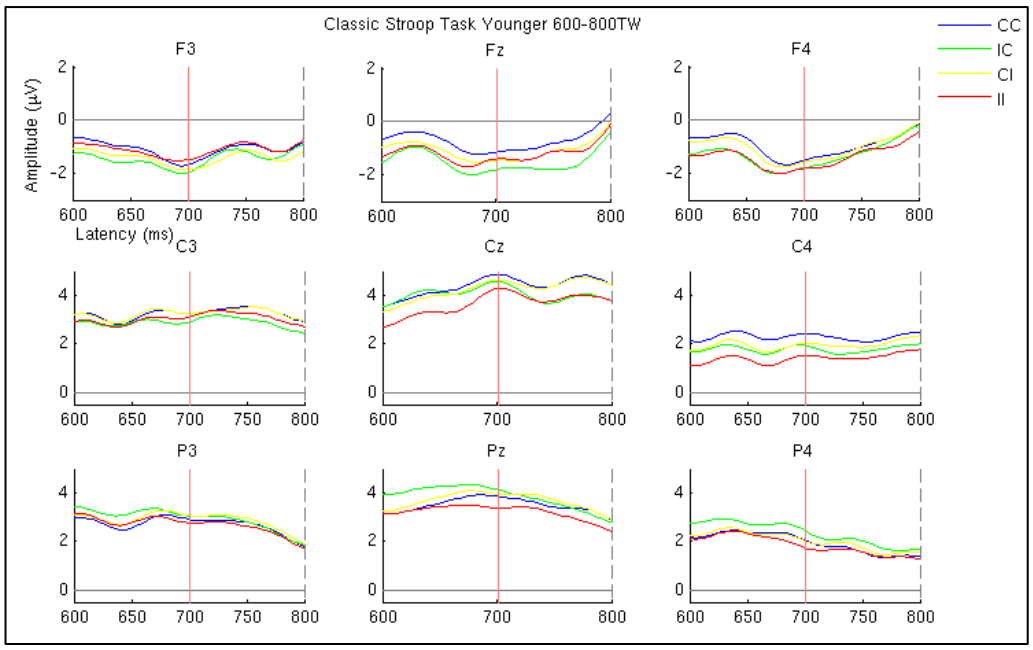

Figure 13 - Grand average ERP waveforms of stimulus-locked Stroop trials (CC, IC, CI, II) recorded in younger adults. The data are limited to the 600-800 ms time-window (zoomed in). The 9 electrodes selected for the analyses are displayed. Note that, in order to make the waveforms more clear, the y scales relative to central and parietal electrodes are different with respect to those relative to frontal ones.

Correlations

In younger adults the *trial n* by *trial n-1* congruency interaction in the 600-800 ms TW was present both in frontal and parietal electrodes. Indeed this modulation showed significant correlations with behaviour. Similarly to what we have done for the 400-500 ms TW, we calculated the mean voltage difference between the CI and CC waves, and between the II and IC waves, which should be linked to the behavioural Stroop effect when the preceding trial is, respectively, congruent or incongruent. Overall RTs in P4 correlates with both the CI-CC and II-IC difference (respectively r(20) =- 0.59, p = .006 and r(20) = -0.56, p = .01).

The amplitude analysis in the single conditions revealed also that overall RTs negatively correlated with all 4 conditions in all three frontal electrodes [CC: F3 (r(20) = -0.70, p < .001), Fz (r(20) = -0.72, p < .001), F4 (r(20) = -0.62, p = .004) - IC: F3 (r(20) = -0.50, p = .026), Fz (r(20) = -0.69, p < .001, F4 (r(20) = -0.61, p = .004) - CI: F3 (r(20) = -0.53, p = .017), Fz (r(20) = -0.55, p = .011), F4 (r(20) = -0.60, p = .005) - II: F3 (r(20) = -0.49, p = .030), Fz (r(20) = -0.63, p = .003), F4 (r(20) = -0.56, p = .011)]

Older adults

Mirroring the procedure used for younger adults we ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed that the 4-way interaction was significant [$F(4, 76) = 4.28, p = .01$]. We therefore ran three separate Trial *n* X Trial *n-1* X Side ANOVAs, one for each scalp region: frontal, central and parietal.

In frontal electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 4.88, p = .028$]. Hence we explored each electrode (F3, Fz, F4) with a Trial *n* X Trial *n-1* ANOVA. In electrode F3 the only significant effects was the main effect of *trial n-1* congruency [$F(1, 19) = 11.65, p = .003$] (See Figures 14 and 17). In Fz the congruency of *trial n* and congruency of *trial n-1* interacted [$F(1, 19) = 8.04, p = .011$, whereas in F4 neither of the two factors showed a significant effect (all *p*s >.18].

In central electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 5.87, p = .006$]. Hence we analysed each electrode (C3, Cz, C4) with a Trial *n* X Trial *n-1* ANOVA. Both in C3 and Cz congruency of *trial n* and congruency of *trial n-1* interacted [C3: $F(1, 19) = 5.96, p = .025$; Cz: $F(1, 19) = 10.79, p = .004$], whereas in C4 only the main effect of congruency in *trial n* was significant [$F(1, 19) = 10.2, p = .005$].

In parietal electrodes the Trial *n* X Trial *n-1* X Side interaction was not significant [$F(2, 38) = 2.08, p = .14$]. However the Trial *n* X Side two-way interaction was significant [$F(2, 38) = 5.53, p = .009$]. Hence we averaged the voltage of CC and IC trials and of CI and II trials of the parietal electrodes and ran a Trial *n* X Side ANOVA. Congruency of *trial n* and side factors did not interact [$F(2, 38) = 1.38, p = .256$], whereas *trial n* congruency was significant [$F(2, 38) = 28.94, p < .001$], suggesting that *trial n* congruency exerts the same effect in all three parietal examined electrodes examined (Figure 14, see also Figure 17).

Correlation

In the 600-800 ms TW older adults showed a *trial n* by *trial n-1* congruency interaction in C3, Cz and Fz. Therefore, we calculated the correlation between the modulations caused by *trial n* congruency when the preceding trial was

congruent (CI-CC) and by *trial n* congruency when the preceding trial was incongruent (II-IC). CI- CC correlated with accuracy Stroop in Fz [r(20) = -0.72, $p < .001$) and Cz (r(20) = -0.67, $p < .001$].

In C4 the current trial congruency modulation correlated with CRI [r(20) = 0.55, $p = .011$] and VIQ [r(20) = 0.47, $p = .034$].

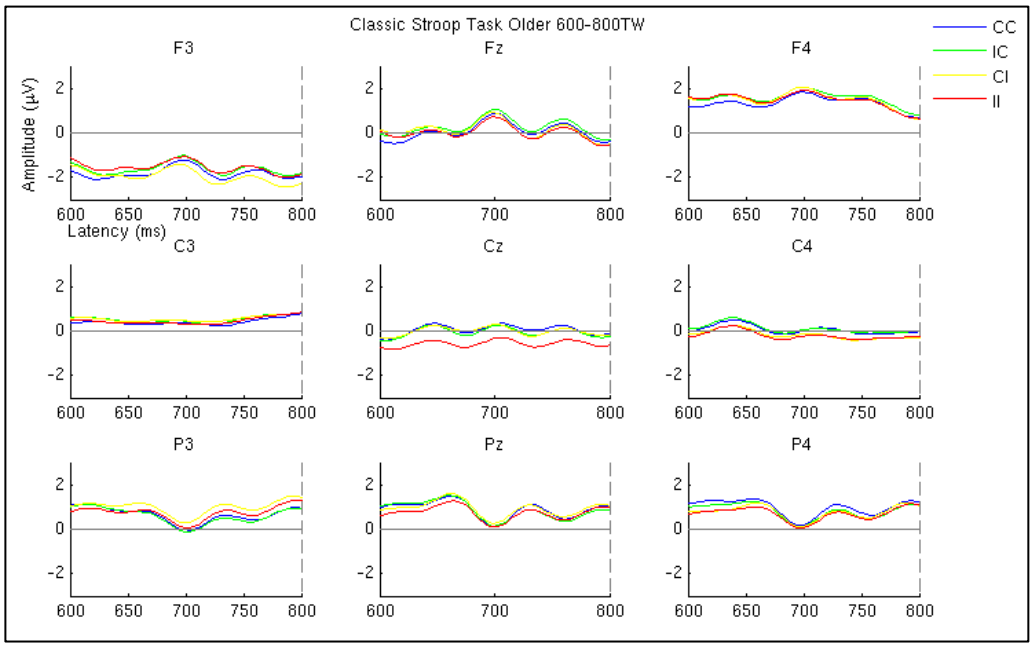

Figure 14 - Grand average ERP waveforms of stimulus-locked Stroop trials (CC, IC, CI, II) recorded in older adults limited to the 600-800 ms TW. The 9 electrodes selected for the analyses are displayed.

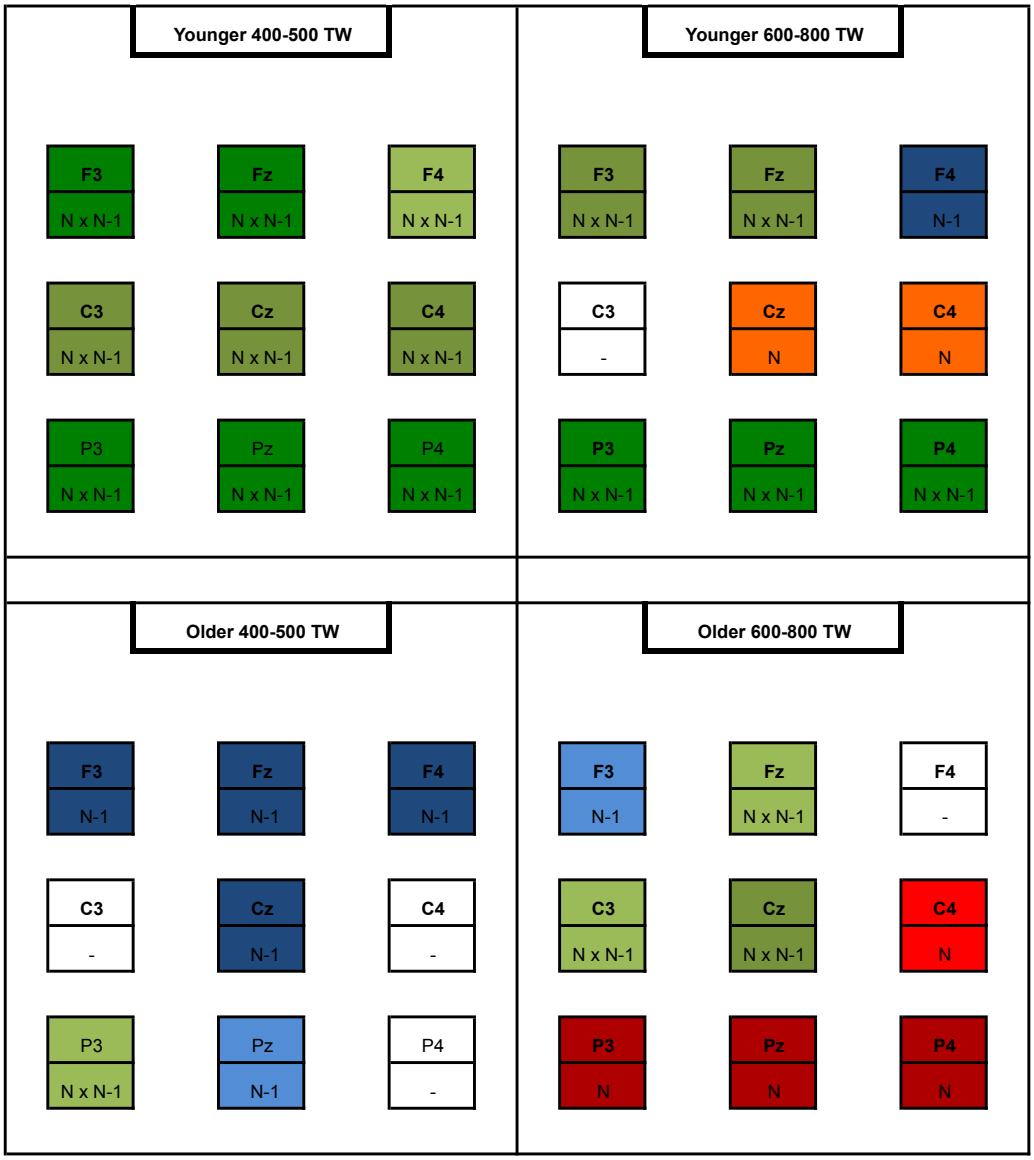

Figure 15 – Schema of significant effects of *trial n* congruency (N – red scale), *trial n-1* congruency (N-1 – blue scale) and of *trial n* and *trial n-1* congruency interaction (N x *n-1* – green scale) in younger (upper part of the picture) and older adults (lower part of the picture) in each examined TW: between 400 and 500 ms (left side of the picture) and between 600 and 800 ms (right side of the picture). The colour darkness reflects the significance strength ($p < .05, p < .01, p < .001$).

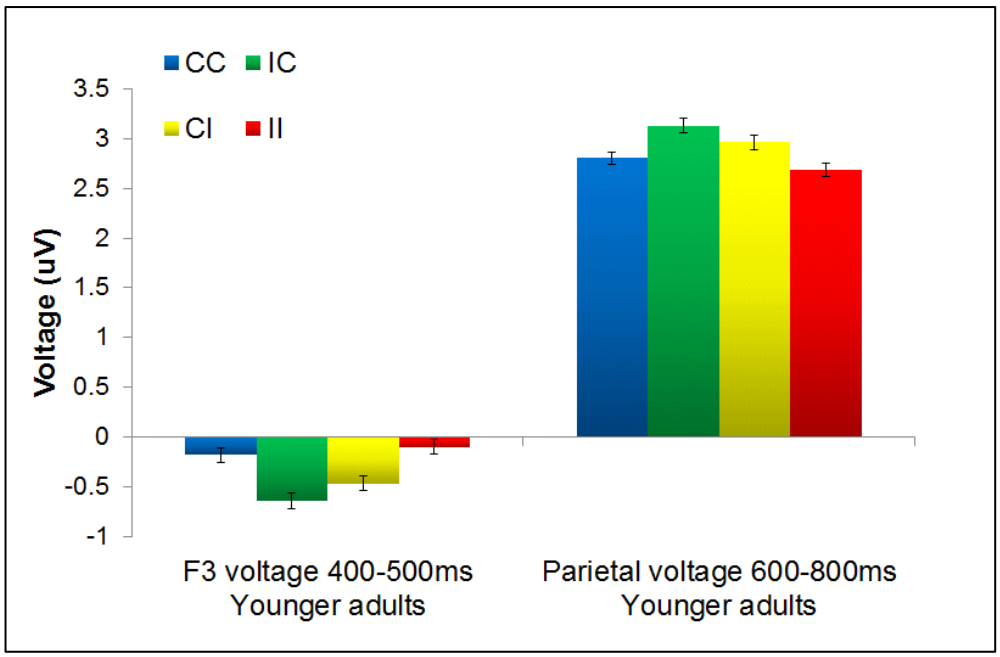

Figure 16 – Average amplitude recorded in F3 in the 400-500 ms TW and average amplitude recorded in parietal electrodes in the 600-800 ms TW as a function of Stroop condition in younger adults.

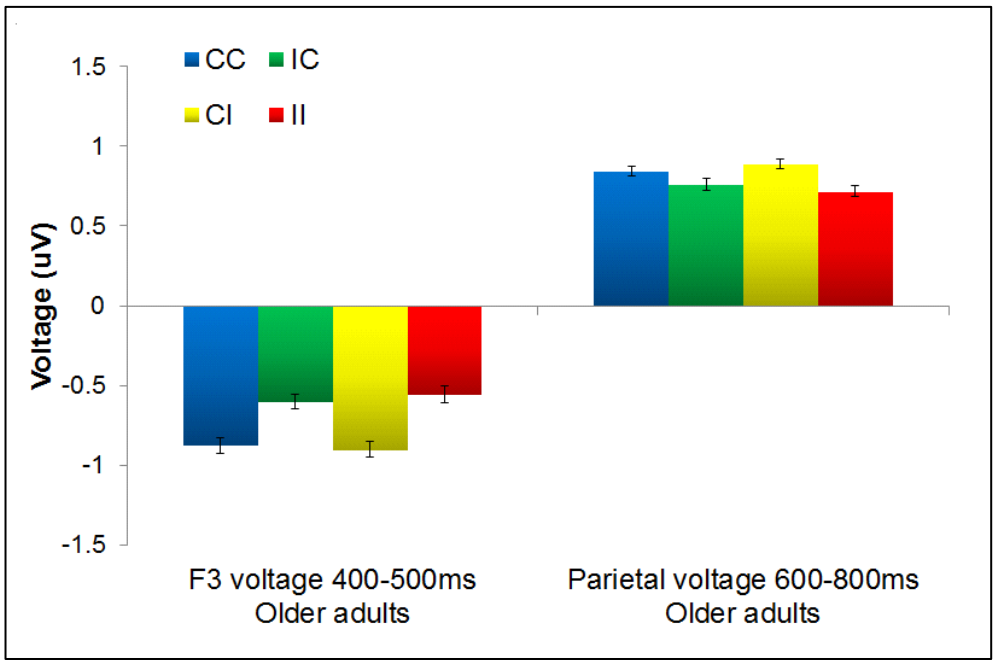

Figure 17 – Average amplitude recorded in F3 in the 400-500 ms TW and average amplitude recorded in parietal electrodes in the 600-800 ms TW as a function of Stroop condition in older adults.

Discussion

In this study we used electrophysiology in order to investigate the neural mechanisms that underlie the verbal conflict resolution ability. As in Experiment 3, we used a Stroop task that allows the minimizes the priming effects exerted by features repetition.

Single feature conditions, that is, Colour Naming and Black Words, were processed faster with respect to current incongruent Stroop trials and as fast as current congruent Stroop trials both in younger and older adults. This suggests that, independent of age, the simultaneous presence of two features, as it is for a Stroop trial, exerts interference effects only if such features are incongruent. The presence of two congruent features does not exert facilitation, except for a little increase of accuracy in older adults in the case of Congruent-Congruent sequences. However, in older adults, age correlates with the amount of RT difference between Stroop task and Colour Naming task trials. This suggests that the older one is, the higher the interference that arises when simultaneously processing two features instead of one is.

Despite a comparable level of accuracy, older adults were systematically slower with respect to younger ones in of all the considered conditions (CN, BW, Stroop CC, IC, CI and II conditions), confirming the presence of an age-related general slowing effect (Salthouse, 1991; 1996). Contrary to the majority of previous findings, conflict resolution, measured as Stroop effect, was spared in healthy aging in terms of both response speed and accuracy.

Conflict adaptation effects were not present in RTs of either age-group. However the accuracy analysis suggests that in younger adults the accuracy Stroop effect is reduced whenever the previous trial is incongruent, since in the II condition accuracy is greater than in CI. For what concerns the effects of modulatory variables, we found that the CRI index negatively correlated with the general slowing phenomena.

Conflict-related ERPs in younger adults

Event-related potentials were used to examine how neural activity over time could reflect conflict processing and cognitive control as compared to conflict monitoring. Based on previous literature and visual inspection of our data we

examined two TWs (400-500 and 600-800 ms). In younger adults the analysis of the 400-500 TW confirms the presence of a phasic negativity in the fronto-central electrodes and a sustained positivity in the parietal region as reported by previous literature (e.g., Larson et al., 2009; Liotti et al., 2000; West & Alain, 2000a, 2000b). In the 600-800 TW a sustained potential (SP) was found, with negative polarity in the frontal region and positive polarity in the central and temporo-parietal regions, again supporting the outcomes of some previous studies (Larson, Kaufman & Perlstein, 2009; Liotti, Woldorff, Perez, Mayberg, 2000; West, 2004; West & Alain, 2000b; West & Moore 2005; West & Schwarb 2006). All of these modulations in younger adults reflect the interaction between *trial n* and *trial n-1* congruency. In particular the amplitude of the frontal phasic negativity in the 400-500 TW and the parietal SP show the same (although reversed in polarity) voltage pattern of IC = CI > CC = II (see Figure 16). This modulation seems to reflect a conflict adaptation mechanism, since the waveform for sequences with repeated conflict levels (i.e., CC and II) are similar, and differ from those where the conflict level changes in two subsequent trials (i.e. CI and IC).

This result goes against findings from previous studies, which often showed the 400 ms negative deflection to increase its negativity in incongruent trials, and the SP to be more positive for incongruent trials. However, as we extensively discussed in previous sections, there are two main issues that tangle the comparison between previous studies and our own: the control of both sequential effects and priming.

Indeed the majority of previous studies compared congruent versus incongruent trials without considering the fact that current and previous trial congruency effects could interact. In our case, since we verified that such an interaction is present in the waveforms, we cannot drive conclusions only with respect to current trial congruency.

Additionally, the fact that previous studies found increased positivity (i.e., decreased negativity) for congruent trials in the N400 might be due to the uncontrolled priming modulation. Indeed there is evidence showing that repetition priming elicits a positive-going shift in ERPs that is greater after 400 ms from the stimulus onset (e.g., Doyle, Rugg & Wells, 1996; Kiefer, 2005). Some authors claim to have applied measures to control for priming. For

example, Larson (Larson et al., 2009) reported that, in order to control for associative priming, trials that repeated the same stimulus colour and trials wherein the colour of the incongruent current-trial stimulus corresponded to the word of the preceding incongruent trial stimulus were a posteriori excluded from the analysis. However this procedure cannot be considered a satisfactory priming control (See Chapter 2), as the same authors pointed out.

In the waveforms of the two TWs the modulation reflecting the *trial n* and *trial n-1* interaction showed some interesting correlations with behavioural data. In particular both the amplitude difference reflecting the modulation caused by *trial n* congruency when the preceding trial was congruent (CI-CC) and the one reflecting the modulation caused by *trial n* congruency when the preceding trial was incongruent (II-IC) correlates with the Stroop effect and the overall RTs as well. These correlations suggest that the higher the CI vs CC and the II vs IC amplitude differences are, on one side, the smaller the Stroop effect and the shorter the RTs are, on the other side. A similar relationship is valid for years of education and IQ: the higher their values are, the greater the CI-CC and II-IC wave difference is.

Previous studies suggested that the N450 modulation could be interpreted as a more automatic congruency detection mechanism and that the late SP reflects a more top-down regulated conflict-processing mechanism (Liotti et al., 2000; Perlstein et al., 2006; West, 2003, 2004; West et al., 2005).

Our results showed that in younger adults a sequential congruency modulation is already present in the 400-500 ms waveforms and is maintained in the later ERPs. Moreover this modulation seems to improve the performance by reducing the conflict negative effects.

Additionally, the hypothesis according to which the N450 negativity is a simple automatic congruency detection mechanism clashes with evidence that proposes the ACC as the generator site for such modulation, since the ACC is more likely involved in top-down regulation rather than bottom-up regulation. The fact that CC and II ERPs are very similar in N450 of younger adults, disconfirms the hypothesis that this modulation is a simple marker of incongruence detection.

The frontal previous by current trial congruency interaction revealed by the statistical analysis interestingly dissociates with the absence of a similar

interaction in the behavioural data. Indeed while the RT pattern is CC = IC < II = CI (or CC = IC > II > CI for accuracy) (see Figure 8), the voltage pattern recorded in frontal electrodes is CC = II > IC =CI (Figure 16).

We suggest that this voltage pattern in frontal sites corresponds to a signal generated in the 400-500 ms time window, which reflects the adjustment of attentional resources needed in the current trial with respect to the previous one. This signal is directed to parietal sites, where it modulates the neural activity recorded in the 600-800 ms TW resulting in a sustained potential that reflects the same pattern (with reversed polarity) of CC = II < IC =CI (Figure 16) shows by the earlier phasic frontal negativity. The proposed mechanism is compatible with Botvinick's conflict monitoring theory, but contrarily to what has been shown by previous studies, here we provide direct evidence of a neural mechanism that seems to successfully adjust the attentional resources on the basis of both the previously experienced conflict and the current one.

Conflict-related ERPs in older adults

For what concerns age-related differences, our analyses revealed that younger and older adults presented very different electrophysiological patterns for the conflict resolution-related processing. Similarly to younger adults, older adults' ERPs present a frontal negativity in the 400-500 ms TW. However, the event-related statistical analyses of sequential conditions revealed that, contrary to younger adults, older adults do not show the interaction between *trial n* and *trial n-1* congruency in frontal regions. Frontal and central sites reflect instead a modulation based on *trial n-1* congruency only (see Figures 12 and 15). Moreover the peak of frontal negativity appears to be left lateralized and delayed in time in older adults with respect to younger controls. Nevertheless in left temporo-parietal sites a SP is visible, reflecting an interaction between *trial n* and *trial n-1* congruency. However the voltage pattern of this component is not compatible to that found in younger adults since it only differentiated II sequences with respect to the other ones.

In the 600-800 ms TW the SP was present only in frontal lateral sites (with opposed polarity in the left versus right side) and it showed a preceding trial congruency effect only (see Figures 14 and 17). On the other hand, in the 600-

800 ms TW a significant *trial n* by *trial n-1* interaction was present in ERPs recorded in central sites (mainly in Cz). This interaction led to an amplitude pattern that was IC ≈ CI ≈ CC > II, mirroring the one found in the previous time window, and correlated with the Stroop effect, suggesting a predicting role of this modulation on behavioural output. As for younger adults, the greater the difference in CI-CC amplitude was, the smaller the accuracy Stroop effect was. On the other hand the modulation with respect to current trial congruency present in C4 was associated with CRI and VIQ.

Older adults seem to use a very different mechanism, both functionally and topographically, with respect to younger ones. It is clear that the mechanism of attentional adjustment described for younger adults is not present in older ones (Figure 15). In older adults, the frontal N450 modulation reflects only the previous trial congruency. This fact suggests that older adults may implement a proactive strategy, modulating a preparatory mechanism with respect to previous trial congruency, in order to be pre-activated for a new incoming trial.

On the other hand, the fact that in older adults the modulation in N450 is limited to previous trial congruency could be interpreted as the tendency to be anchored to the just experienced stimulus and the inability to be sensitive to the current congruency. Such an inability is overcome during the second TW, where the current by previous trial interaction is present and it would prevent a decline in performance, but imply a slowing cost not evidenced in our data.

Later on a modulation based on both current and previous trial congruency appears (600-800 ms SP). It is important to point out that younger adults' responses usually fall within the 600-800 ms TW, whereas older adults' responses take place after it. This suggests that processing taking place in the 600-800ms TW could regulate the response of older adults. This could explain why, despite a general slowing effect, older adults that show this electrophysiological pattern did not show an increase in the Stroop effect. Indeed, our older participants reached a level of performance comparable with that of the younger group. Therefore it is likely that such electrophysiological differences reflect an age-related compensatory rearrangement.

Chapter 4 – Cognitive Control in the Spatial domain

Similar to what we have done in Chapter 3 for the verbal domain, in the present chapter we report the steps undertaken to investigate cognitive control in the spatial domain. First, we addressed the problem of disentangling the priming/binding contribution and that of cognitive control per se in a new spatial Stroop task with 4 alternative-forced choices. This task is completely comparable to the colour-word one used to investigate the verbal domain. Afterwords, we report an investigation concerning spatial conflict adaptation phenomena and their age-related modifications by means of a priming-free version of the spatial Stroop task (cf., Chapter 2). At the end of the chapter, we will report an ERP study where we explored electrophysiological evidence relative to the modification of conflict resolution processes occurring during older age comparing normal aging adults with younger controls.

Introduction to spatial conflict

As already reported in Chapter 2, the colour-word Stroop task has been widely used in order to explore verbal conflict resolution (e.g., Dyer, 1973; MacLeod, 1991; Posner and Snyder, 1975; Stroop, 1935), whereas its spatial version has been used less frequently (e.g., Funes et al., 2010; Lu and Proctor, 1995). In the spatial version of the Stroop task, the stimulus is usually an arrow positioned in a specific position on the screen. The task consists of responding according to the direction of the arrow (target) while ignoring its position (distractor). If the distractor and the target refer to the same spatial feature, the stimulus is considered "congruent", whereas when they refer to different spatial features conflict takes place, and the stimulus is therefore referred to as "incongruent". Conflict is usually measured as the Stroop effect, that is the performance difference between incongruent (I), or conflict present, trials and congruent (C), or conflict absent, trials.

The conflict sequential effects, widely mentioned in previous chapters, have been reported also in many different spatial tasks, such as the Simon (Kunde and Wühr, 2006; Notebaert et al., 2006; Strümer et al., 2002; Wühr, 2005; Vallesi and Umiltà, 2009) and flanker (Gratton et al., 1992) ones. However, the spatial

correspondence evidenced by the Simon task and the congruence effect verified with the Stroop task seem to involve different stages of processing (Simon & Berbaum, 1990). Indeed the spatial Stroop task engages both the spatial correspondence between stimulus and response and the spatial congruence between the relevant and irrelevant features.

Unfortunately, to the best of our knowledge, there are no studies that used a 4 alternative-forced choice spatial Stroop paradigm. Therefore, both for behavioural and electrophysiological data it was not possible to make direct comparisons between our results and previous ones. Furthermore, spatial conflict resolution tasks (spatial Stroop and Simon) usually involve only two positions and two directions (or two symbols connected to two response buttons). This feature clearly prevents the possibility of avoiding repetition priming in two subsequent trials and to simultaneously have all four types of congruency sequences (Congruent-Congruent, Incongruent-Congruent, Congruent-Incongruent, Incongruent-Incongruent). Similarly, there is a lack of studies that investigated age-related effects on spatial conflict resolution while controlling for sequential effects and priming confounds.

The aim of this part of the thesis was to explore spatial conflict-resolution processes taking into account not only the current trial congruency, but also the preceding trial congruency, after controlling for the possible confounds due to priming or binding effects.

Moreover, since conflict resolution processes are supposed to be regulated by neural networks located in frontal and prefrontal cortex (Botvinick et al., 1999; Floden et al., 2011; Gehring & Knight, 2000; Kerns et al., 2004; Mansouri, et. al., 2000; Pardo et al., 1990), and both the FLH (West, 1996) and the inhibitory deficit theory (Connelly, Hasher, & Zacks, 1991; Hasher, Stoltzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988) suggest that aging is affected by a frontal lobes decline, we wanted to investigate whether there is an age-related deficit specific for spatial conflict resolution.

Afterward, in order to investigate the age-related spatial conflict resolution modifications, we compared younger adults' and older adults' performance of our priming-free 4-AFC spatial Stroop task (Experiment 6).

Finally, in Experiment 7, we explored the spatial conflict-related ERPs and their modifications as a function of age. Another goal of the Experiments 6 and 7

was to disentangle age-related general slowing and a specific conflict resolution deficit. Furthermore this work was aimed at investigating whether intelligence and some factors influenced by socio-economic status, such as cognitive reserve (CR) and years of education, might partially account for age-related inter-individual variability in performance (cf., Chapters 1 and 2).

4.1. Disentangling priming and conflict adaptation in the spatial Stroop task – Experiment 5

In Chapter 2 we report the methodological issues linked to the fact that conflict effects have been shown to be influenced by previous trial congruency (sequential congruency effects), at least in numerous studies that used the classic Stroop task.

If sequential congruency effects are due to a top-down general attentional system, such effects are likely to be present also in conflict tasks that do not involve the verbal domain, such as spatial ones. In order to explain sequential effects, at least three main accounts have been proposed: the conflict-monitoring theory (Botvinick et al., 2001), repetition priming (Mayr, Awh & Laurey, 2003, Nieuwenhuis et al. 2006), and the Theory of Event Coding (Dutzi & Hommel, 2009; Hommel 2011; Hommel, Proctor & Vu, 2004; Notebaert, Soetens & Melis, 2001;). These accounts and their implications have been described in Chapter 1. Experiments 1 and 2 of Chapter 3 were aimed at disentangling priming/binding and conflict adaptation influence in determining congruence sequential effects in the verbal domain. In Experiment 5 we addressed the same issue relative to the spatial domain.

In Chapter 2 we explained the need of having a task with at least four alternative forced choices (4-AFC) in order to minimize priming influence. To the best of our knowledge, there are no studies on spatial sequential effects that used a 4-AFC spatial task. Indeed, spatial conflict processes have been usually investigated by means of two-alternative forced choice (2AFC) spatial Stroop or Simon (again usually 2AFC) tasks (e.g., Kunde and Wühr, 2006; Notebaert et al., 2006; Strümer et al., 2002; Wühr, 2005; Vallesi and Umiltà, 2009). Therefore, it has not been possible to disentangle whether priming/binding

factors or conflict adaptation determine sequential effects, since a 2-AFC task does not allow for priming-free pairs of subsequent trials. To solve this problem, a spatial Stroop task with four directions/responses and four positions was designed, and in Experiment 5 it was run allowing the presentation of all the possible sequences, including those that contain feature repetitions. A posteriori we analysed separately the conflict adaptation depending on the type of feature repetition/alternation.

If sequential congruency effects are (partially or totally) due to high-level conflict adaptation mechanisms, they should occur even in a context of complete alternations. On the other hand, if they are due to perceptual or mnemonic priming mechanisms or to binding processes, they should exclusively emerge when feature repetitions are present.

Hereafter, as in Chapter 3, we will refer to feature repetition contributions as priming. However, since our design does not allow separating priming from binding accounts (see Chapter 1 and 2), these two possible explanations are both valid.

Methods

Participants

Nineteen younger adults (mean age = 25 years, range 18-35; 9 females) participated in this study. All participants were native Italian-speakers and right-handed, as measured with the Edinburgh Handedness Inventory (Oldfield, 1971). All participants had normal or corrected-to-normal vision. An additional male participant was excluded because he resulted to be an outlier for RTs (> 3 SD from the group mean).

Design and stimuli

Participants were individually tested in a dimly lit room, sitting at a distance of about 50 cm from the computer LCD monitor to perform the Stroop test. Participants were administered three spatial Stroop blocks. An instruction page preceded the presentation of each task. In each condition, the stimuli were presented against a light-gray background.

Participants were asked to maintain their gaze on a fixation cross shown in the middle of the screen. Four response buttons were arranged in order to reflect the upper-right, upper-left, lower-right and lower-left directions (see Figure 18). Participants were asked to give a response as fast and accurately as possible by using the index and middle fingers of both hands.

In each trial one arrow out of four (pointing to the upper-right, upper-left, lower-right or lower-left) appeared in one out of the four positions on the screen (upper right and left, lower right and left). Participants were required to ignore the position and to respond according to the pointing direction of the arrows by pressing the spatially corresponding button. The Stroop stimuli were categorized as congruent (e.g., upper-right pointing arrow positioned in the upper right part of the screen) and incongruent (e.g., upper-right pointing arrow positioned in the upper left part of the screen). We categorized subsequent pairs of trials according to the congruency status of *trial n-1* and *trial n* as: congruent-congruent (CC), congruent-incongruent (CI), incongruent-congruent (IC), incongruent-incongruent (II).

In order to become familiar with the task, participants performed a training phase at the beginning of the Stroop task, composed of 16 trials, with all possible position-direction combinations. During the training phase, each stimulus remained on the screen until a response was detected. Then feedback on accuracy and speed appeared for 1200 ms, followed by an Inter-Trial-Interval of 500 ms. The feedback was "Good" (in Italian: "Bene"), for a correct response within 2000 ms from trial onset; "Correct, but try to be faster ..." (in Italian: "Corretto, ma cerca di essere piú veloce . . . ") for a correct response which occurred later than 2000 ms after stimulus onset; "Wrong" ("Sbagliato") for incorrect responses. If participants made more than 6 errors out of 16 trials during the training phase, they had to repeat this phase. This was the case for five older adults, who had to repeat the training phase.

The test phase was divided in to three blocks, each one composed of 2 sub-blocks of 64 stimuli each. Each sub-block was composed of at least 30 congruent trials, in order to minimize the influence of task strategies related to unbalanced frequencies of congruency conditions (Gratton et al., 1992; see also Vallesi, 2011). Each of the four possible sequential conditions (CC, CI, II, and IC) was presented in at least 15 trials (cf., Mordkoff, 2012). In each test trial, the

target stimulus appeared at the center of the screen for 500 ms, followed by a blank screen of 2000 ms whose offset corresponded to the response deadline (2500 ms). An extra blank screen, which lasted randomly and continuously between 250 and 700 ms, was presented before the onset of the next trial.

Sequential pairs of trials were a posteriori divided into: *Complete Repetition, Complete Alternation* and *Partial Repetition*. Moreover *Partial Repetition* sequences were subdivided into five subcategories: *Target Repetition, Distractor Repetition, Target to Distractor, Negative Priming,* and *Inversion* (see Chapter 2).

In Target Repetition sequences, the target (i.e., direction) was the same in *trial n-1* and *trial n*, but the distractors (i.e., position) were different. In Distractor Repetitions sequences the target was different in *trial n-1* and *trial n* while the distractor was the same position. Target to Distractor indicates sequences in which the target of *trial n-1* became the distractor of *trial n*, while the distractor of *trial n-1* was different with respect to the target of *trial n*. Negative Priming sequences were those in which the distractor of *trial n-1* became the target of *trial n*, while the target of *trial n-1* was different with respect to the distractor of *trial n.* Inversion refers to sequences in which the target of *trial n-1* became the distractor of *trial n* and the distractor of *trial n-1* became the target of *trial n*. All the different types of trials and sequences were presented randomly to the participants.

Data analysis

Trials with RTs faster than 100 and slower than 1,500 ms were excluded (0.6% of total trials).

For each participant, trials above and below 3 SD from their mean RT were also excluded (1.34% of remaining trials). Error trials and trials following an error were not considered in the RT analysis to avoid post-error slowing confounds (Burns, 1965).

We ran a 2 × 2 ANOVA with congruency of *trial n* and congruency of *trial n-1* as within-subject factors.

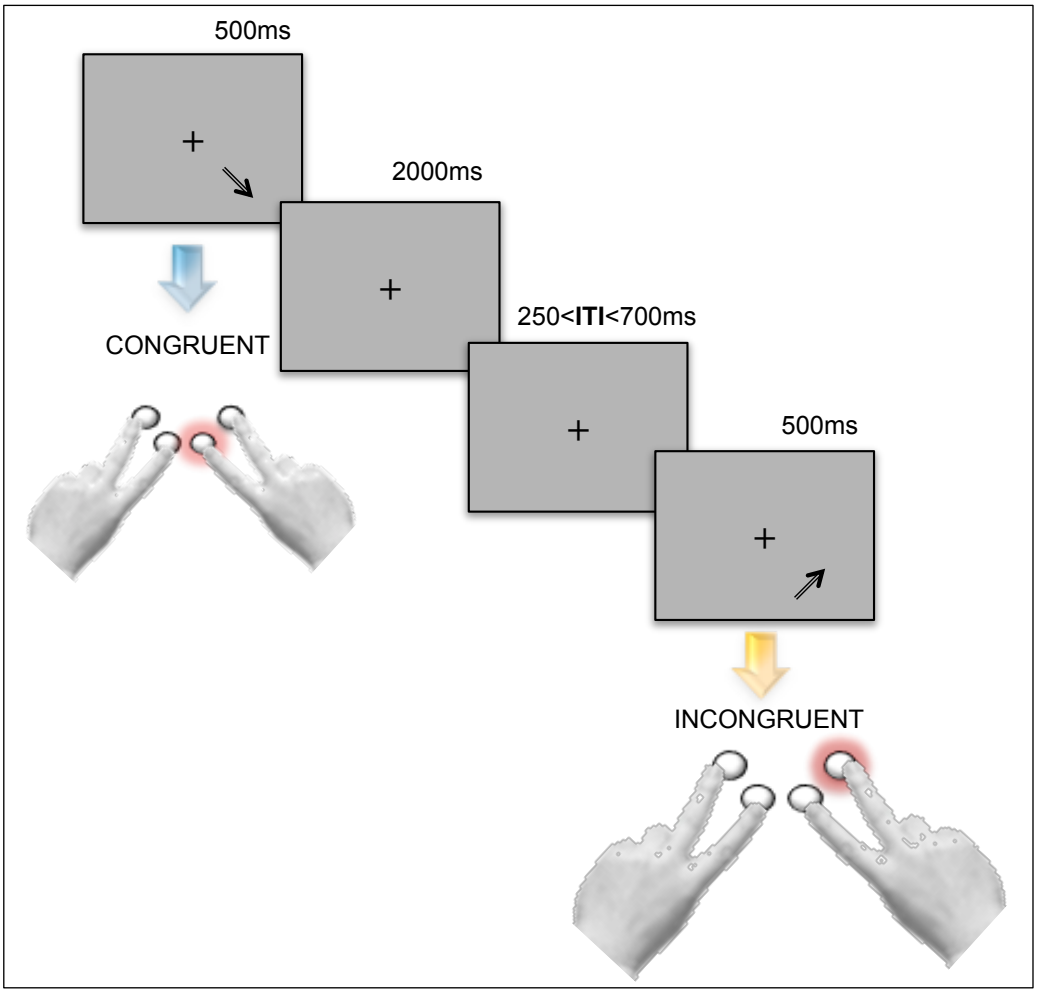

Figure 18 - **Experimental design**. During the spatial Stroop task each stimulus was presented for 500 ms, followed by a blank screen showing a fixation cross and lasting 2000 ms. Before the onset of the subsequent stimulus, an Inter-Trial-Interval (ITI) varying randomly and continuously between 250 and 700 ms was presented. Stroop stimuli were divided into Congruent and Incongruent with respect to the direction of the displayed arrow and its position on the screen. Participants were asked to respond by pressing one of four response buttons displayed as shown in the panel. In the picture, two Stroop trials are represented.

Since the raw accuracy data were not normally distributed, a non-parametric Wilcoxon test was used to directly compare pairs of conditions. We moreover used the accuracy Stroop effect (measured as the difference between incongruent and congruent trials), which was instead normally distributed, as a dependent variable to perform a repeated measures ANOVA with congruency of *trial n-1* as a within-subject factor to clarify the effect of the preceding trial on the current trial accuracy Stroop effect.

Since we suppose that priming could exert a relevant effect on conflict-related indexes, we compared congruency and sequential congruency effects of a condition where the priming effect is at the maximum level with those obtained

in a condition where the priming effect is at the minimum level. We therefore ran three different analyses. First, all trials together were analyzed, which included all possible sequences. Second, only complete alternation sequences were taken into account to reveal the strength and the type of sequential effects in the absence of priming. A third analysis focused on sequences supposed to elicit positive priming only (i.e., Complete Repetitions, Target Repetition and Distractor Repetition) (cf. Chapter 2). This specifically highlighted the contribution of repetition priming on sequential effects.

Results

All sequences

The first analysis was run including all possible sequences.

Response times

The mean RTs are shown in Figure 19a. The main effect of current trial congruency was significant [$F(1,18) = 262.3$, $p < .001$], indicating that responses to congruent trials were faster compared to those incongruent trials, with a Stroop effect of 76 ms. The main effect of preceding trial was significant [$F(1,18) = 12.3$, $p = .003$]. The interaction between the congruency on *trial n* and the congruency on *trial n - 1* also resulted significant [$F(1,18) = 66.2$, $p < .001$]. Bonferroni post-hoc test revealed that responses on congruent trials were influenced by the preceding trial congruency [$p < .001$], being faster when *trial n-1* was congruent (CC) than when it was incongruent (IC). RTs on incongruent current trials did not significantly depend on *trial n-1* congruency [II vs CI, $p = .094$].

Accuracy

The effect of preceding trial congruency on accuracy Stroop effect was significant [$F(1,18) = 9.22$, $p = .007$]. Accuracy on congruent trials was not modulated by congruency on preceding trials [CC vs IC, Wilcoxon's $T = 13$, $Z = 1.48$, $p = .139$], as shown in Figure 19b. Incongruent trials had a higher accuracy when preceded by another incongruent trial than by a congruent one [CI vs II, Wilcoxon's $T = 33.5$, $Z = 2.47$, $p = .013$].

Complete alternations only

Among all of the possible sequences, complete alternation pairs of trials only were included in this analysis. This means that both the position (distractor) and the direction (target) of *trial n* were different with respect to the position and the direction of *trial n-1*, nullifying first order priming effects.

Response times

Figure 19c shows that the main effect of current trial congruency was significant [$F(1,18) = 179.2$, $p < .001$], indicating that to congruent trials were faster compared to the incongruent trial ones and showed a Stroop effect of 79 ms. The main effect of preceding trial congruency was not significant [$F(1,18) = 1.3$, $p = .264$]. The interaction between the congruency on *trial n* and the congruency on *trial n-1* was significant [$F(1,18) = 5.4$, $p = .033$]. However Bonferroni post-hoc test revealed that CC are comparable to IC [$p = .147$] and II to CI [$p > .99$].

Accuracy

The effect of preceding trial congruency on the accuracy Stroop effect was significant [$F(1,18) = 5.236$, $p = .034$]. Accuracy on congruent trials was not modulated by congruency on preceding trials [CC vs IC, Wilcoxon's $T = 3$, $Z = 1.57$, $p = .116$], as shown in Figure 19d. Incongruent trials had a slightly higher accuracy when preceded by another incongruent trial than by a congruent one [CI vs II, Wilcoxon's $T = 35$, $Z = 1.96$, $p = .049$].

Positive priming sequences

Since repetitions elicit different types of phenomena that could facilitate or, on the contrary, impair conflict resolution, only sequences thought to elicit positive priming were included in this analysis, that is, complete repetition, target repetition and distractor repetition sequences.

Response times

The main effects of current trial congruency [$F(1,18) = 45.3$, $p < .001$; Stroop effect: 73 ms] and of the preceding trial congruency [$F(1,18) = 16.7$, $p = .001$] were significant (Figure 19e). The current by preceding congruency

interaction was also significant [$F(1,18) = 45.3$, $p < .001$]. Preceding trial congruency modulation on RTs of incongruent trials showed a strong trend [II vs CI, Bonferroni's $p = .06$], while RTs on congruent trials were significantly shorter when preceded by a congruent trial than by an incongruent one [CC vs IC, Bonferroni's $p < .001$].

Accuracy

The effect of preceding trial congruency on accuracy Stroop effect was significant [$F(1,18) = 6.25$, $p = .022$]. Accuracy on congruent trials was not modulated by congruency on preceding trials [CC vs IC, Wilcoxon's $T = 13$, $Z = 0.16$, $p = .866$], as shown in Figure 19f. Incongruent trials had a higher accuracy when preceded by another incongruent trial than by a congruent one [CI vs II, Wilcoxon's $T = 21.5$, $Z = 2.40$, $p = .016$].

Global analysis

In order to directly explore repetition influences on sequential congruency effects, we ran two 3 X 2 ANOVAs with Repetitions (All Sequences, Priming Sequences, Complete Alternations Sequences) and congruency of the previous trial (congruent vs incongruent) on RT Stroop effect and accuracy Stroop effect. The RT Stroop effect was not modulated by the Repetitions factor [$F(1,18) = 0.24$, $p = .79$], but the effect of preceding trial congruency was significant [$F(1,18) = 49.6$, $p < .001$]. The interaction between Repetitions and preceding trial congruency was significant [$F(1,18) = 9.99$, $p < .001$], suggesting that repetition priming exerts different effects on sequential congruency effects on the basis of preceding trial congruency. Bonferroni post-hoc test revealed that preceding trial congruency exerts an effect on Stroop effect in All Sequences [$p = .001$] and Priming sequences [$p < .001$] conditions, but not in Complete Alternation sequences [$p = .061$]. Moreover the Stroop effect when the preceding trial was congruent is different in Complete Alternations with respect to Priming Sequences. When considered together, these results suggest that the presence of priming increases the overall sequential effects, with respect to a priming neutral condition (i.e., Complete Alternations condition), because it

specifically increases the congruency (Stroop) effect when the preceding trial is congruent (Figure 20, upper part).

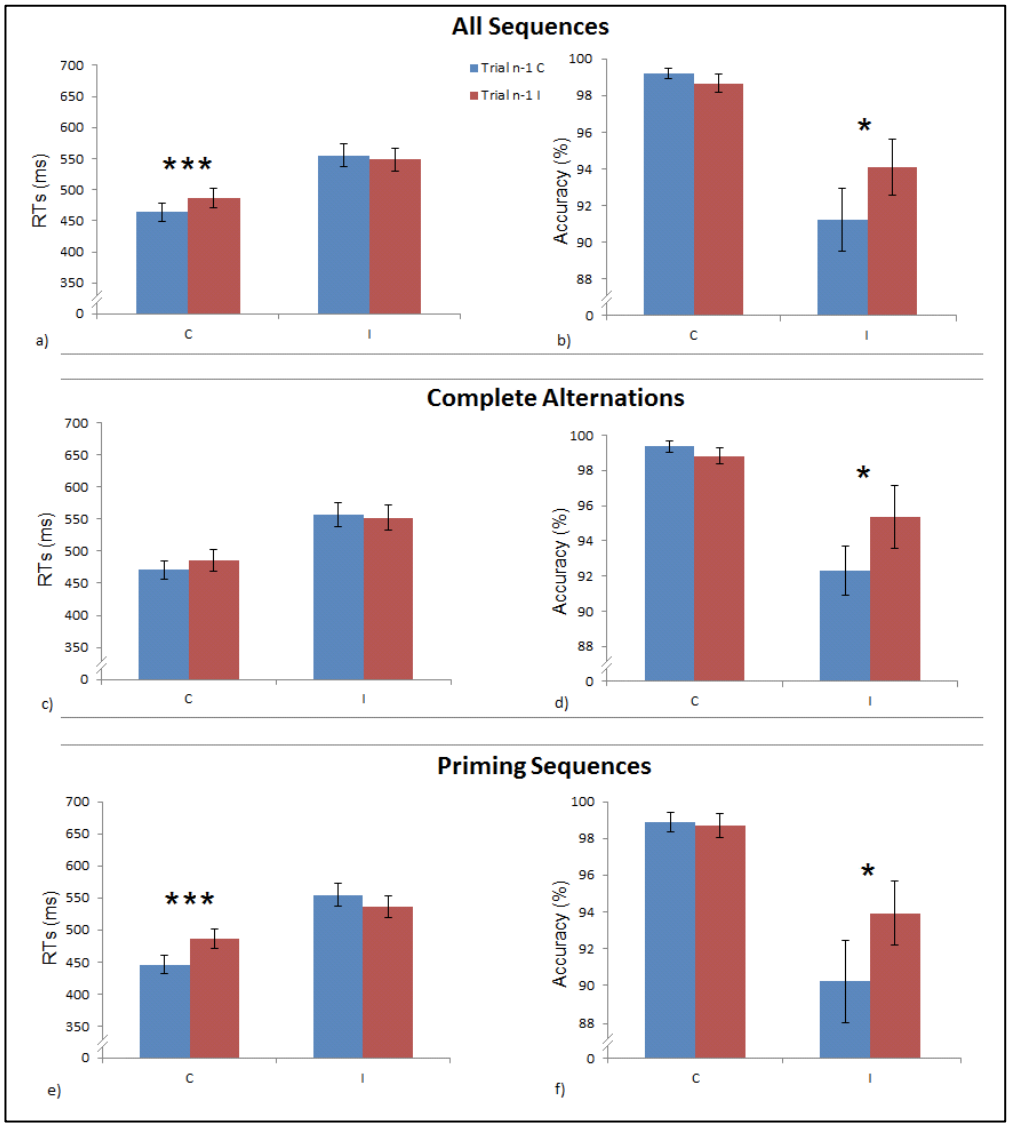

Figure 19 - Response times in ms (a, c, e) and accuracy (b, d, f) in Experiment 5 as a function of current (*n*) and previous (*n-1*) trial congruency. Error bars represent the standard error of the mean. (a, b) - All the different types of sequences were included in the graphs. (c, d) - Complete alternation sequences only were included in the plotted data. (e, f) - Sequences involving positive priming only were included in the plotted data.

The fact that the Stroop effect when trial *n-1* was congruent increased in priming sequences could arise from three situations:

a) priming reduces RTs on CC sequences and exerts no effect on CI;

b) priming increases RTs on CI and exerts no effect on CC;

c) priming reduces RTs on CC sequences and increases RTs on CI

We therefore compared both CC trials in Complete Alternations sequences and Priming ones, and we did the same for CI trials. RTs of CC trials were significantly shorter in Priming Sequences (446 ms) with respect to Complete Alternations (470 ms) [t-test: $t\,(18) = 4.46, p < .001$]. On the other hand, RTs of CI trials were just slightly shorter in Priming Sequences (554 ms) with respect to Complete Alternations (557 ms) [t-test: $t\,(18) = 0.63, p = .053$].

In the accuracy Stroop analysis the effect of preceding trial congruency was significant [$F(1,18) = 7.42, p = .013$], whereas both the Repetitions main effect and the interaction between Repetitions and preceding trial congruency were not significant [respectively $F(1,18) = 1.27, p = .292$; $F(1,18) = 0.19, p = .83$] (Figure 20, lower part).

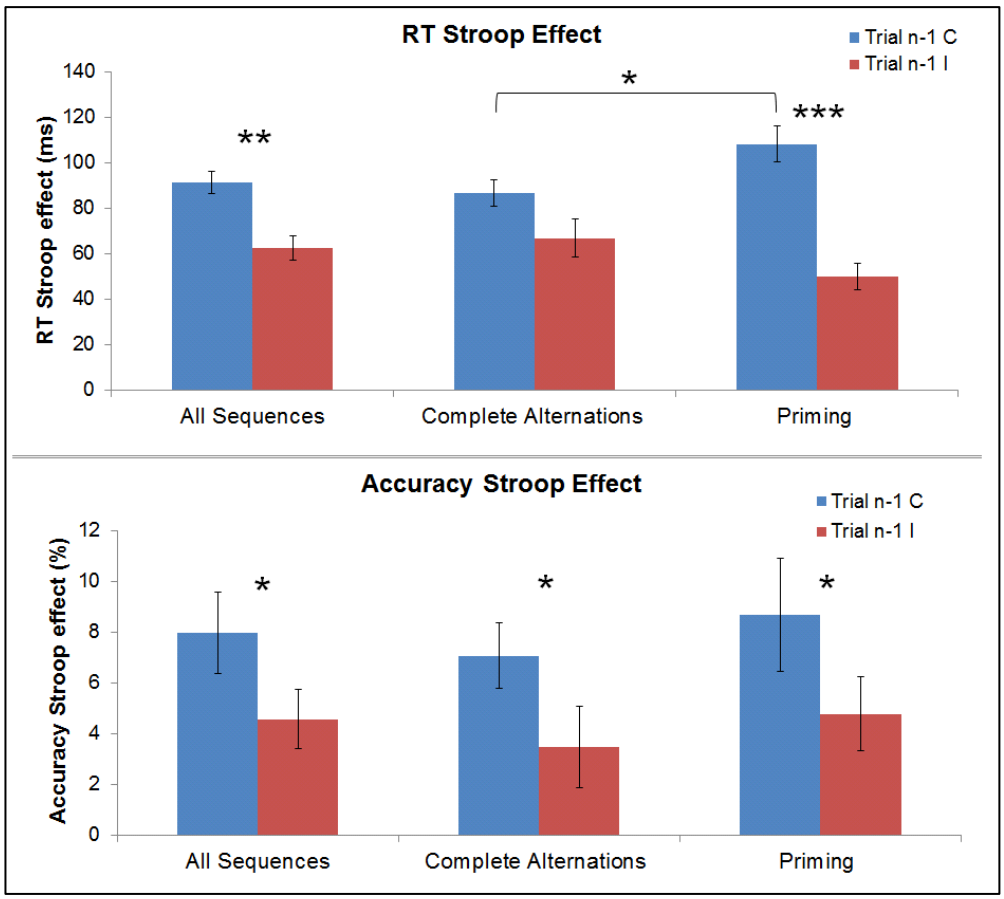

Figure 20 – RT Stroop effect (upper part of the graph) and accuracy Stroop effect (lower part of the graph) as a function of the three types of repetition sequences considered and previous (*n-1*) trial congruency. Error bars represent the standard error of the mean.

Discussion

Despite many studies having explored conflict resolution in the verbal domain, evidencing the presence of sequential congruency effects, there is a lack of comparable studies in the spatial domain. Classic conflict adaptation effects have been usually described as reduced congruency effects (e.g., Stroop effect) whenever the preceding trial is incongruent. Previous studies in the verbal domain showed this phenomenon also as a behavioural facilitation of CC with respect to IC sequences and a facilitation of II with respect to CI sequences. It has been proposed that such sequential effects could be due to a top-down, domain independent, attentional mechanism, as proposed by Botvinick's Conflict Monitoring hypothesis, or to priming/binding modulation (e.g., Hommel, Proctor, Vu, 2004; Mayr, Awh & Laurey, 2003).

The present study aimed at separating feature repetition from conflict adaptation contributions in the spatial conflict resolution processes, in order to clarify the origin of sequential effects in a spatial Stroop task with 4 positions and 4 directions responses. All possible sequences were presented randomly to the participants and, only afterward, the data analyses were subdivided with respect to the type of features repetitions.

When all types of repetitions are considered, RT sequential congruency effects are present, since RTs of current trials are influenced by previous trial congruency, and congruent trials responses are faster when preceded by another congruent. Results of complete alternation only sequences suggested that, when the priming contribution is minimized, RT sequential congruency effects are still present. Priming sequences (i.e., repetitions and positive priming eliciting sequences) shows strong sequential congruency effects in RTs, with a marked reduction of RTs in congruent trials when preceded by another congruent one.

The accuracy analysis showed that accuracy sequential congruency effects are present in incongruent trials only, since incongruent trials produce fewer errors if preceded by another incongruent one. This modulation is constant in all three types of repetition conditions.

When considering the RT Stroop effect with respect to feature repetitions, it appears that the presence of priming strongly increases the sequential congruency effect. In particular, in priming sequences with a congruent *trial n-1*,

the Stroop effect was greater than in priming-free conditions. This occurs because priming specifically facilitates current congruent trials preceded by another congruent trial (CC) and exerts a minimal effect on incongruent trials preceded by congruent ones (CI). On the contrary, if conflict has been experienced in *trial n-1*, the performance is not modulated by priming, and the Stroop effect is similar for every feature repetition condition. On the other hand accuracy sequential effects are present in our sample independent of the priming contribution.

The results show two different patterns related to the congruency of the present trial. For current congruent trials sequential congruency effects disappeared in priming-free conditions and increased when considering priming sequences (i.e., partial and complete repetitions) with respect to non-priming sequences (complete alternations). This suggests that sequential effects relative to current congruent stimuli are due to priming and cannot reflect a conflict adaptation mechanism.

On the other hand, current incongruent trials did not show sequential effects in RT analyses but they did show sequential effects in accuracy. Indeed accuracy results to be influenced by previous trial congruency in all features repetition conditions. Unfortunately, the lack of previous studies with a comparable design makes it hard to directly compare our results with preceding ones.

It is necessary to point out that our study was not designed to disentangle perceptual priming contributions from binding ones. Future studies should be designed in order to disentangle if contributions from feature repetitions on sequential effects are due to priming processes, or can be better explained by binding mechanisms.

In conclusion, the findings arising from this experiment demonstrate that the presence of priming exerts an effect when target and distracting information are not in conflict (i.e., congruent trials), while it does not exert a significant effect in incongruent trials. Cognitive control mechanisms seem to be present both in congruent and incongruent trials, improving the performance whenever the same type of congruency has just been experienced, especially in incongruent conditions.

4.2. Cognitive Control in the spatial domain and its age-related modifications: behavioural evidence - Experiment 6

The main aim of this study was to verify if there is an age-related deficit specific for spatial conflict resolution, after controlling for possible confounds due to priming or binding effects. We addressed this issue by using a priming-free spatial Stroop design (at least in terms of first-order trial sequences, see Chapter 2), similar to the one adopted in our previous studies, which were focused on verbal conflict resolution (see Experiment 3, Chapter 3) in order to minimize the contribution of repetition priming on conflict resolution.

Another goal of the study was to explore whether intelligence and some factors influenced by socio-economic status, such as cognitive reserve (CR) and years of education might partially account for age-related inter-individual variability in performance. To assess each participant's Intelligence Quotient (IQ) we used a set of WAIS subtests (Wechsler, 1981), in addition to a measure of CR obtained with the Cognitive Reserve Index questionnaire (Nucci et al., 2012, see Chapter 2). Additionally, we decided to consider years of education not only as a contribution to the CR score, but also as a separate independent predictor. Intelligence and CR might have distinct compensatory impacts on cognitive functioning (Stern, 2002, 2009). Therefore, we decided to measure and treat cognitive reserve and intelligence separately; indeed, we anticipate here that the absence of a significant correlation between CR and IQ in our sample (see Table 3) supports our assumption.

Methods

Participants

Seventeen older adults (mean age = 73 years, range 69-79; 8 females) and eighteen younger controls (mean age = 24 years, range 18-34; 9 females) participated in this study. All participants were native Italian-speakers and right-handed, as measured with the Edinburgh Handedness Inventory (Oldfield, 1971). All participants had normal or corrected-to-normal vision and normal colour perception, as assessed with a computerized version of the Ishihara Color Vision Test (Ishihara, 1962). The two age-groups had attained the same years of

formal education on average (younger, range: 9–18, M = 13.4 years; older, range: 6–18, M = 12.5 years, [t(33) = 0.764, p = 0.449]). None of the older adults met the criteria for dementia as assessed with the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005; score range: 26–30/30). Five of them reported regular consumption of medications for cardiovascular disease. Two additional participants were excluded: an older participant because of a low MoCA score (24/30), and a younger participant because of low intelligence scores (IQ = 72). The present study was approved by the SISSA ethical committee. Each participant signed an informed consent form and received 15 Euros for taking part in the experiment. All participants also performed the verbal Stroop task presented in Chapter 3 (Experiment 3) in a different session, on a different day (in a counterbalanced order).

Design and Stimuli

The task design is the same as described in Experiment 5. The only difference is that in this spatial Stroop task only complete alternation sequences were used, that is, in two subsequent pairs of trials the position (distractor) and the direction (target) of the stimuli in trial *n* were always different from the position and direction of trial *n-1* (e.g., upper-right arrow in the lower right part, followed by upper-left arrow in the lower left part). Subsequent pairs of trials were also categorized as congruent-congruent (CC), congruent-incongruent (CI), incongruent-congruent (IC) and incongruent-incongruent (II) according to the congruency status of trial *n-1* and trial n.

Additionally, at the beginning of the experimental session two single-feature tasks were administered in order to have specific baselines: Direction Only, Position Only. In the Direction Only task, the fixation cross disappeared at stimulus onset and was replaced with one out of four different arrows (2.5 cm long × 1.5 cm wide) pointing to upper–right, upper–left, lower–right or lower–left. Participants were asked to indicate the direction of the arrow by pressing the corresponding button.

In the Position Only condition, stimuli were Xs (each arm 2.5 cm) appearing in one out of four different positions on the screen: upper-right,

upper-left, lower-right, lower-left part of the screen (about 8 cm from the fixation cross). Participants were asked to indicate the position of each stimulus by pressing the corresponding button. For each of the two single-feature tasks, 32 test trials were administered, preceded by 2 training trials.

Nine subtests of the WAIS-R (Wechsler, 1981) were administered to the participants in order to calculate their IQs. The selected subtests were: Block Design, Arithmetic, Vocabulary, Similarities, Comprehension, Digit Span, Digit-Symbol, Object Assembly and Picture Completion. WAIS subtests were administered during the intervals between Stroop blocks in two separate sessions (counterbalanced order) run on different days. Younger and older adult samples resulted to have comparable IQs (younger, range: 79–120, M = 100; older, range: 93–109, M = 100, [$t(33) = -0.03$, $p = 0.97$]).

In order to quantify CR, after the last Stroop block older participants only were administered the "Cognitive Reserve Index questionnaire" (CRIq; Nucci et al., 2012: see Chapter 2). The CRI score of the sample ranged from 101 to 136, with an average score of 121 ± 11.

Data analysis

Trials with RTs faster than 100 and slower than 1500 ms were excluded (1.97%). For each participant, trials above and below 3 SD from their mean RT were also excluded (1.06% of total trials). Error trials and trials following an error were not considered in the RT analysis to avoid post-error slowing confounds (Burns, 1965).

Since we were interested in exploring the possible age-related effect specifically on conflict resolution, we applied a logarithmic transformation of RT data in the analysis, which was intended to compare the two age-groups (see Verhaeghen et al., 2005). This transformation converts proportional effects into additive ones. We thus assumed age-related slowing to be constant across conditions, allowing subsequent ANOVAs to compare younger and older adults across conditions in the absence of group differences in speed. Hence, significant interactions that resist logarithmic transformations can be considered as due to true condition-specific effects. On the contrary, if interactions that were significant before the logarithmic transformation are not significant any

more after it, it is possible to ascribe the effects to general factors such as age-related slowing (Salthouse, 1996; Salthouse and Babcock, 1991).

After logarithmic transformation of raw RT data, we ran a 2×2×2 mixed ANOVA with congruency of *trial n* and congruency of *trial n-1* as within-subjects factors and age-group as the between-subjects factor. However, we used raw RTs for the analyses conducted within each group (e.g., correlations).

Since the raw accuracy data were not normally distributed, we used the accuracy Stroop effect (measured as the difference between incongruent and congruent trials), which was instead normally distributed, as a dependent variable to perform a 2×2 mixed ANOVA with congruency in a *trial n-1* as the within-subjects factor and age-group as the between-subjects factor. Moreover, we ran a 2×2×2 mixed ANOVA with congruency of *trial n* and congruency of *trial n-1* as within-subjects factors and age-group as the between-subjects factor and applied a permutation test to evaluate the interaction between age-group and congruency conditions. The Mann–Whitney U test was applied whenever the analysis intended to compare the two age-groups across conditions.

In order to explore the amount of interference or facilitation that the presence of two features, either conflicting with each other or not, could produce when responding to a stimulus, we also ran the same analysis considering the performance on Direction Only as a baseline. Thus, after logarithmic transformation, we subtracted the RTs on Direction Only from those of the other conditions (Position Only, CC, IC, CI, II), whereas, for accuracy, we subtracted the percentage of accuracy for all conditions from that of Direction Only.

Additionally, in order to measure the amount of learning that took place across the three blocks, we ran a 2×2×3 ANOVA (age-group × *trial n* congruency × block) on log-RTs, whereas, for the same kind of analysis on accuracy data, given their non-normality, we ran a 2-way ANOVA (age-group × block) on accuracy Stroop effect. We also conducted correlation analyses between RT Stroop data and measures of CR, intelligence and years of education. Since these analyses were run separately for each age-group, we did not use logarithmic transformations but rather raw data. Furthermore, considering that we collected CR information in only the older group, we wanted to explore the separate contribution of CR and age in the older adults. Hence an ANCOVA was run for the older group only, using age and CRI as predictors.

Results

Direction only and position only conditions

Average RTs and accuracy are reported in Table 2. Both younger and older adults showed better performance in the Position Only condition with respect to the Direction Only one. RTs were indeed significantly shorter on Position Only than on Direction Only for younger ([t(17) = 5.29, $p < 0.001$], mean RT: 403 and 447 ms, respectively) and older adults ([t(16) = 5.44, $p < 0.001$], mean RT: 534 and 603 ms, respectively) (see Figure 21a). Younger adults also showed a slightly higher accuracy level on Position Only with respect to Direction Only [Wilcoxon's $T = 2$, $Z = 2.02$, $p = .04$], whereas this was only a tendency for older adults [Wilcoxon's $T = 13$, $Z = 1.78$, $p = .07$] (see Figure 21b). Even after logarithmic transformation of RTs, the older group was slower with respect to the younger one both for Position Only [t(33) = -5.79, $p < 0.001$, mean RT: 534 and 403 ms, respectively] and for Direction Only [t(33) = -7.64, $p < 0.001$, mean RT: 603 and 447 ms]. Younger and older adults showed a comparable level of general accuracy on both single-feature tasks [Position Only: younger: 99%, older: 98%; Mann–Whitney U = 119, Z = 1.10, $p = 0.27$; Direction Only: younger: 98%, older: 96%; Mann–Whitney U = 105, Z = 1.57, $p = 0.12$].

Spatial Stroop task

Average RTs and accuracy are reported in Table 2. The group main effect on RTs was significant [$F(1, 33) = 48.4$, $p < 0.001$], showing that the older group was slower than the younger one. Both the main effects of congruency of *trial n* (i.e., the Stroop effect) and congruency of *trial n-1* were significant [respectively, $F(1, 33) = 393.7$, $p < 0.001$; and $F(1, 33) = 19.7$, $p < 0.001$]. The interaction between *trial n* and *trial n-1* congruency was also significant [$F(1, 33) = 80.4$, $p < 0.001$], showing a modulatory effect of *trial n-1* on the Stroop effect in *trial n* (see Figure 21a). A post-hoc Bonferroni comparison showed that both age-groups responded faster to CC sequences than to IC ones [ps < 0.001]; moreover, older adults responded faster to II sequences than to CI ones [$p < 0.05$], while younger adults did not [$p = 0.16$]. The interactions involving group × *trial n* congruency, group × *trial n-1* congruency and the three

way group × *trial n* congruency × *trial n-1* congruency interaction failed to reach significance [for all, $p > 0.33$].

The analysis concerning interference, considering Direction Only as the baseline, confirmed the results reported above. Both the main effects of *trial n* and *trial n-1* congruency were significant [$F(1, 33) = 392.8$, $p < 0.001$; and $F(1, 33) = 20.8$, $p < 0.001$, respectively]. The interaction between these two factors was also significant [$F(1, 33) = 78.5$, $p < 0.001$]. Neither the main effect of age-group [$F(1, 33) = 1.1$, $p < 0.31$] nor the interaction between this factor and *trial n* and *trial n-1* congruency were significant [p = 0.89 and $p = 0.42$, respectively]. Thus, independent of age, processing of CC sequences required the same time as the Direction Only condition, whereas there was some residual interference if a congruent trial was preceded by an incongruent one (IC). On the contrary, processing of incongruent *trials n* implied greater interference with respect to Direction Only, and such interference was not modulated by *trial n-1* congruency.

Table 2 - Mean RTs (ms) and accuracy (%) with respect to conditions and age-groups. SD in parentheses.

		CC	IC	CI	II	Direction Only	Position Only
Younger	RTs	437 (49)	459 (61)	551 (84)	544 (83)	447 (48)	403 (51)
	Accuracy	99.5 (.7)	99.7 (.6)	92.5 (7.5)	94.7 (.5)	98.6 (2.1)	99.4 (1.2)
Older	RTs	610 (106)	640 (113)	772 (124)	753 (120)	603 (81)	529 (86)
	Accuracy	99.1 (1.4)	99.1 (1.5)	91.0 (11.5)	94.4 (10.6)	96.5 (3.6)	98.1 (2.9)

Regarding accuracy, as specified above, the Stroop effect was used as the dependent variable. The main effect of group was not significant [p = 0.848], whereas the main effect of *trial n-1* congruency was significant [$F(1, 33) = 8.283$, $p < 0.01$]. The interaction between age-group and *trial n-1* congruency was not significant [$F(1, 33) = 0.442$, $p = 0.511$], suggesting that the modulatory effect of *trial n-1* on the accuracy Stroop effect of *trial n* is not age-dependent. Due to its non-normal distribution, accuracy was further explored with a permuted mixed model ANOVA in order to check for the group × *trial n*

congruency × *trial n-1* congruency interaction. Such interaction failed to reach significance [N = 1000 permutations, p = 0.57].

We repeated both analyses considering Direction Only as the baseline: using the Stroop effect as a dependent variable and the mixed model ANOVA coupled with the permutation procedure. The results were perfectly comparable to those of the analyses performed using the raw data. The results therefore suggest that accuracy does not differ between the two age-groups and is modulated by congruency of the current trial only (see Figure 21b).

The analysis conducted for exploring the learning rate showed that both age-groups increased their speed along the three blocks [main effect of block [F(2, 33) = 40.6, p < 0.001]. On the other hand, the interaction with age and *trial n* congruency were not significant [all ps > 0.16], suggesting a non-relevant reduction for the RT Stroop effect throughout the three blocks for both age-groups.

Regarding the accuracy Stroop effect, the main effect of block was significant [F(2, 33) = 5.70, p < 0.005], whereas neither the main effect of age-group nor the interaction between blocks and age-group were significant [p = 0.749 and p = 0.275, respectively], supporting the presence of age-independent learning phenomena for conflict resolution in terms of accuracy.

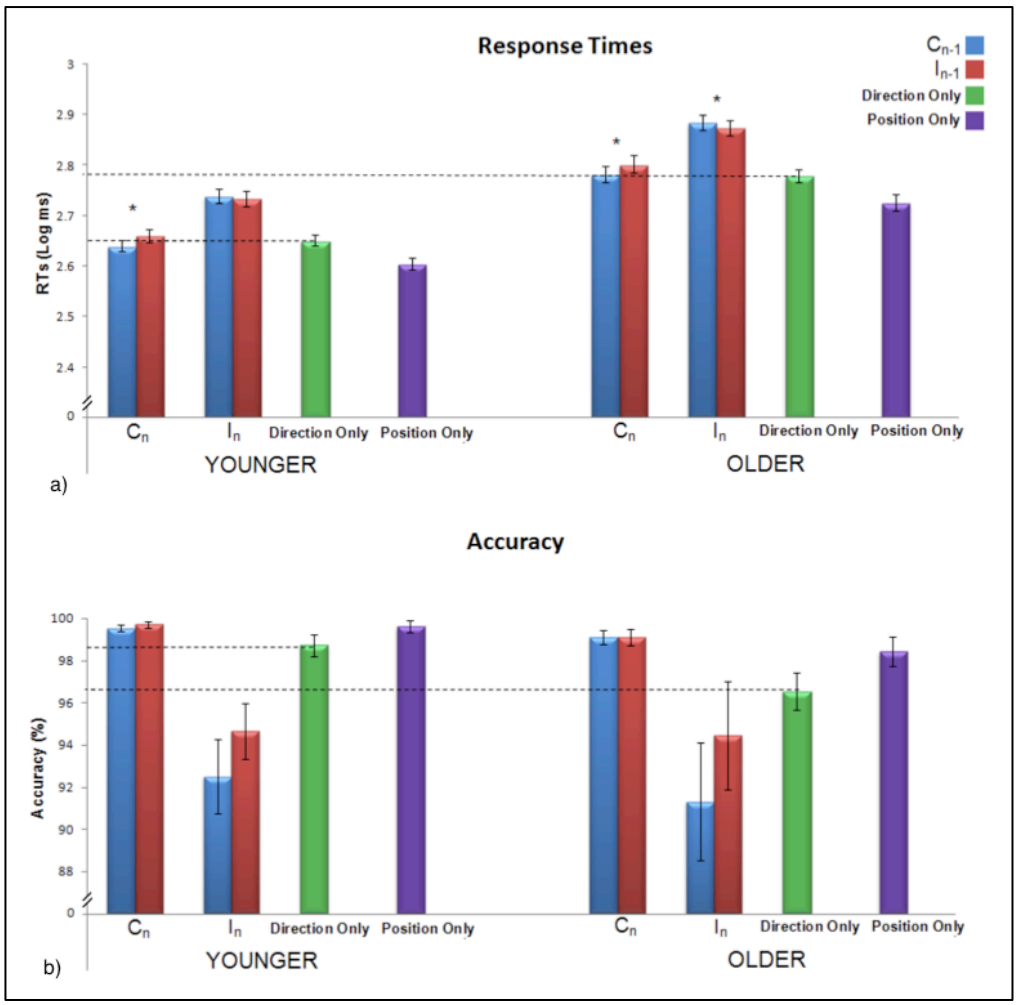

Figure 21 - Response times in ms (Panel A) and accuracy percentage (Panel B) of the spatial Stroop task for both age-groups are shown. On the x axis the two spatial Stroop *trial n* conditions are displayed: Congruent (C) and Incongruent (I), * $p < 0.05$; in addition to the single-feature conditions: Direction Only and Position Only. The colours of the different columns refer to previous trial congruency, as shown in the legend. Dotted lines representing the average performance in Direction Only are drawn to easily compare this condition with the Stroop ones. Error bars represent the standard error of the mean.

Correlational analysis

Table 3 summarizes bivariate correlations among variables. In older adults, the CRI was associated with a reduction of influence of congruency in *trial n-1* on conflict resolution in *trial n*: the greater the CRI was, the smaller the RT difference between CI and II sequences was [$r(15) = -0.51$, $p = 0.036$, $r^2 = 0.26$] (see Figure 22). The ANCOVA considered the RT difference between CI and II sequences as the dependent variable: this analysis revealed that a reduction of such a difference was associated with a high CRI [$F(1, 14) = 4.91$, $p = 0.043$], whereas the impact of age was not significant [$F(1, 14) = 0.02$, $p = 0.879$].

Learning, measured as the difference between RT Stroop effects obtained in the first and third blocks, did not correlate in either age-group with either age [Younger: r(16) = -0.046, *p* = 0.857; Older: r(15) = -0.421, p = 0.092], or education [Younger: r(16) = -0.015, p = 0.951; Older: r(15) = -0.453, *p* = 0.068], although these correlations showed a trend in the older group.

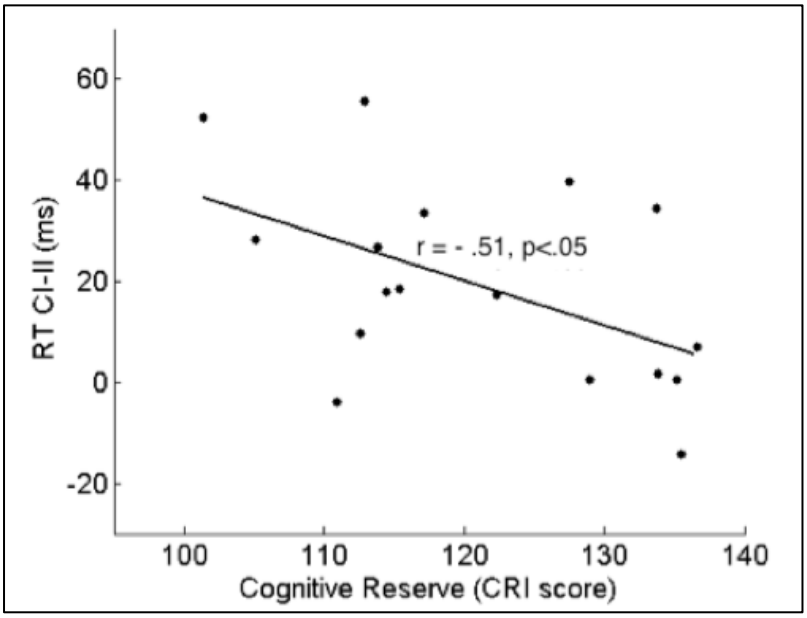

Figure 22 - Response time difference between congruent-incongruent (CI) and incongruent-incongruent (II) sequences as a function of cognitive reserve, measured as Cognitive Reserve Index, in older adults.

Discussion

This study investigated whether aging affects spatial conflict resolution and conflict adaptation, and whether CR, years of education and intelligence may play a compensatory role against age-related deficits in the spatial domain. Many studies reported age-related deficits in verbal conflict resolution, as marked by a substantial increase of the verbal Stroop effect in older adults (e.g., our Experiment 3 in Chapter 3; MacLeod, 1991; West and Alain, 2000; West and Moore, 2005), but whether aging also affects spatial conflict resolution has not been investigated as extensively. Some previous studies used spatial Stroop-like tasks with this aim (Castel et al., 2007; Bialystok et al., 2004; Proctor et al., 2005; Van der Lubbe and Verleger, 2002), and found a significant age-related increase of spatial interference.

Table 3 – Correlation between measures. Dashes indicate data not available. *p < 0.05 ; ** p < 0.001

	Age	Education	IQ	CRI
YOUNGER				
Education	0.36			
IQ	0.35	0.31		
RTs	0.02	-0.01	-0.09	---
RT Stroop	0.10	-0.07	-0.25	---
RT CI-II	-0.46	-0.03	0.12	---
Accuracy	-0.04	-0.03	0.18	---
Accuracy Stroop	0.03	0.08	-0.22	---
Accuracy II-CI	0.31	0.25	0.20	---
Accuracy Stroop after congruent	0.13	0.14	-0.12	---
Run3 – Run1 accuracy Stroop	-0.05	-0.01	-0.03	---
OLDER				
Education	-0.05			
IQ	0.05	0.59*		
CRI	-0.06	0.81**	0.30	
RTs	-0.15	-0.02	-0.26	0.03
RT Stroop	-0.42	-0.12	-0.19	-0.03
RT CI-II	0.07	-0.27	-0.20	-0.52*
Accuracy	-0.46	0.45	0.23	0.58*
Accuracy Stroop	0.41	-0.44	-0.26	-0.54*
Accuracy CI-II	-0.11	-0.37	-0.52*	-0.37
Accuracy Stroop after congruent	0.35	-0.47	-0.37	-0.56*
Run3 – Run1 accuracy Stroop	-0.42	-0.45	-0.33	-0.54*

Despite the fact that many authors claimed that priming has a relevant influence in the conflict resolution process (e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006), and as we showed in Experiments 1 and 2 of Chapter 3, none of the designs used so far to investigate aging effects on spatial conflict resolution clearly isolated priming effects from pure conflict resolution. Wühr and colleagues, using a Simon-type task, showed the presence of correspondence sequential modulations even after a partial removal of stimulus-response repetitions (Wühr, 2005; Kunde and Wühr, 2006). However, the same authors suggested using a 4-Alternative Forced Choice (4-AFC) version of their task in order to eliminate all possible stimulus-response repetitions (Kunde and Wühr, 2006). Moreover, when investigating aging effects, it is even more important to control for priming contributions, since priming itself is likely to be differentially affected by aging (Connelly et al., 1991; La Voie and Light, 1994; Mayas et al., 2012; McDowd and Oseas-Kreger, 1991;). We partially circumvented this problem by designing a spatial Stroop task that did not present stimuli with feature repetitions in any two subsequent trials. Thus, priming

influences were substantially reduced. For our study, we considered the Stroop effect as a measure of spatial conflict resolution, and therefore calculated it as the difference between the performance on congruent and incongruent trials. Furthermore, we assessed the performance on two single-feature conditions, where the two features composing the stimuli used for the spatial Stroop task, namely direction and position, had to be processed separately. In all of the conditions administered (Position Only, Direction Only and Spatial Stroop), older adults were systematically slower with respect to younger adults, although the accuracy level was comparable, confirming the well-known age-related slowing effect (e.g., Rabbitt, 1979; Salthouse, 1985).

We confirmed that position-related information is stronger than direction-related information, since the Position Only condition was processed faster and more accurately than the Direction Only condition. In the spatial Stroop task, where both types of information are simultaneously part of the stimulus, participants were asked to respond with respect to the direction and to suppress the position information. As expected, we found a significant Stroop effect for both RTs and accuracy. This priming-free spatial Stroop task revealed that older adults were slower than younger controls. Notably, the interaction between age-group and congruency was not significant either for speed or for accuracy, indicating that the overall spatial Stroop effect did not differ in the two age-groups. We also assessed the role of the preceding trial congruency, in order to investigate the influence that it could exert on the spatial Stroop effect. The two age-groups equally showed the well-known sequential effects for congruent trials (Botvinick et al., 2001; Notebaert et al., 2006; Notebaert and Verguts, 2007; West and Moore, 2005): RTs were reduced if another congruent trial preceded the current trial, although accuracy was at ceiling. For incongruent trials older adults, but not younger controls, were influenced by the congruency of the *trial n-1*, increasing RTs whenever a congruent trial preceded the current trial. This pattern of results was also confirmed by the analyses run on the interference occurring in each age-group with respect to its own performance in the Direction Only condition. These results are in conflict with the age-related increase of spatial interference that some previous studies reported (Bialystok et al., 2004; Castel et al., 2007; Proctor et al., 2005; Van der Lubbe and Verleger, 2002). However, as we mentioned above, none of the previous spatial conflict

studies adopted experimental designs which satisfactorily controlled for priming or binding factors; thus they could not properly isolate the aging effects on priming with respect to those on pure conflict resolution. Moreover, some of the previous studies did not apply corrections to account for general slowing and did not match groups for years of education.

Despite a non-significant age-related increase of the general Stroop effect, older adults, unlike younger controls, showed an increased difficulty on incongruent trials whenever a congruent trial preceded them. Interestingly, such an age-related modulation negatively correlated with the CR index, but not with intelligence or years of education. Hence our findings suggest that the reduction of specific attention abilities that usually take place in normal aging is attenuated when individuals have a high level of CR. Future samples displaying a wider range of CRI would be useful to investigate these associations further.

Although some studies used IQ as a measure of cognitive reserve (e.g., Alexander et al., 1997; Albert and Teresi, 1999), other evidence suggested that reserve is more deeply influenced by education and everyday life experiences. Our results support the latter findings, suggesting that intelligence, education and cognitive reserve act separately on building up reserve (Evans et al., 1993; Mortel et al., 1995; Rocca et al., 1990; Stern et al., 1994, 1995). Stern's group (Scarmeas et al., 2001; Stern, 2009) reported that in a non-demented older adults sample, individuals who were more engaged in leisure activities, both intellectual and social, had a reduced risk of developing dementia independent of the type of activity. Moreover, leisure activities include both physical (Colcombe et al., 2006; Colcombe & Kramer, 2003) and mental exercises that have an impact not only on the pure cognitive aspects of reserve, but also on the brain structure, such an increased brain volume (Stern, 2009). Finding an effect of CR measured with the CRIq but not of education per se, suggests that there is something above and beyond the education level that is related to a lower impact of cognitive aging. Therefore, a questionnaire like the one we used to measure cognitive reserve, which considers at the same time education, occupational attainment and leisure activities, seems to be a good proxy for investigating such a complex and still not sharply defined construct. Nevertheless, we think that this instrument could be further improved in the future, particularly by increasing its reliability.

Furthermore, considering that participants were administered three blocks, we explored the potential learning effects that took place. Older adults obtained the same advantage as younger controls from practicing, confirming previous findings (e.g., Davidson et al., 2003): both age-groups similarly increased their overall speed and accuracy in conflict resolution (i.e., a comparable reduction of the accuracy Stroop effect) over the three blocks.

Participants in the present study also took part in Experiment 3, described in Chapter 3, in which they were administered a matched colour-word Stroop task. This allows us to draw reasonable inferences about the difference that cognitive aging exerts on conflict resolution-related to two different domains: verbal and spatial.

In the present study, we showed that spatial Stroop is not affected by aging, whereas the verbal Stroop effect exhibits a marked age-related increase in RTs (but not in accuracy), and roughly an opposite pattern was obtained for sequential effects, as shown by Experiment 3 (Chapter 3). Indeed, in the verbal Stroop task, sequential effects are spared in aging. In both younger and older adults, the RT Stroop effect was nullified after preceding incongruent trials, and sequential effects relative to current congruent trials disappeared, suggesting that they are not due to conflict adaptation, but rather they are likely due to priming (or binding) phenomena. On the contrary, here we show that for the spatial Stroop switching from a congruent to an incongruent trial entails a cost in aging, and sequential effects relative to current congruent trials are present in both age-groups, even after controlling for priming contribution.

Therefore, our findings concerning verbal and spatial conflict resolution, when considered together, suggest the existence of two at least partially different, domain-specific mechanisms responsible for conflict resolution, rather than a general one. These two separate mechanisms seem to be differentially prone to cognitive aging, since verbal conflict resolution abilities are specifically reduced in older adults, whereas spatial conflict resolution seems to suffer from general slowing only. Further studies, possibly with bigger sample sizes, should further test this hypothesis. Another possibility to explain the different results obtained in the verbal conflict resolution study with respect to the spatial one, could be that the two tasks require different conflict resolution demands.

It is important to point out that an experimental manipulation of intelligence and CR is not possible, since it is both practically and ethically unfeasible (see paragraph 5.2.2 of Chapter 5). Therefore, a causal relation between CR and a reduced impact of cognitive aging cannot be inferred. Therefore, adopting longitudinal designs is extremely useful in order to understand whether CR is a reliable predictor of which individuals will be less prone to age-related cognitive decline (e.g., Riley et al., 2002; Salthouse and Ferrer-Caja, 2003; Snowdon et al., 1997; Stern et al., 1999; Wilson et al., 2002;). Moreover, such an approach could also clarify if the reduced impact of cognitive aging shown by some individuals is due to a compensatory phenomenon, as suggested by the reserve hypothesis, or rather to pre-existing neural and cognitive characteristics (Nyberg et al., 2012).

In conclusion, the current study suggests that, contrary to verbal conflict resolution, spatial conflict resolution seems to be only marginally affected in healthy cognitive aging. Older adults' performance on spatial conflict resolution and spatial conflict adaptation processes is predominantly affected in terms of a reduction of the overall general speed. Older adults exhibit an age-related deficit in switching from congruent to incongruent conditions, rather than a selective impairment for spatial conflict resolution itself. Nonetheless, this deficit appears to be reduced when the cognitive reserve level is high. It could be that CR plays a compensatory role in maintaining the flexibility of active problem solving in tasks for which solutions cannot be simply derived from prior knowledge or formal education (Horn and Cattell, 1967; Stuart-Hamilton, 1996; Tranter and Koutstaal, 2008), flexibility which is usually prone to an age–related decline. Therefore, our study suggests that older adults whose lives have been characterized by a high level of cognitive reserve might cope better with some aspects of age-related attentional decline.

4.3. Cognitive Control in the spatial domain and its age-related modifications: electrophysiological evidence - Experiment 7

In the previous experiment we investigated spatial conflict resolution with a priming-free spatial Stroop task. We showed that a spatial congruency effect (Stroop) is present, and that sequential congruency effects are relevant as well. The comparison between younger and older adults showed that normally aging adults are prone to general slowing effects, but they do not suffer from a specific conflict resolution deficit in the spatial domain as expressed by the constant Stroop effect.

In this last experiment, the electroencephalogram was recorded in two new samples of younger and older adults, while they were performing the priming-free spatial Stroop task. Indeed the choice of EEG was made in order to address many issues of the present project: first it allowed the investigation of covert effects involved in spatial conflict resolution and their temporal evolution, making it possible to draw inferences on the neural mechanisms that underlie the observed behavioural performance. Second, since Experiment 6 showed that older adults' conflict-related performance was not different with respect to the younger adults' one, the ERPs could reveal whether the neural processes that underlie the overt performance are the same in the two age-groups or rather if they undergo some age-related modifications. Third, the electrophysiological pattern and related interpretation of the neural mechanisms that regulate the spatial conflict resolution processes could be directly compared with those obtained for the verbal domain, increasing the body of evidence for a comparison between the two domains for what concerns conflict resolution. Indeed, the spatial Stroop data were collected in the same experimental session as the colour-word Stroop ones, from the same participants included in Experiment 4.

Conversely to the verbal domain, very few studies have been carried out in order to explore spatial conflict resolution, or at least not with a similar complexity to what has been done for the verbal domain. This is true also for what concerns the use of EEG, and to the best of our knowledge, there are no studies that used a 4-AFC spatial Stroop task (or very similar ones) that aimed at exploring the electrophysiological aspects of conflict and sequential congruency

effects with the experimental control that we stated in the present research project. Therefore, since the comparison with previous studies could not be done, assuming that spatial conflict resolution processes would share at least some general supra-domain mechanism with the verbal ones, we oriented our analyses on the basis of previous verbal conflict resolution studies (see section 3.3 of Chapter 3).

Methods

Participants

Twenty younger controls (mean age = 25 years, range 18-35; 9 females) and 19 older adults (mean age = 73 years, range 66-80; 9 females) took part in this study. Participants were native Italian speakers, selected in order to match the two age-groups for years of formal education: younger, range: 6-20, M = 12.6 years; older, range: 8-23, M = 14 years, [$t(37) = -1.06$, $p = .29$]. The Edinburgh Handedness Inventory (Oldfield, 1971) and the Ishihara Color Vision Test (Ishihara, 1962) were used to check participants' handedness and colour perception, respectively. Participants were all right-handed, with normal or corrected-to-normal vision and normal colour perception. Older adults were also screened for dementia using the Montreal Cognitive Assessment (MoCA) in order to exclude those presenting dementia symptoms (Nasreddine et al., 2005; score range: 26-30/30): none of the selected volunteers had a score under the cut-off. Seven older adults reported the use of regular medications for cardiovascular disease. Three additional participants (one young and two older) were excluded because they were outliers for accuracy or accuracy Stroop scores (> 3 SD from the respective group mean).

Participants signed an informed consent form which explained the EEG recording procedure, the structure of the task and the general aims of the study. For volunteering in the study each participant received 25 €. This study was approved by the SISSA ethical committee.

Design and stimuli

Participants took part in two experimental sessions during which they were tested individually in a silent room. During the first session they were informed

about the general aim of the experiment. Then they were administered the test battery for checking handedness (Edinburgh Handedness Inventory; Oldfield, 1971), colour blindness (Ishihara Color Vision Test; Ishihara, 1962). All of the older participants were also administered the Cognitive Reserve Index questionnaire (CRIq; Nucci et al., 2012) and the Wechsler Adult Intelligence Scale revised (WAIS-r), in order to quantify respectively their cognitive reserve and Intelligence Quotient (IQ). Older participants only were also administered the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) to screen them for mild cognitive impairment and, in case, exclude those who scored under 26. This session lasted approximately one and a half hours.

The second session took place 3 to 10 days after the first one. During the EEG cap preparation each participant was given some advice on how to avoid producing artifacts during the EEG recording, such as to relax, and to reduce as much as possible eye movements and blinks.

The task design is the same as in Experiments 5 and 6 (described in the *Methods* section of Experiment 5 – paragraph 4.1). The only difference with respect to Experiment 5 is that, similarly to Experiment 6, only complete alternation sequences were used (cf. Chapter 2, paragraph 2.1).

Participants were also administered a verbal version of the Stroop task (Experiment 7 of Chapter 3), structured in the same way as the spatial Stroop task described above. The order of the two tasks was counterbalanced across subjects and the whole session lasted approximately two hours.

EEG recording

A Biosemi™ ActiveTwo 128-channel EEG system was used to record scalp voltage from 128 scalp sites using sintered Ag-AgCl electrodes (of a modified 10/20 system headcap) (see Figure 7, Chapter 3). The EEG signal was continuously sampled at 256 Hz, and meanwhile it was referenced online to mastoid electrodes. Eight additional surface electrodes were symmetrically placed on the right and left sides of the subject's face: on the external canthi, to record horizontal EOG signals, on the infra-orbital ridges, to record vertical EOG signal, on the mastoids and on the peri-auricular areas to record muscular

activity. All electrodes were adjusted in order to maintain the offset of each electrode below 40 mV.

At the end of the experimental session, 7 EEG datafiles were recorded for each participant: 2 Position Only, 2 Direction Only and 3 Spatial Stroop blocks. The first part of EEG signal pre-processing was done separately for each datafile using EEGLab v12.0.0.0b (Delorme & Makeig, 2004). The average-reference was used to re-reference all electrodes offline. In order to minimize the very slow drifts of the EEG signal, a 0.1 Hz high-pass filter was applied to the EEG signal. Then, to exclude noise derived from external electrical devices, a 20 Hz low-pass filter was applied. After that, all files belonging to the same participant were merged and the signal was visually explored in order to cut the sections where there were clear artifacts due to subject movement, coughing and so on. An automatic procedure implemented in EEGLab permitted us to identify noisy electrodes, and to interpolate them. The EEG signal was then subdivided into epochs. Each epoch started 200 ms before the stimulus onset and ended 2600 ms after it. A baseline correction was applied selecting as reference the time windows from -200 ms to 0 ms preceding the stimulus onset.

To reject bad epochs, the EEGLab epochs rejection procedure was applied, setting the threshold to -/+ 1000, and allowing a maximum of 5% of rejections per iteration. EEGLab Independent Component Analysis (ICA) was then applied to identify components that visibly reflect artifacts originating from blinks, horizontal eye movements and possible bad electrodes not pinpointed before.

Correct trials only were selected and then categorized with respect to the task and sequential conditions: Position Only, Direction Only, CC, CI, IC and II.

Results

Behavioural results

RT analysis was performed after excluding trials with RTs shorter than 100 ms and longer than 1500 ms (1.88% of the totals) and outlier trials (i.e. above and below 3 *SD* from each subject's mean RT) (1.33% of remaining trials). Error trials were also excluded.

Raw data were logarithmically transformed when the analysis aimed at the comparison between younger and older adults. This approach entails the

Table 4 - Mean RTs (ms) and accuracy (%) with respect to conditions and age-groups. SD in parentheses.

		CC	IC	CI	II	Direction Only	Position Only
Younger	RTs	483 (74)	575 (78)	575 (78)	574 (78)	482 (63)	442 (82)
	Accuracy	99.8 (0.4)	99.3 (1.1)	92.8 (5.9)	95.4 (3.2)	98.6 (2.2)	99.6 (0.7)
Older	RTs	652 (91)	688 (102)	811 (99)	798 (100)	656 (86)	592 (81)
	Accuracy	99.2 (0.9)	98.9 (1.3)	92.3 (6.8)	95.8 (4.3)	97.2 (2.8)	98.2 (2.1)

reduction of age-related slowing confounds (Verhaeghen and De Meersman,1998; see Chapter 2).The analysis of single feature tasks revealed that younger adults were systematically faster with respect to older adults both in Direction Only [younger = 482 ms; older = 656 ms, t-test*:* t (38) = -7.29, p < .001] and Position Only [younger = 442 ms; older = 592 ms, t-test*:* t (37) = -5.71, p < .001]. The two age-groups also showed a significant difference in the level of accuracy in both the Direction Only [younger = 98.6%; older = 97.2%, Mann–Whitney U =19, Z = -4.89, p < .001] and Position Only [younger = 99.6%; older = 98.2%, Mann–Whitney U =32, Z = -4.43, p < .001], with younger being slightly more accurate than older adults.

The comparison among single feature conditions and Stroop ones showed that in younger adults the presence of two features that are incongruent exerts RT interference with respect to both Direction Only [Direction = 482 ms; Incongruent trials = 576 ms, t-test*:* t (19) = -10.18, p < .001] and Position Only [Position = 442 ms; Incongruent trials = 576 ms, t-test*:* t (19) = -12.24, p < .001]. The same effect is shown by older adults as well both for Direction Only [Direction = 656 ms; Incongruent trials = 807 ms, t-test*:* t (19) = -8.59, p < .001] and Position Only [Position = 591 ms; Incongruent trials = 807 ms, t-test*:* t (18) = -10.35, p < .001].

Congruent Stroop trials also exert interference with respect to Position Only in both age-groups [Younger: Position = 442 ms; Congruent trials = 494 ms, t-test*:* t (19) = -7.58, p < .001; Older: Position = 591 ms; Congruent trials = 667 ms, t-test*:* t (18) = -4.31, p < .001]. On the other hand, in both age-groups congruent Stroop trials are not statistically different from Direction Only trials [all ps > .14].

This suggests that the presence of two incongruent types of information (e.g., incongruent Stroop stimuli), does exert interference on RT with respect to the same task with the relevant information only (Direction Only), whereas congruent distracting information (e.g., congruent Stroop stimuli) does not exert interference.

In order to analyze our data we used a 2x2x2 mixed ANOVA with age-group (Younger vs Older) as the between-subjects factor and congruency of the current and the preceding trial (for both, Congruent vs Incongruent) as within-subjects factors.

In the 2x2x2 ANOVA, the three-way Trial *n* X Trial *n-1* X Group interaction was nearly significant [$F(1, 38) = 3.6$, $p = .064$].

As expected, both age-groups and trial *n* main effects were significant. Younger adults responded more rapidly than older ones [$F(1, 38) = 57.7$, $p < .001$; mean RT 533 ms and 734 ms, respectively] and responses to congruent trials were faster than ones to incongruent trials [$F(1, 38) = 287$, $p < .001$; mean RT 583 ms and 691 ms, respectively]. These two outcomes confirm the well known age-related slowing and Stroop effects. The *Trial n-1* congruency main effect was significant [$F(1, 38) = 33.2$, $p < .001$] and the two-way interaction of Trial *n* X Trial *n-1* congruency was also significant [$F(1, 38) = 75$ $p < .001$]. The latter interaction indicates the presence of sequential congruency effects. Trial *n* X Group and Trial *n-1* X Group did not interact [$F(1, 38) = 2.6$, $p = .113$; $F(1, 38) = 0.1$, $p = .716$, respectively] indicating that there is not an age-related difference in Stroop and sequential congruency effects. The almost significant three-way interaction, suggests that sequential congruency effects might go through age-related modifications. The significant Trial $_n$ X Trial *n-1* congruency interaction allowed a Bonferroni post-hoc comparison, which revealed that CC and IC trials are different in both younger [$p < .001$] and older adults [$p < .001$], whereas CI and II stimuli were not different in either age-group [both ps $>.49$].

We computed a 2x2 ANOVA also on the Stroop effect, that is, the RT difference between incongruent and congruent trials. This further analysis confirms the previous one. Again, the Trial *n-1* congruency main effect was significant [$F(1, 38) = 75.2$, $p < .001$], whereas the Group main effect was not $F(1, 38) = 2.61$, $p = .115$]. The interaction between *Trial n-1* and Group was

very near to significance level [$F(1, 38) = 3.87, p = .056$], again suggesting a possible sequential congruency effects difference in older adults (Figure 23a).

Accuracy data were not normally distributed. Therefore it was not possible to apply a parametric test such as an ANOVA.

Younger participants made less errors than older ones in Position Only [Mann–Whitney U =112, $Z = 2.17, p = .029$] whereas the two age-groups reached the same level of accuracy in the Direction Only task [Mann–Whitney U =132, $Z = 1.82, p = .067$]. Within each group the two single feature tasks were performed with the same accuracy [ps >.08]

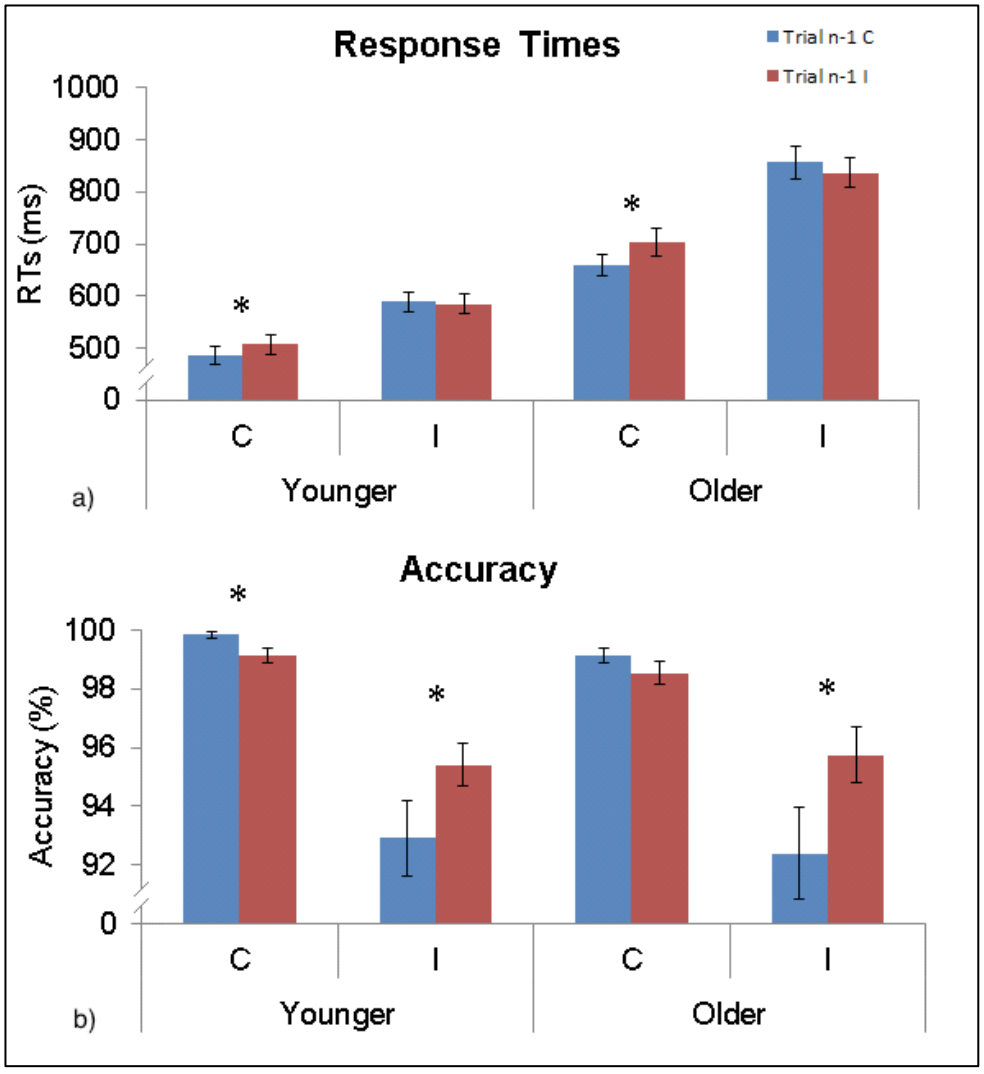

Figure 23 - Response times in ms a) and accuracy in percentage b) of Experiment 7 as a function of previous (*n - 1*) and current (*n*) trial congruency. Error bars represent the standard error of the mean.

Comparisons among single feature conditions and Stroop ones, showed that in both age-groups the presence of two incongruent features exerts accuracy interference with respect to both of the single feature conditions Direction Only [Younger: Direction = 98.6%; Incongruent trials = 94.2%, Wilcoxon's $T = 11$, $Z = 3.51$, $p < .001$; Older: Direction = 97.2%; Incongruent trials = 94.2%, Wilcoxon's $T = 22$, $Z = 2.94$, $p = .003$] and Position Only [Younger: Position = 99.6 %; Incongruent trials = 94.2%, Wilcoxon's $T = 0$, $Z = 3.92$, $p < .001$; Older: Position = 98.2 %; Incongruent trials = 94.1%, Wilcoxon's $T = 15$, $Z = 3.22$, $p = .001$].

To compare the two age-groups' accuracy in the spatial Stroop task, a Mann–Whitney *U* test was used: older and younger age-groups reached the same level of accuracy, 96.6% (older) and 96.9% (younger) [Mann–Whitney $U = 193$, $Z = 0.18$, $p = .85$). We then verified that trial *n* congruency had a significant effect on accuracy (i.e. accuracy Stroop). A Wilcoxon signed-rank test was used to compare congruent and incongruent trials *n* separately in the two age-groups. In both age-groups the effect of trial *n* (Stroop) was significant [younger: Wilcoxon's $T = 0$, $Z = 3.92$, $p < .001$; older: Wilcoxon's $T = 3.5$, $Z = 3.79$, $p < .001$].

Wilcoxon signed-rank tests were used also to compare pairs of conditions within each group in order to compare CC vs IC and CI vs II conditions. These comparisons revealed that in younger and older adults CI vs II sequential conditions were statistically different [younger: Wilcoxon's $T = 2.72$, $Z = 3.92$, $p = .006$; older: Wilcoxon's $T = 11.5$, $Z = 3.36$, $p < .001$]. On the other hand, the difference between CC vs IC accuracy was not significant in older adults [Wilcoxon's $T = 25$, $Z = 1.43$, $p = .15$] and at the significance threshold in younger adults [Wilcoxon's $T = 4$, $Z = 1.96$, $p = .049$], suggesting that the accuracy level in current congruent trials partially depends on the previous trial's congruency.

We then used the accuracy Stroop effect (i.e., the difference in accuracy between incongruent and congruent trials, normally distributed) to run a 2 × 2 mixed ANOVA with congruency at trial *n-1* as the within-subjects factor and age-group as the between-subjects factor. The main effect of trial *n-1* congruency [$F(1, 38) = 27.89$, $p < .001$] was significant, whereas neither the main effect of group [$F(1, 38) = 0.09$, $p = .76$] nor the interaction between age-

group and trial *n-1* congruency [$F(1, 36) = 0.28$ $p = .60$] were significant (Figure 23b).

Since the non-parametric analysis made on the accuracy data revealed a difference in the sequential effects in the two age-groups, in order to verify the Group x Trial *n* X *Trial n-1* interaction, we applied a permutation procedure based on Manly's approach (Manly, 2007) (see Chapter 2).

The Group main effect was not significant [N = 1000 permutations, F = 0.23, $p = .63$], confirming that older and younger adults reached the same level of accuracy. The effects of both *trial n* and *trial n-1* were significant [N = 1000 permutations, respectively F = 74.94, $p < .001$ and F = 4.69, $p = .032$], indicating the presence of a strong Stroop effect and a relevant preceding trial congruency effect. The *trial n* and *trial n-1* interaction was significant [N = 1000 permutations, F = 8.47, $p = .004$], suggesting that congruency of preceding trial does exert an effect on the current one (sequential congruency effects). None of the interactions with the Group factor resulted significant [all *p*s > 0.66].

Correlation analysis of behavioural data

It is important to point out that all the correlations we calculated are not corrected for multiple comparisons. Therefore they have to be considered as exploratory analyses.

Younger adults' performance resulted to be modulated by IQ. IQ indeed correlates both with overall accuracy [r(20) = 0.56, $p = .011$] and Incongruent trials accuracy [r(20) = 0.55, $p = .011$]. There was also a correlation between IQ and the accuracy Stroop effect [r(20) = -0.54, $p = .015$]. In particular IQ correlated with the accuracy Stroop effect after congruent trials [r(20) = -0.56, $p = .011$] but not with the accuracy Stroop effect after incongruent trials [r(20) = -0.36, $p = .120$]. In older adults CRI was associated with congruent trial accuracy [r(20) = 0.50, $p = .022$].

Electrophysiological data

After the rejection procedures, we obtained an average (±SD) of 302 ± 21 (range: 268–356) trials for younger adults and 296 ± 13 (range: 254–337) trials for older ones.

Current trial congruent waveforms contained an average of 155 ± 12 trials per subject (range: 136–180) in the younger group and 150 ± 12 trials per subject (range: 126–171) in the older one. Incongruent current trials waveforms contained an average of 147 ± 12 trials per subject (range: 126–176) in the younger group and 146 ± 14 trials per subject (range: 112–166) in the older one. When broken down to examine potential conflict adaptation effects, the number of trials retained in the younger adults group was: 78 ± 7 CC trials (range: 64–90), 72 ± 6 CI trials (range: 60–83), 76 ± 6 IC trials (range: 67–90), and 76 ± 8 II trials (range: 64–95). The number of trials per condition in the older group was: 76 ± 6 CC trials (range: 68–86), 71 ± 8 CI trials (range: 49–84), 74 ± 8 IC trials (range: 56–87), and 75 ± 7 II trials (range: 62–89).

We selected 9 electrodes from the 10/20 system spatially distributed in a 3 by 3 matrix: P3, Pz, P4, C3, Cz, C4, F3, Fz, F4 (See Figures 23 and 24).

There are not comparable studies that focused on the spatial Stroop effect. However, since we aimed to directly compare the spatial Stroop results with the ones obtained with the verbal Stroop task in Experiment 4, we decided to run statistical analyses on two time windows (TW) with the same latency: one between 400 and 500 ms and the other between 600 and 800 ms from the stimulus onset. These TWs were chosen on the basis of results of preceding studies (e.g., West & Alain, 2000a, 2000b; Larson et al., 2009; Liotti et al., 2000).

In the time windows specified above, the mean amplitude was computed, relative to a 200 ms baseline preceding the stimulus presentation, and this was the dependent variable for our analyses. The Greenhouse-Geisser correction was applied when evaluating effects with more than one degree of freedom in the numerator (Greenhouse & Geisser, 1959). The adjusted degrees of freedom and *p*-values are reported.

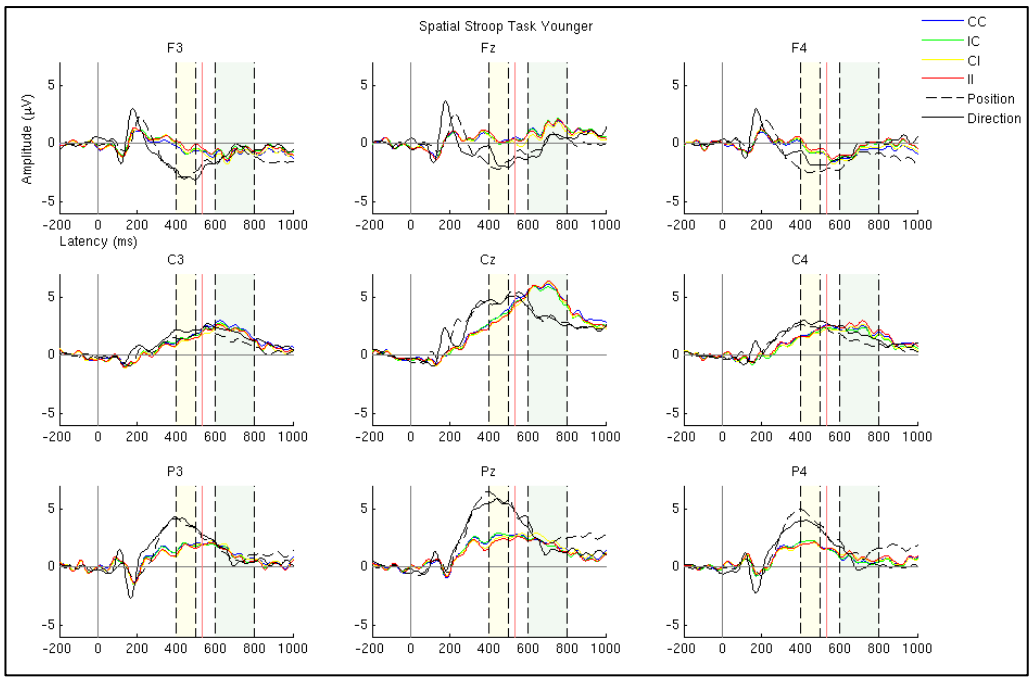

Figure 24 - Grand average ERP waveforms of stimulus-locked spatial Stroop trials (CC – Congruent-Congruent, IC – Incongruent-Congruent, CI – Congruent-Incongruent, II – Incongruent - Incongruent) and single feature trials (Position – Position Only; Direction – Direction Only) recorded in younger adults. The 9 electrodes selected for analyses are displayed. The two colour-shaded areas indicate the analyzed time windows. The red vertical line indicates the average RT of the group.

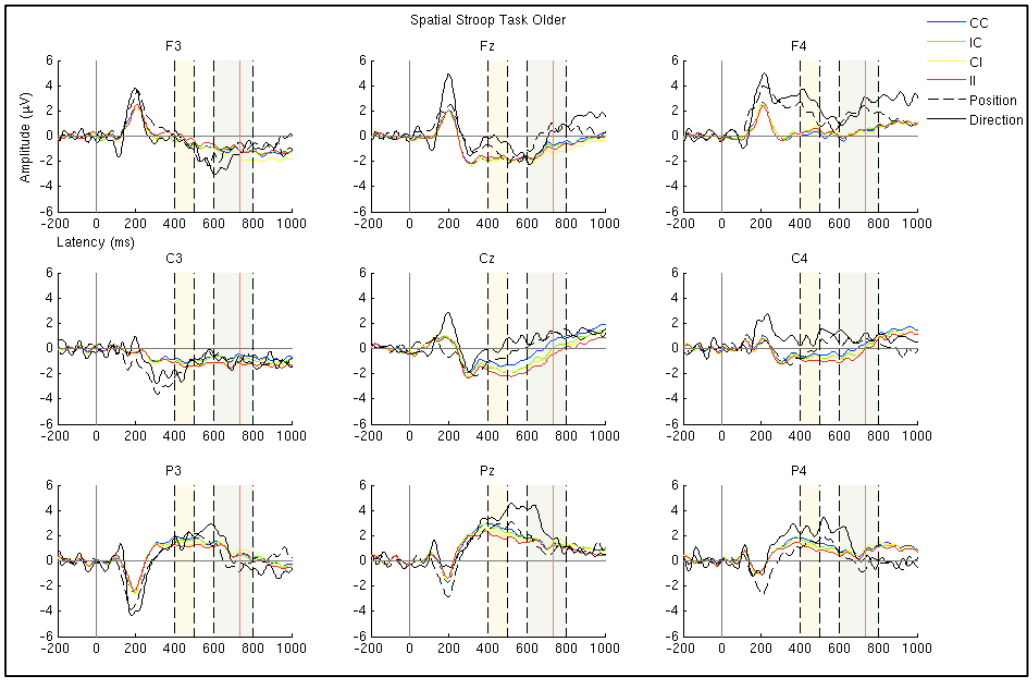

Figure 25 - Grand average ERP waveforms of stimulus-locked spatial Stroop trials (CC – Congruent-Congruent, IC – Incongruent-Congruent, CI – Congruent-Incongruent, II – Incongruent - Incongruent) and single feature trials (Position – Position Only; Direction – Direction Only) recorded in older adults. The 9 electrodes selected for analyses are displayed. The two colour-shaded areas indicate the analyzed time windows. The red vertical line indicates the average RT of the group.

400-500 Time Window

In order to analyze our data we first ran a 2x2x2x3x3 mixed ANOVA with age-group (Group: Younger vs Older) as the between-subjects factor and 4 within-subjects factors: congruency of *trial n* (*Trial n*: Congruent vs Incongruent), congruency of *trial n-1* (*Trial n-1*: Congruent vs Incongruent), scalp position (Scalp: Frontal vs Central vs Parietal), side position (Side: Left vs Midline vs Right). This first ANOVA revealed a significant 4 way interaction: Trial *n* X Trial *n-1* X Scalp X Side [$F(4, 152) = 3.00$, $p = .025$]. Since the Group X Trial *n* X Trial *n-1* X Scalp X Side interaction showed a strong trend [$F(4, 152) = 2.36$, $p = .06$] we decided to run separate analyses for younger and older adults to break down this complex interaction and facilitate the interpretation of the results.

Figure 30 reports a schema of the significant effects in the 9 selected electrodes.

Younger adults

We ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed that in younger adults the only relevant significant effect is *trial n-1* congruency [$F(1, 19) = 4.79$, $p = .041$].

However, we separately explored the 9 selected electrodes with *Trial n* X *Trial n-1* ANOVAs. Congruency of current trial showed a significant effect in electrodes C3 [$F(1, 19) = 7.60$, $p = .013$], Pz [$F(1, 19) = 7.18$, $p = .015$] and in Cz as a trend [$F(1, 19) = 3.88$, $p = .064$], whereas congruency of *trial n-1* showed a significant effect in F3 only [$F(1, 19) = 5.678$, $p = .028$] (Figures 26 and 31).

Correlations

No relevant correlation was found between the electrophysiological and behavioural data in younger adults for the 400-500 ms TW.

Older adults

We ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed that the 4-way interaction was significant [$F(4, 76) = 4.19$, $p = .014$]. We therefore ran three separate Trial *n* X Trial *n-1* X Side ANOVAs, one for each scalp region: frontal, central and parietal.

In frontal electrodes the Trial *n* X Trial *n-1* X Side interaction was significant [$F(2, 38) = 6.40$, $p = .01$]. Hence we explored each electrode (F3, Fz, F4) with a Trial *n* X Trial *n-1* ANOVA. In F4 the congruency of *trial n* and congruency of *trial n-1* significantly interacted [$F(1, 19) = 6.119$, $p = .023$], whereas both in F3 and in Fz such an interaction was present as a trend [$F(1, 19) = 4.08$, $p = .058$; $F(1, 19) = 4.32$, $p = .051$, respectively].

In central electrodes the 3-way ANOVA revealed as significant the main effect of Trial *n* [$F(1, 19) = 15.63$, $p < .001$] and the interaction between *trial n-1* and Side [$F(2, 38) = 7.50$, $p = .002$]. We therefore averaged the conditions for *trial n* and ran three separate one-way ANOVAs in order to check the effect of *trial n-1* congruency on each one of the three levels of the Side factor: left, midline, right (i.e., C3, Cz, C4). The *trial n-1* congruency had a significant effect in both Cz [$F(1, 19) = 32.63$, $p < .001$] and C4 [$F(1, 19) = 4.89$, $p = .039$].

In parietal electrodes both *trial n* [$F(1, 19) = 35.66$, $p < .001$] and *trial n-1* [$F(1, 19) = 11.97$, $p = .002$] main effects were significant, but none of the interactions were [all ps > .25] (Figures 27 and 32).

600-800 Time Window

With the same approach used for the 400-500 ms TW analysis, we first ran a 2x2x2x3x3 mixed ANOVA with age-group as the between-subjects factor and congruency of *trial n*, congruency of *trial n-1*, scalp and side as within-subjects factors.

In this ANOVA the 2-way interactions Trial *n* X Group was significant [$F(1, 38) = 9.52$, $p = .004$] and also the Trial *n-1* X Side X Group interaction [$F(2, 76) = 3.68$, $p = .034$]. In order to explore the difference between younger and older adults we ran separate analyses for the two age-groups considering the above mentioned interactions.

In order to explore the Trial *n* X Group interaction we ran a one-way ANOVA for younger adults and another for older adults, averaging all the 9 electrodes and considering only congruency of *trial n* as factor. The *Trial n* effect resulted to be non-significant [t-test*:* $t(19) = -0.85$, $p = .040$] in younger adults and to be significant [t-test*:* $t(19) = 3.15$, $p = .005$] in older adults. For what concerns the Trial *n-1* X Side X Group interaction we ran a two-way Trial

n-1 X Side ANOVA for younger adults and another for older ones. The Trial *n-1* X Side interaction revealed a trend in younger adults [$F(2, 38) = 3.16, p = .06$] and was significant in older adults [$F(2, 38) = 4.18, p = .038$]. Further one-way ANOVAs revealed that in older adults the *trial n-1* effect was significant in midline [$F(1, 19) = 12.4, p = .002$] and right-side [$F(1, 19) = 6.77, p = .017$] electrodes.

Moreover we performed the analysis separately for the two age-groups taking into account all the within-subjects factors: congruency of *trial n*, congruency of *trial n-1*, scalp and side factors. Figure 30 reports a schema of the significant effects in the 9 selected electrodes.

Younger adults

We ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it revealed the presence of two separate interactions: a Trial *n* X Scalp X Side interaction [$F(4, 76) = 3.33, p = .025$] and a Trial *n-1* X Scalp interaction [$F(2, 38) = 16.02, p < .001$].

In order to explore the Trial *n* X Scalp X Side interaction we ran a Trial *n* X Side ANOVA for each level of Scalp factor (Frontal, Central, Parietal).

In frontal areas the Trial *n* X Side interaction was significant [$F(2, 38) = 3.66, p = .037$], and further analyses revealed that *trial n* exerts a significant effect in the Fz electrode only [$F(1, 19) = 5.33, p = .032$].

In central electrodes the Trial *n* X Side interaction was significant [$F(2, 38) = 4.53, p = .025$], and subsequent analyses revealed that *trial n* exerts a significant effect in C3 and C4 electrodes [$F(1, 19) = 6.38, p = .021$; $F(1, 19) = 7.11, p = .015$].

In parietal electrodes Trial *n* X Side interaction was significant [$F(2, 38) = 5.85, p = .007$], and further analyses revealed that *trial n* exerts a significant effect in P4 electrode only [$F(1, 19) = 6.83, p = .017$].

For what concerns the Trial *n-1* X Scalp interaction we ran a one-way ANOVA for each level of Scalp factor (Frontal, Central, Parietal), averaging data for the Side factor. The latter analyses showed that *trial n-1* exerts an effect in frontal [$F(1, 19) = 17.11, p < .001$] and parietal [$F(1, 19) = 9.00, p = .007$] electrodes, but not in central ones [$F(1, 19) = 0.236, p < .632$] (Figures 28 and 31).

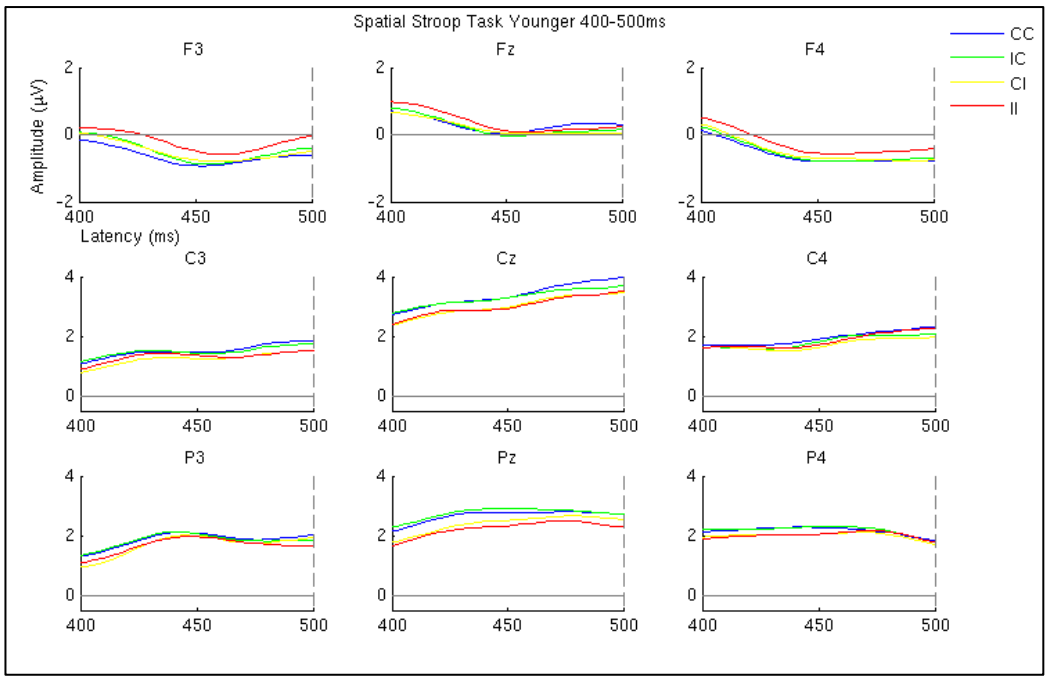

Figure 26 - Grand average ERP waveforms of stimulus-locked spatial Stroop trials (CC, IC, CI, II) recorded in younger adults (the 400-500 ms time window only is shown). The 9 electrodes selected for the analyses are displayed. Note that, in order to make the waveforms more clear, the y scales relative to frontal electrodes are different with respect to those relative to central and parietal electrodes.

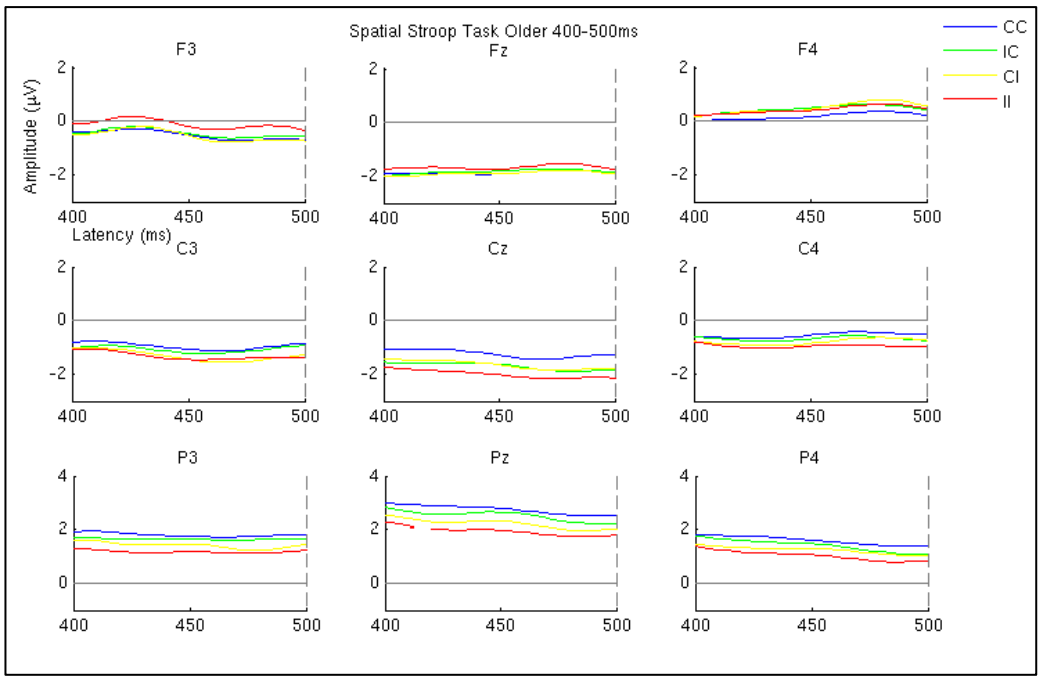

Figure 27 - Grand average ERP waveforms of stimulus-locked spatial Stroop trials (CC, IC, CI, II) recorded in older adults (the 400-500 ms time window only is shown, zoomed in). The 9 electrodes selected for the analyses are displayed. Note that, in order to make the waveforms more clear, the y scales relative to parietal electrodes are different with respect to those relative to central and frontal ones.

Correlations

In younger adults *trial n* and *trial n-1* congruency produced dissociable effects. The *trial n* modulation (i.e., the voltage difference between congruent and incongruent *trial n*) correlated with RT in P4 [r(20) = 0.65, p = .002]. Indeed RTs were shorter when incongruent trials were more positive than congruent ones. In parietal electrodes the *trial n-1* modulation (i.e., the voltage difference between congruent and incongruent *trial n-1*) correlated with the RT Stroop effect after incongruent trials [r(20) = -0.59, p = .006]. This suggests that whenever the waveforms for incongruent trials *n-1* were more positive than those for congruent trials *n-1* the Stroop effect after incongruent trials was reduced.

Older adults

Mirroring the approach used for previous analyses we ran a Trial *n* X Trial *n-1* X Scalp X Side (2x2x3x3) ANOVA and it indicated that the 3-way interaction Trial *n* X Trial *n-1* X Scalp was significant [F(2, 38) = 5.63, p = .007]. We therefore ran three separate Trial *n* X Trial *n-1* ANOVAs, one for each scalp region: frontal, central and parietal. The Trial *n* X Trial *n-1* interaction was significant in both frontal [F(1, 19) = 35.05, p < .001] and central electrodes [F(1, 19) = 27.8, p < .001], whereas in parietal electrodes only the trial *n-1* main effect was significant [F(1, 19) = 5.69, p = .028] (Figures 29 and 32).

Correlations

In older adults the *trial n* by *trial n-1* congruency interaction was present in frontal and central electrodes. We calculated the correlation between the modulations caused by *trial n* congruency when the preceding trial was congruent (CI-CC) and by *trial n* congruency when the preceding trial was incongruent (II-IC).

CI-CC modulation correlated with VIQ in C3 [r(20) = 0.51, p = .021] suggesting that this factor could influence the amount of such a modulation and that when the VIQ is high the CI wave is less negative than CC.

II-IC modulation correlated with CRI in Fz [r(20) = 0.60, p = .005] and Cz [r(20) = 0.50, p = .026]. This shows that a high CRI is associated with IC trials being more negative than II.

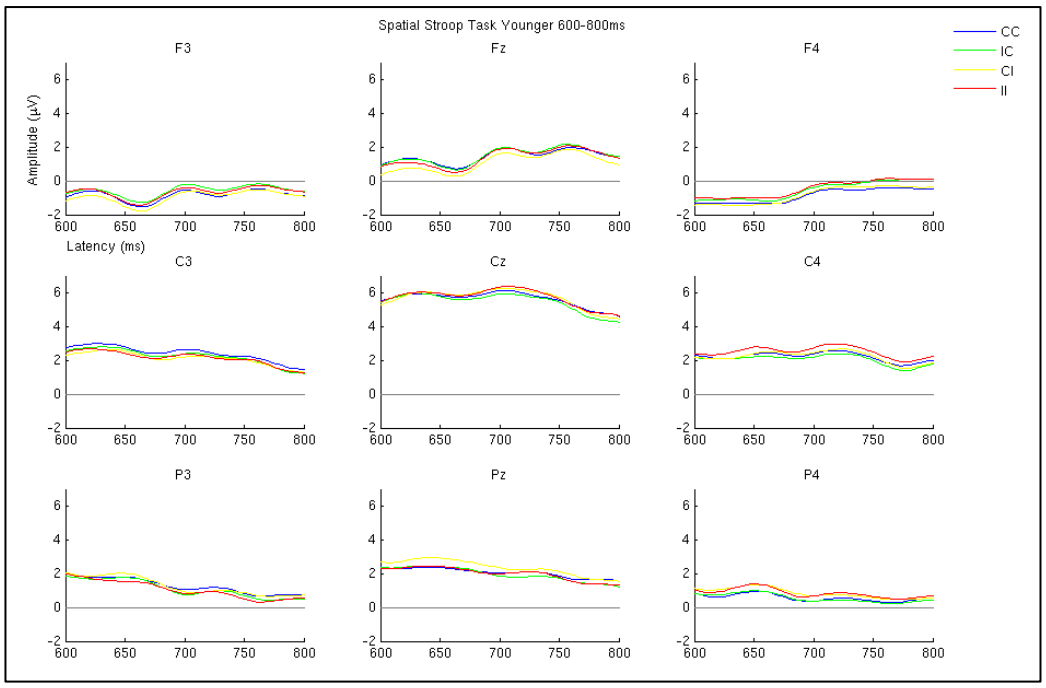

Figure 28 - Grand average ERP waveforms of stimulus-locked spatial Stroop trials (CC, IC, CI, II) recorded in younger adults relative to the 600-800 ms TW. The 9 electrodes selected for the analyses are displayed.

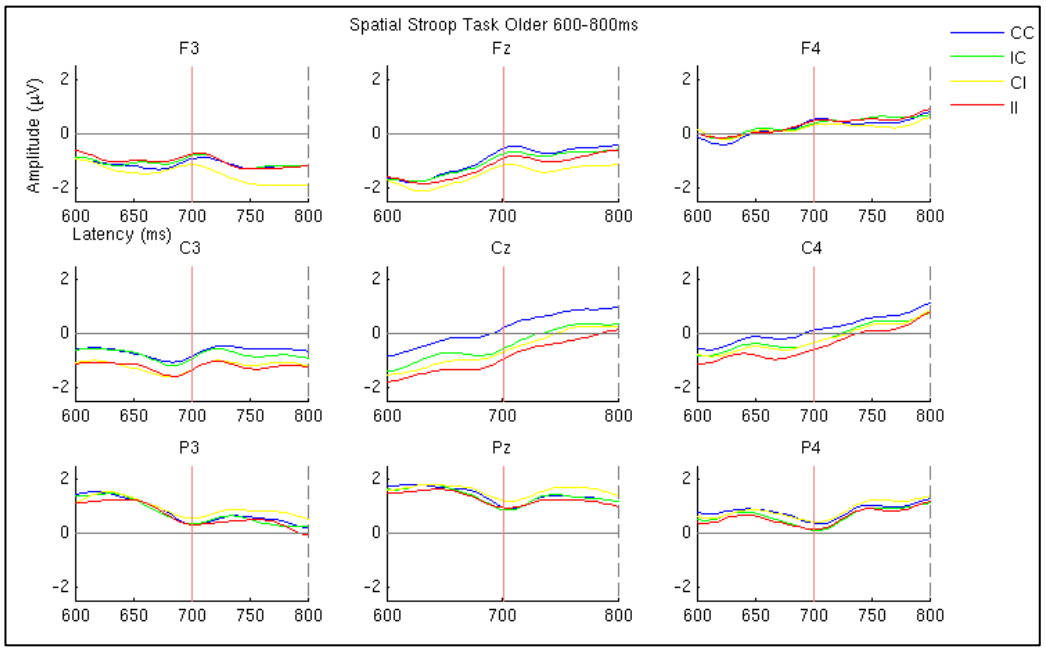

Figure 29 - Grand average ERP waveforms of stimulus-locked spatial Stroop trials (CC, IC, CI, II) recorded in older adults relative to the 600-800 ms TW. The 9 electrodes selected for the analyses are displayed.

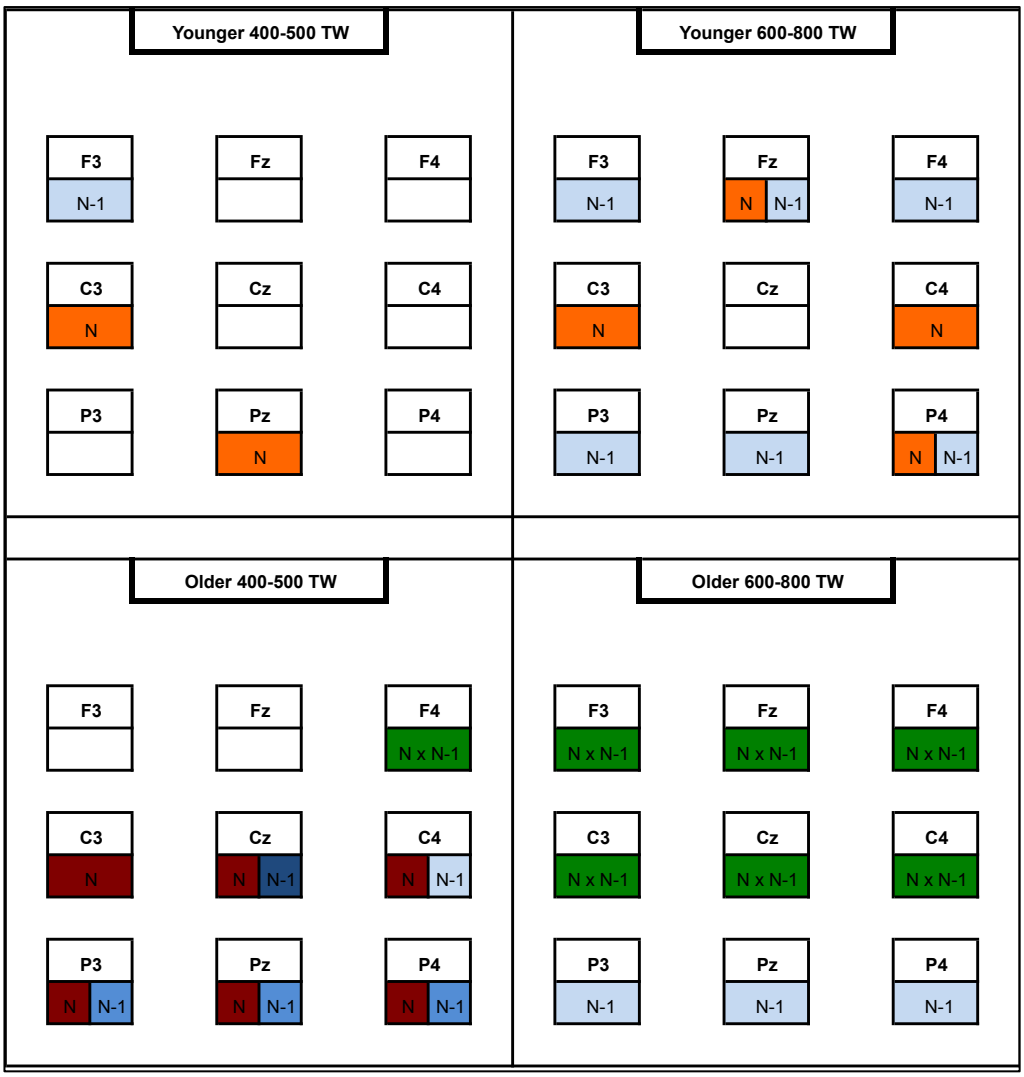

Figure 30 – Schema of significant effects of *trial n* congruency (N – red scale), *trial n-1* congruency (N-1 – blue scale) and of the *trial n* and *trial n-1* congruency interaction (N x *n-1* – green scale) in younger (upper part of the picture) and older adults (lower part of the picture) in each examined TWs: between 400 and 500 ms (left side of the picture) and between 600 and 800 ms (right side of the picture). The colour darkness reflects the significance strength ($p < .05$, $p < .01$, $p < .001$).

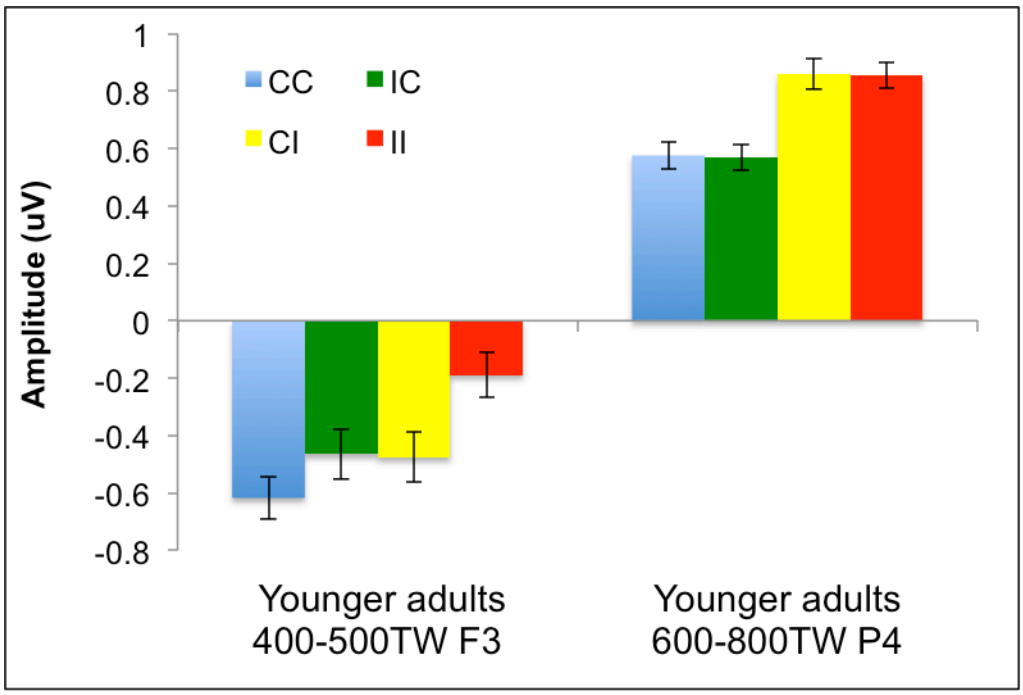

Figure 31 – Average amplitude recorded in F3 in the 400-500 ms TW and average amplitude recorded in P4 in the 600-800 ms TW as a function of spatial Stroop condition in younger adults.

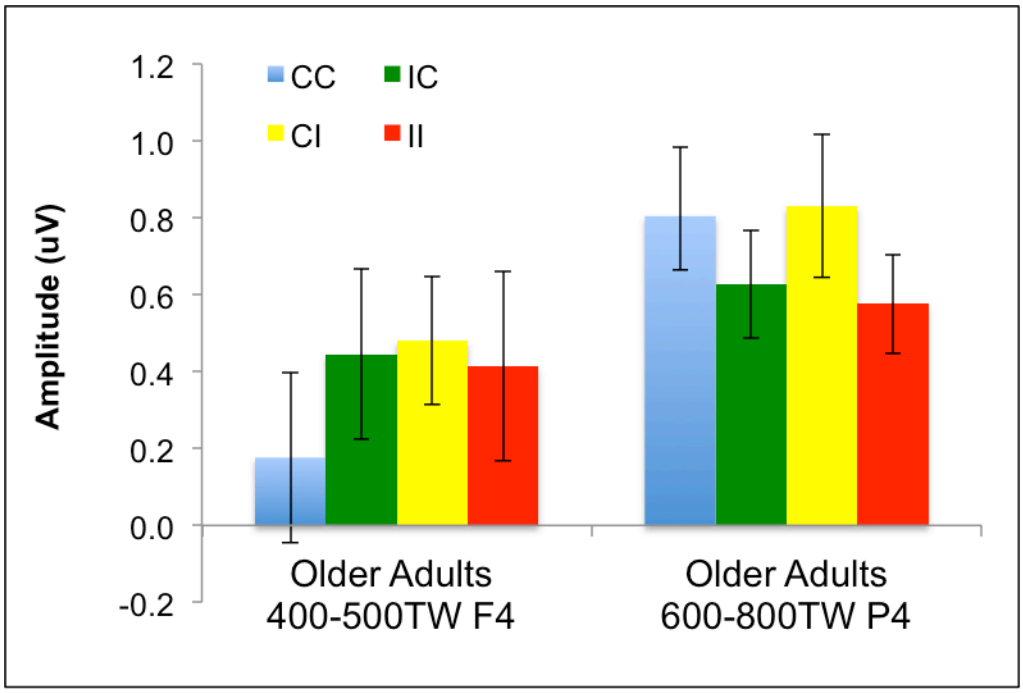

Figure 32 – Average amplitude recorded in F3 in the 400-500 ms TW and average amplitude recorded in P4 in the 600-800 ms TW as a function of spatial Stroop condition in younger adults.

Discussion

In this study electrophysiology was used in order to investigate the neural mechanisms that underlie spatial conflict resolution abilities. As in Experiment 6, a 4-AFC spatial Stroop task was used that allows the minimization of priming effects exerted by feature repetition.

Single feature conditions, that is, Position only and Direction only, are processed faster with respect to current incongruent Stroop trials. Current congruent trials are processed slower with respect to Position only, but they are as fast as Direction only trials. These effects are not different in younger and older adults. This suggests that the presence of two incongruent sources of information (e.g., incongruent Stroop stimuli) produces interference in RTs with respect to the same task with the relevant information only (Direction Only), whereas congruent distracting information (e.g., congruent Stroop stimuli) does not produce interference, as one may expect.

Despite a comparable level of accuracy, in the spatial Stroop task older adults were systematically slower with respect to younger ones in all the considered conditions (Direction only, Position only, Stroop CC, IC, CI and II conditions), confirming the presence of an age-related general slowing effect (Salthouse, 1991; 1996). Conflict resolution, measured as the Stroop effect (both in terms of RTs and accuracy), was evenly present in both age-groups suggesting that in healthy aging spatial conflict processes are unimpaired.

Sequential congruency effects were equally present both in RTs and accuracy for both age-groups (despite a trend suggesting that sequential congruency effects could be slightly different in older adults). Such sequential effects arise from facilitation due to a conflict adaptation for current congruent trials in speed (i.e., CC faster than IC), and from a conflict adaptation for current incongruent trials in accuracy (i.e., II more accurate than CI). The Stroop effect is then reduced (in terms of speed or errors) whenever the previous trial has the same conflict level as the current one. For what concerns the effects of modulatory variables, we found that in younger adults the accuracy Stroop effect is reduced in cases of high IQ, whereas in older adults the CRI index correlates with congruent trial accuracy.

Conflict-related ERPs in younger adults

Event-related potentials were used to examine how neural activity over time could reflect conflict processing and sequential congruency effects due to cognitive control. Because of a lack of preceding studies that used a comparable spatial Stroop task, we oriented our analysis on the basis of ERP studies on the classic Stroop task (e.g., Larson et al., 2009; Liotti et al., 2000; West & Alain, 2000a, 2000b), and in particular on the comparable ERP experiment that we ran in order to investigate in the verbal domain (Experiment 4, Chapter 3).

Therefore we examined two TWs (400-500 and 600-800 ms). In younger adults the analysis of the 400-500 ms TW shows a spread trial *n-1* congruency effect. However this effect is well pronounced in the left frontal electrode only (F3), where there is a negative deflection more pronounced for preceding congruent trials with respect to preceding incongruent ones. A sustained potential (SP) reflecting current trial congruency was present in the centro-parietal regions, where congruent stimuli elicited more positive waveforms than those elicited by incongruent ones. The presence of a phasic negativity in the fronto-central electrodes and a sustained positivity in the parietal region has been reported also by previous literature in verbal conflict resolution tasks (e.g., Larson et al., 2009; Liotti et al., 2000; West & Alain, 2000a, 2000b), but the parietal SP was usually detected in later time windows.

In the 600-800 ms TW the pattern for younger adults is similar to the one found in the earlier TW. A bilateral frontal negativity (until about 700 ms) and a positive sustained potential (SP) in centro-parietal electrodes were found, again partially supporting outcomes from previous studies in the verbal domain (Larson, Kaufman & Perlstein, 2009; Liotti, Woldorff, Perez, Mayberg, 2000; West, 2004; West & Alain, 2000b; West & Moore 2005; West & Schwarb 2006). Preceding trial congruency is reflected by frontal and parietal electrodes while current trial congruency is reflected mainly bilaterally in central electrodes. Unexpectedly, younger adults' ERP modulation never reflects the interaction of current and preceding trial spatial congruency which is present in the behavioural data.

In the first TW we observed that the frontal negativity is modulated by preceding trial congruency only, being it more negative for congruent trials *n-1*

with respect to incongruent ones, whereas the parietal SP showed increased positivity for congruent current trials with respect to incongruent ones (see Figure 31).

The parietal modulation reflecting current trial congruency may indicate the strength of the perceptual signal elicited by the current stimulus. Indeed the parietal voltage is higher for congruent with respect to incongruent trials. On the other hand, considering the fact that the behavioural data present a well-marked sequential effect pattern, we suggest that the frontal negativity could reflect a cognitive control signal determined by previous trial congruency. In particular, since the ERP voltage is higher (i.e., more negative) for preceding congruent trials, this could reflect a deactivation of proactive inhibition. Some studies indeed proposed that the cognitive control default state is proactive inhibition settled up whenever a situation could require the prevention of automatic and not appropriate stimulus responses (Boulinguez, Ballanger, Granjon, & Benraiss, 2009; Criaud, Wardak, Hamed, Ballanger, & Boulinguez, 2012; Jaffard, Longcamp, Velay, Anton, Roth, Nazarian, & Boulinguez, 2008). The cognitive control phasic adjustment could therefore consist of reducing the proactive inhibition in this case. If this is true, a congruent trial *n-1* could lead to the generation of a signal that reduces such proactive inhibition to make automatic faster processing of the stimulus possible, whereas, if the preceding trial is incongruent, proactive inhibition is more likely to be maintained.

Areas involved in movement regulation may be the targets of this signal. Indeed fMRI evidence suggests that medial prefrontal cortex and the inferior parietal cortex are the loci of cognitive control regulation on proactive inhibition and primary motor cortex, supplementary motor cortex and putamen are the final objective of the cognitive control modulation (Jaffard et al., 2008).

The second TW indicates that, after the processes that took place in the first TW, a modulation expressing both current and preceding trial is present in centro-frontal and parietal right electrodes; however the ERP voltage never reflects an interaction between the current and previous trial congruency. Following our hypothesis the frontal signal generated in the first TW adds, to parietal SP, a modulation based on the preceding trial's conflict level with respect to the modulation centred on the current trial congruency already present.

It is likely that behavioural sequential congruency effects could, in fact, originate from the simultaneous and not interactive modulation of current and previous conflict level. It is important to point out that the average response is given before the occurrence of the second TW, and therefore it is unlikely that neural mechanisms shown within 600 and 800 ms could directly influence the performance on the current trial.

However, it is likely that the voltage pattern evidenced in the second TW (600-800 ms) could mirror the mechanism that directly regulated the performance. Indeed in parietal electrodes the trial *n-1* congruency modulation, that we supposed to originate from the cognitive control mechanism, correlates with a reduction of the RT spatial Stroop after incongruent trials. Such correlation suggests a link with the presence of sequential congruency effects in the behavioural data, which involved a reduction of Stroop costs whenever the preceding trial was incongruent.

Similarly, still in parietal electrodes, the trial *n* congruency modulation (that we proposed to reflect the strength of the neural signal directly elicited by the feature characteristics of the stimulus) correlates with the overall speed.

Conflict-related ERPs in older adults

Older adults showed similar conflict-related ERP components (left frontal negativity, and sustained parietal positivity) with respect to younger adults. However, different from younger adults, in older adults the left frontal negativity is attenuated and reflects the interaction between current and previous trial congruency. Sustained potentials are present in central (negative polarity) and parietal (positive polarity) electrodes and show two simultaneous but distinct effects for current and previous trial congruency (see Figure 30). Indeed the *trial n* modulation found in parietal and central electrodes (i.e., voltage difference between congruent trial *n* and incongruent *trial n*) strongly correlates with RT, suggesting that the more such a modulation is pronounced (with congruent conditions being more positive than incongruent ones), the shorter RTs are.

In the 600-800 ms TW older adults do show a SP characterized by a positive almost monotonic increase of voltage in frontal and central electrodes (see Figure 29). Such SP clearly reflects a significant *trial n* by *trial n-1* interaction.

Moreover, the modulations caused by *trial n* congruency when the preceding trial was incongruent (II-IC) correlates with CRI. This indicates that a higher CRI is associated with II being less negative than IC.

It is important to note that we cannot distinguish between the fact that higher CRI correlates with an increased positivity of II or with an increased negativity of IC. In the same TW, parietal electrodes show that the average voltage reflects the preceding trial congruency being more positive for congruent trial *n-1* with respect to incongruent ones.

In older adults, both the frontal N450 modulation and the 600-800 ms SP reflect a modulation based on both current and previous trial congruency (see Figure 32). It is important to point out that younger adults' response usually falls before the 600-800 ms TW (average RT 533 ms), whereas older adults' responses take place during it (average RT 734 ms). This suggests that processing taking place in the 600-800 ms TW could still regulate the response of older adults but cannot regulate the younger adults' one.

Despite a general slowing effect, older adults do not show a specific spatial conflict resolution deficit behaviourally. However, in the present data, this absence of difference comes together with a completely different conflict-related electrophysiological pattern both functionally and topographically. It is therefore likely that such electrophysiological differences could reflect an age-related compensatory rearrangement.

Botvinick's conflict-monitoring hypothesis suggests that the anterior cingulate is an important node for conflict monitoring, and sends signals to the dorsolateral prefrontal cortex for conflict resolution, resulting in conflict adaptation at the behavioural level. This theory is supported by previous studies focusing on verbal conflict, which suggested that the N450 modulation could be interpreted as a more automatic congruency detection mechanism and that the late SP reflects a more top-down regulated conflict-processing mechanism (Liotti et al., 2000; Perlstein et al., 2006; West, 2003, 2004; West et al., 2005). However, our results, both behavioural and electrophysiological, suggest that this approach may not fully explain the spatial conflict-related processes.

In younger adults we showed that frontal electrodes reflect the modulation of previous trial congruency, rather than congruency of the current trial. We

therefore suggest that cognitive control, for what concerns the spatial domain, could more likely regulate a proactive inhibition mechanism.

Moreover assuming a key role of prefrontal cortex as a general conflict monitoring system, the lack of a relevant impact of aging on behavioural spatial conflict resolution found in this experiment (and also in Experiment 6), contrasts with West's selective frontal-lobe-damage hypothesis (FLH) of cognitive aging (West, 1996). Indeed on the basis of FLH we should expect a marked difference in the conflict resolution and conflict adaptation related performance in older adults with respect to younger ones.

Moreover, from the electrophysiological point of view, the presence of frontal ERPs reflecting sequential congruency effects in older adults, but not in younger adults, clashes with the assumption of both FLH and conflict monitoring hypotheses. However, making anatomical inferences with ERPs recorded from the scalp is difficult without good source analysis.

Importantly, the absence of sequential congruency modulation in younger adults coupled with its presence in older adults for the spatial task is probably task-specific and not due to the samples, since the very same younger participants showed the ERP sequential congruency modulation in the verbal Stroop task performed during the same experimental session (see Experiment 4, Chapter 3). A possible explanation that could unify theories and data for what concerns spatial conflict could be that in younger adults the cognitive control mechanism involves frontal areas and it regulates the attentional resources mainly on the basis of previous trial congruency. Older adults, suffering from a decline of frontal neural networks functionality, as predicted by the FLH, need to recruit more posterior cortical areas in order to maintain a high performance level. As highlighted by our electrophysiological data, the recruitment of different areas implies the use of different neural mechanism and strategies. However, future neuroimaging studies should be run in order to test this hypothesis.

Chapter 5 – Discussion & Conclusions

5.1. Cognitive Control: conflict and sequential congruency effects beyond priming confounds

In 1935 the American psychologist John Ridley Stroop published a study were he first showed one of the most famous phenomena of cognitive psychology: the Stroop effect. The Stroop effect (and its related colour-word task) is the most frequently used measure to quantify the cognitive conflict arising from two discording types of information. Beyond the effect specifically linked to the classic colour-word task, the Stroop effect, considered as the performance difference between congruent and incongruent stimuli belongs to the wider family of so called "congruency effects". Indeed it refers to the fact that the performance level (response speed and/or accuracy) on congruent conditions is higher than that on incongruent ones.

Among many investigations focusing on congruency effects, some studies pointed out that the congruency effect relative to a current trial could be modulated by the preceding trial's congruency, giving rise to sequential congruency effects (Kerns et al., 2004). These effects have been usually reported as a reduction of response times (or accuracy increase) for congruent trials preceded by another congruent trial and for incongruent trials preceded by another incongruent one. Given this pattern, they have been also referred to as "conflict adaptation effects" and have been explained by means of a conflict monitoring hypothesis (Botvinick, 2001). The conflict monitoring hypothesis suggests the existence of a conflict detection mechanism that modulates the attentional resources on the basis of preceding trial congruency, giving rise to a facilitation whenever two subsequent trials have the same level of conflict. Sequential effects have also been summarized as a reduction of the congruency effect whenever the preceding trial is incongruent.

As widely expressed in chapters 1 and 2, since alternative explanations indicate priming/binding factors as a source of sequential congruency effects (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Notebaert,

Gevers, Verbruggen & Liefooghe, 2006), we designed a conflict-related task that excluded partial and full repetitions of features in any two subsequent trials (see Chapter 2), in order to investigate congruency and sequential congruency effects in both the verbal and spatial domains after minimizing the possible effects of these confounding factors.

Verbal domain

Behavioural data concerning the verbal domain (Experiments 1, 2, 3 and 4) confirmed the presence of a marked congruency effect, but partially challenged evidence of sequential congruency effects. Indeed, in a (almost) priming-free context, sequential congruency effects were not present in current congruent trials and were present (although reduced) in incongruent trials.

Repetition priming (Experiment 2), instead, increased the difference produced by previous trial congruency on current congruent trials (i.e., CC vs IC sequences), producing a significant difference in the congruency (Stroop) effect when preceded by congruent versus incongruent trials that previous studies observed and referred to as conflict adaptation in congruent current trials.

The facilitation for incongruent trials given by a preceding incongruent trial with respect to a preceding congruent one (i.e., IC vs II sequences) was instead present even after controlling for priming, and can be therefore interpreted as a conflict adaptation phenomenon that is likely to be regulated by a cognitive control mechanism. We have to point out that such an effect was not very strong because, despite the fact that conflict adaptation in incongruent trials was significant in all the experiments, the modulation of previous trial congruency on the Stroop effect resulted significant in Experiments 1, 2 and 3 but did not reach the significance level in Experiment 4. Moreover some findings suggest that response speed and intelligence are correlated, inasmuch participants with a higher intelligence score were faster with respect to the ones with a lower IQ.

Although sequential congruency effects were marginal in the overt performance, electrophysiological evidence (Experiment 4) showed that ERPs reflected sequential congruency effects. In agreement with results from previous studies (Larson et al., 2009; Liotti et al., 2000; West, 2004; West & Alain, 2000a, 2000b; West & Moore 2005; West & Schwarb 2006), we observed a

phasic negativity (N450) in the frontal scalp regions and a parietal sustained potential. Younger adults showed modulations due to sequential congruency effects in both of these two components and such a modulation seems to reflect a conflict adaptation mechanism: frontal waveforms indeed are similar for sequences of repeated conflict levels (i.e., CC and II) and differ for those sequences where the conflict changes in two subsequent trials (i.e., CI and IC). This ERP modulation is associated with performance advantages, since it correlates with a reduction of the Stroop cost and with an increase of response speed.

West and Alain (1999) suggested that, on incongruent trials, conflicting information activates a competing representation in a conceptual level processing system, leading to the suppression of activation of the irrelevant information marked by the increased negativity of the N450 for incongruent trials with respect to congruent ones. Our data do not support this hypothesis, since it would imply similar reduced voltage for CC and IC trials and higher voltage for CI and II ones. Indeed younger adults during the first time window, in frontal sites showed that the ERP voltage pattern was CC ≈ II > CI > IC (see Figure 16). This pattern rather suggests that such a modulation in younger adults could reflect the increase of attentional resources required by the current stimuli when their congruency status changes from that of the previous one.

Indeed in CC and II trials the attentional resources have to be maintained with respect to previous trials, whereas, when a conflict level change takes place, a modification in the amount of dedicated attentional resources is needed. We therefore hypothesize that the phasic frontal negative modulation could reflect a neural signal generated in frontal sites and aimed at the regulation of parietal ones, in order to adjust the attentional resources on the basis of both current and previous trial congruency. Indeed after the frontal negative component, the parietal sustained one reflects the very same modulation. The conflict monitoring hypothesis (Botvinick, 2001) fits well with the present data, inasmuch as it proposes that cognitive control is responsible for monitoring the conflict level and afterward appropriately reallocating attentional resources. Our study, with respect to previous ones, highlighted the electrophysiological evidence of a top-down regulation based simultaneously on current and previous conflict.

Spatial domain

Conflict resolution processes were investigated with a spatial version of the priming-free Stroop task, in order to have a spatial task which was comparable with the verbal one used for the investigation of the verbal domain. Behavioural data concerning the spatial domain were collected in Experiments 5, 6 and 7. In all three experiments we corroborated the presence of a marked spatial congruency effect, and of sequential congruency effects leading to a modulation of Stroop effect due to previous trial congruency.

This matches with previous findings which used a Simon task with a partial priming exclusion (Wühr, 2005; Kunde and Wühr, 2006). Indeed, beyond repetition priming influences, the Stroop effect was reduced when the preceding trial was incongruent. Going into the details, these sequential effects arose from a conflict adaptation effect in both congruent and incongruent current trial. Noticeably the former was limited to RT performance and the latter was limited to accuracy performance only. In younger adults reduced errors and spatial congruency effects were correlated with higher IQ, which suggest that intelligence can modulate spatial conflict resolution performance.

However, there are small incongruencies among the experiments: in Experiment 7 a marginal conflict adaptation effect was present in accuracy of congruent trials (Accuracy CC > IC), differently from Experiments 5 and 6, and, moreover, in Experiment 5 we did not find significant effects of conflict adaptation in RT for congruent trials (RTs CC ≈ IC).

The presence of priming modulated the conflict resolution-related results by increasing sequential congruency effects, since it caused a marked reduction of RTs in congruent trials when preceded by another congruent one (i.e., RTs CC < IC).

The electrophysiological evidence showed similar ERP components with respect to those found for the verbal domain: a left frontal negativity and a sustained parietal positivity in both at the examined time windows (the same selected for the verbal domain analysis). However, contrary to the verbal domain findings, ERPs elicited by the spatial task did not reflect sequential congruency

effects. Indeed, their voltage reflected the congruencies of current and preceding trials separately and independently.

Such independent modulations of *trial n* and *trial n-1* congruencies specifically correlated with performance. Indeed the current trial congruency modulation in parietal electrodes strongly correlated with RTs, whereas the parietal modulation of *trial n-1* congruency correlated with the Stroop effect after incongruent trials.

In the first time window, the activity recorded by parietal electrodes is likely to reflect the perceptual properties of the stimuli, since higher voltage is shown by congruent current trials and lower voltage by incongruent current trials.

We suggest that in this first time window the frontal phasic negativity could reflect a signal, originated in frontal sites and directed to the parietal ones, which adjusts the attentional resources modulating the proactive inhibition elicited by the high conflict task. The proactive inhibition account (Criaud et al., 2012; Boulinguez et al., 2009; Jaffard et al., 2008) indeed suggests that whenever the situation requires one to carefully prevent automatic responses (as is the case of conflict stimuli when the irrelevant information is stronger) executive control provides the establishment of a prolonged state of inhibition of the neural networks responsible for movement initiation. The phasic stimuli-based modulation exerted by cognitive control would indeed consist of decreasing the default inhibition in the target areas.

Indeed after the frontal negativity, parietal electrodes mirror not only the present trial congruency, but also the preceding trial one. Correlational analyses with the performance data support this hypothesis, since the parallel modulations of trial *n* and trial *n-1* congruencies in the late parietal SP are associated, respectively, with overall speed and Stroop effect, and possibly give rise to the observed sequential congruency effects.

5.2. Cognitive Aging and Cognitive Control

5.2.1. Does cognitive aging exert effects on cognitive control?

The present project aimed at investigating both cognitive control in younger adults and its age-related modifications. Therefore, data were collected from younger adults and from older ones. Participants over 65 years of age were included in the older adults group (beside other inclusion criteria described in Chapter 2). In Chapters 3 and 4 findings relative to both behavioural and electrophysiological evidence in the verbal and spatial domain for younger and older adults performing conflict resolution (Stroop) tasks are reported.

It is important to point out here that, since our design was cross-sectional and not a longitudinal one, we cannot draw strong conclusions about age-related "changes", but rather we can discuss the "differences" displayed between younger and older adults. Therefore, similarly to what we did for younger adults, a conflict-related task that excluded priming repetition in two subsequent trials (see Chapter 2) was used in older adults, in order to investigate congruency and sequential congruency effects in both the verbal and spatial domains.

Verbal domain

The findings from the verbal domain (Experiments 3 and 4 of Chapter 3) showed that older adults suffered from marked general slowing phenomena, inasmuch they were slower, with respect to younger adults, in every task. After partially correcting for general slowing (see Chapter 2) our findings indicated that older adults showed a behavioural pattern very similar to the younger adults' one for what concerns sequential congruency effects.

Indeed both Experiment 3 and 4 showed the absence of RT sequential effects and the presence of a slight conflict adaptation in incongruent trials (i.e., accuracy CI < II). In both age-groups we noticed that while in the behavioural Experiment 3 the difference between CI and II was present, in Experiment 4

(run while ERPs were recorded) this difference was markedly reduced, up to the point of being not different in older adults.

Evidence for an age-related increase of the verbal Stroop effect was contradictory. In Experiment 3 we found a significant increase of the Stroop effect in older adults with respect to younger adults, whereas the behavioural results of Experiment 4 suggested that the Stroop effect was comparable in younger and older adults. This discrepancy could result from many factors. First, when comparing RTs of younger and older adults in the two experiments we observed that both younger and older adults had longer RTs in Experiment 4 than in Experiment 3. This increase was very large for incongruent trials performed by younger participants in Experiment 4. This led to a different level of the Stroop effect in younger adults in the two experiments: 30 ms in Experiment 3 and 102 ms in Experiment 4 [t-test*:* t (40) = 6.67, p < .001], whereas the Stroop effect in the older adults was almost comparable (89 ms and 129 ms respectively) [t-test*:* t (40) = 2.07, p = .045].

Second, since post-error slowing (Burns, 1965) could also distort the analysis, in the behavioural only studies, such as Experiment 3, trials following an incorrect one were excluded from the RT analysis. In Experiment 4 we decided instead, not to exclude post error trials in order to keep more ERP trials and increase the limited signal-to-noise ratio. This avoided that the behavioural and the electrophysiological analyses were run on different data pools. In order to verify this hypothesis, an analysis excluding post-error trials was run, confirming that the Stroop effect was still not different in the two age-groups [t-test*:* t (38) = -1.59, p = .12].

Third, it could be the case that the task-setting could influence performance. The behavioural test setting is quite usual for younger subjects, whereas it could be not so familiar for older adults, giving to the former group an advantage that is task-independent. The EEG recording setting is instead a non-usual and uncomfortable situation for both groups, thus leading to a disappearance of the setting advantage.

Fourth, also in West and Moore (2005) the same phenomenon happened: the Stroop effect was increased in older adults in the behavioural only experiment (Experiment 1) whereas it was comparable in older and younger adults in a similar task with EEG recording. However, in their study the age-

groups of the first experiment were different on years of formal education, whereas in the second experiment the two age-groups were matched for years of education.

Finally, it could also be that this inconsistency among results is due to sampling errors, and it was caused by the fact that simply the younger sample of Experiment 3 was more skilled than the one of Experiment 4.

On the other hand electrophysiological data (Experiment 4) clearly indicated very different patterns in older adults with respect to younger ones. In the earlier time window (400-500 ms) both groups showed a phasic frontal negativity that was left lateralized and delayed in time in older adults, as shown by previous studies (Larson et al., 2009; Liotti et al., 2000; West, 2004; West & Alain, 2000a, 2000b; West & Moore 2005; West & Schwarb 2006) and a parietal sustained potential (limited to the left side in the younger group). In the later TW both younger and older adults presented a sustained potential but, while in younger adults it was picked up by temporo-parietal electrodes, in the older group it was present bilaterally in frontal sites.

Moreover, while in younger adults the waveforms from frontal electrodes reflected sequential congruency effects, older adults' ones were modulated exclusively by preceding trial congruency. In the later TW younger adults still showed sequential congruency modulations, stronger in posterior electrodes, whereas older adults presented a current by preceding trial interaction in central electrodes, showing a posterior to anterior shift in time. In older adults the *trial n-1* by *trial n* congruencies modulation correlated with a reduction of both the RT and accuracy Stroop effects, suggesting the benefit of the modulation itself.

Considering that, beside a general slowing effect, older adults' performance was comparable to the younger adults' one (at least in Experiment 4) the different electrophysiological pattern is likely to be a compensatory rearrangement. Indeed if we assume that frontal sites are involved in top-down attentional modulation, the fact that only previous trial congruency was reflected in frontal ERPs suggests that older adults take advantage of a preparatory mechanism on the basis of the previous trial to solve the new incoming trial.

Another possibility is that the modulation based on preceding trial congruency only would reflect the incapability to disconnect from previous

stimuli to quickly modulate the attentional control regulation with respect to the current ones. The fact that a modulation based on both current and previous trial congruency was present later (in the central SP) suggests that this inability was overcome during the 600-800 ms time window. Indeed, other tasks have evidenced that older adults are slower and had more difficulties in shifting attention from the preceding stimulus to the current one (Cona, Arcara, Amodio, Schiff, & Bisiacchi, 2013; Cona, Bisiacchi, Amodio, & Schiff, 2013). This non-compensatory hypothesis would likely imply a worsening in older adults' performance only for what concern response speed and not conflict resolution or cognitive control and indeed this matches the present data. Therefore, further studies are needed in order to disentangle these two hypotheses.

Spatial domain

Differences between younger and older adults were investigated in Experiments 6 and 7 (Chapter 4). Similar to what we did for the verbal domain we investigated such differences after controlling for general slowing effects (see Chapter 2). Both congruency and sequential congruency effects were present in younger and older adults, and such effects were not statistically different. This suggests that, for what concerns spatial conflict processing, older adults suffered only from the general slowing phenomenon.

Results concerning older adults were comparable in Experiments 6 and 7, with the only exception that CI and II RTs were not different in Experiment 7, whereas they differed in Experiment 6. The same increase in accuracy difference for CI and II trials across the two experiments was shown by younger adults. This fact, paired with an increase of overall RTs in Experiment 7, suggests that in the latter experiment the EEG recording, or the difference in the samples, partially influenced performance.

Experiment 7 aimed to evidence the covert differences between conflict-related processes in older adults with respect to younger by means of ERPs. The first examined TW (400-500 ms) showed the presence of a frontal negativity in both groups (N450), which was attenuated in older adults, and a parietal sustained potential. Similar to what was observed in the verbal domain,

despite a strong correspondence in the waveforms, the two groups were very different for what concerns the ERP modulations by the different task conditions. Indeed the frontal negativity in younger adults was modulated by the preceding trial congruency, whereas in older adults it was determined by the interaction of current by previous trial congruency. Similarly, the parietal SP in younger adults reflected current trial congruency only, and in older adults showed the simultaneous but independent modulation of both current and previous trial congruency.

In the later TW (between 600 and 800 ms) both groups still presented a sustained potential but in older adults it was frontally shifted. Moreover, older adults' SP reflected a sequential congruency modulation whereas younger adults' SP reflected the separate effects of *trial n* and *trial n-1*.

In general, beside a general slowing of the performance, older adults did not show a significant spatial conflict resolution decline with respect to younger controls, but it is likely that in order to maintain the same behavioural efficiency their processes and internal strategies have to be rearranged. Indeed it is possible that the decline of frontal lobe-related functions suggested by the FLH (West, 1996) might take place and force cognitive control to recruit more posterior areas to cope adequately with the incoming conflict stimuli. Newly involved areas are probably not structured in the same way as original the ones, and therefore some mechanisms may change, as suggested by the present data. However, it would not be possible to go further with such speculations about a possible age-related topographical modification without a proper investigation that would involve neuroimaging.

5.2.2. Could intelligence, cognitive reserve or education influence the cognitive aging effects on cognitive control?

The previous literature identified intelligence, socio-economic status, years of education and cognitive reserve as factors that are likely to modulate cognitive aging effects (cf., Chapter 1 and 2). However this kind of investigation presents some methodological problems.

First of all, some of the factors identified as relevant cannot be directly manipulated. There is no way, indeed, to directly manipulate people's intelligence, also because the definition of intelligence itself is debatable. Some other factors, such as years of education, socioeconomic status and CR, could be in principle manipulated, but since they are very relevant in everyday life, the random assignment to a subgroup would be ethically unacceptable besides being practically unfeasible.

A second source of difficulty is the time extension of the study. The best strategies, from the methodological point of view, would be to use a longitudinal design where the factor is directly manipulated. This would imply subdividing a homogeneous sample of the younger population in subgroups and afterward to directly manipulate the factor in each of these groups (not always possible, as we specified above) making them different from each other for the level of the factor itself and measure their conflict resolution abilities when they will become older. Unfortunately this approach would imply create the subgroups when participants are younger and to verify the effect of the manipulation in older age (longitudinal design), making the study duration extremely long.

An alternative possibility could be to implement a cross-sectional study comparing older and younger adults who, in turn, are further subdivided in factor-based subgroups (e.g., high versus low level of the investigated factor). This approach would imply a shorter data-collection time with respect to a longitudinal design, but it would imply increasing the number of participants in order to have a reasonable amount of participants in each subgroup.

Such kind of subdivision, however, still implies some problems. Indeed it is necessary to have at least two levels/subgroups for the division (*high*/*low* level), and therefore it is necessitates a subdivision strategy that may be not the best and/or leads to confounds in the results. For example, making two subgroups of higher and lower intelligence, where *higher* and *lower* are determined by the fact of being above or below the population mean score might not be appropriate or informative, since it could be that intelligence may exert a positive effect only if it is very high in older, and exert a negative effect only if it is very low in younger. If this would be the case, this approach would not permit to evidence it.

As already stated in this and in the previous chapters, the present project is cross-sectional, and we decided not to subdivide the samples a priori in factor-based subgroups both because of the problems expressed in the preceding paragraphs and also because more than one factor was investigated. Therefore the analyses consisted of assessing whether those effects that suffer, actually or theoretically, from an age-related decline present some correlation with personal factors that previous studies have indicated as relevant.

In all of the experiments described here a general slowing effect was found, which seems to be the main source of difference between older and younger adults' performance. This slowing effect resulted to be counteracted by intelligence, years of formal education and cognitive reserve.

Interestingly these effects were limited to the results concerning the verbal domain, since none of these factors correlated with the general speed obtained in the spatial conflict tasks. This may suggest that the effect concerns a non-specific general slowing but with the slowing involving the verbal domain. The verbal task revealed also that verbal intelligence inversely correlated with the size of the Stroop effect. The fact that verbal intelligence was associated with the size of the verbal Stroop effect in older adults corroborates the hypothesis that the mechanism underlying compensation for conflict resolution in the classic Stroop task is a domain-specific one. In particular, older adults can cope better with age-related impairment in verbal conflict resolution if they have higher intelligence skills in the verbal domain.

Spatial conflict-related experiments suggest that CR is associated with a positive effect in increasing accuracy and reducing accuracy congruency effects. CR also correlated with the ERP modulation that reflects the effect of incongruent preceding trial on the current congruency (i.e., II-IC modulation). Moreover the fact that CR was involved in a correlation and years of education was not, suggests that there are some factors that contribute to the CR computation that exert effects beyond those offered by the educational level.

5.3. One or more Cognitive Control systems?

In the "The project" section (paragraph 1.4 of Chapter 1), we introduced that one of the aims of the present thesis was to verify the validity of the predominant hypothesis that cognitive control is a domain-independent mechanism responsible for top-down attentional regulation.

Very few previous studies investigated the modality independence of the cognitive control mechanism comparing evidence belonging to different domains for what concerns either the presentation modality of the stimuli (visual or auditory), or manipulating the cognitive domain involved in the task (verbal or spatial) (see Chapter 1).

In order to gain insight about this issue we planned to conduct a parallel investigation on conflict resolution processes in two different perceptual domains, the verbal and the spatial ones. Indeed for each of these domains we obtained findings regarding the conflict resolution processes with respect to many aspects:

a) two main behavioural indices of conflict resolution processes: the congruency effect and sequential congruency effect

b) the repetition priming modulation

c) the relative electrophysiological evidence

d) the age-related effects

e) correlational relationship with other possibly modulatory factors

Results relative to these indices are summarized in Table 5 in order to easily compare the findings concerning the verbal and the spatial domain.

The tasks belonging to the two domains revealed that some of the examined indices were similar in verbal and spatial domains. A congruency effect was indeed present both in the verbal and in the spatial tasks, indicating that incongruent stimuli exert an interference effect in both domains. Repetition priming exerted similar influences on the verbal Stroop stimuli with respect to spatial ones increasing the conflict adaptation for congruent trials (i.e. CC vs IC difference) in both tasks. Such an increase was so marked in the spatial domain to even significantly increase the sequential congruency effects. Intelligence

was shown to exert a beneficial effect as well, to some extent, in both task types.

However all the other indices appear to be different in the two domains. Once repetition priming was removed from subsequent trials, sequential congruency effects were only marginally present in the verbal domain, whereas they were well marked in the spatial one, and moreover they arose from different sources. Indeed in the verbal domain they were exclusively caused by conflict adaptation in incongruent current trials, whereas in the spatial one a conflict adaptation pattern was present for both congruent and incongruent current trials. Also Spapè and Hommel (2008) observed that in an auditory Stroop-like task sequential congruency effects occur only if the trial sequence involves some kind of repetition (the speaker in this case). This supports our findings and considerations inasmuch as it shows that in a different sensory modality with respect to the one we investigated (i.e., visual) sequential congruency effects are differently influenced by priming (or binding) factors.

ERP data of younger adults showed that during both the verbal and the spatial Stroop tasks two main components were evident: a frontal negativity and a parietal sustained potential. However, these waveforms reflected different modulations relative to the tasks at hand. Indeed, during the colour-word Stroop task these components mirrored an interaction between current and previous trial congruency in both time windows. On the contrary, ERPs relative to the spatial Stroop task reflected the separate effects of current trial congruency and of the previous trial one.

We suggested that during the two verbal tasks different cognitive control strategies take place. Indeed we hypothesized that in order to cope with the verbal conflict the cognitive control action is to adjust the amount attentional resources on the basis of the conflict level change with respect to the previous trial (see discussion of Experiment 4, Chapter 3), whereas spatial conflict data can be accounted for a proactive inhibition mechanism that is modulated by previous trial congruency and that modulates the parallel effect due to present trial congruency (see discussion of Experiment 7, Chapter 4; also cf. paragraph 5.1 of this chapter).

Finally, we observed that, beside the well-known general slowing phenomenon, present in the older adults' performance of both tasks, the age-

related changes in the two domains were different (at least for what concerns conflict resolution processes). Indeed we described a specific increase of the verbal congruency effect (although evidence was contradictory) that contrasts with a spared spatial congruency effect. Additionally, the differences in the ERP modulations, on the basis of the task trial type, that older adults exhibited with respect to younger ones were very different in the two Stroop tasks (cf. paragraph 5.2.1 of this Chapter). Similarly, evidence of age-related decline coming from other tasks involved in cognitive control also cannot be explained by a general cognitive control mechanism, but can rather be accounted for by a set of specific cognitive control mechanisms (Cona, Arcara, et al., 2013).

Furthermore, an experiment run by our group compared monolingual and bilingual volunteers in their performance on the 4-AFC verbal and spatial Stroop tasks. Bilinguals were supposed to have higher cognitive control skills due to their linguistic training. Indeed results revealed that bilinguals have an advantage with respect to monolinguals as a reduction of verbal congruency effect (unpublished results). However, since this advantage was limited to the verbal task and was not present in the spatial one, this evidence suggests that, at least the cognitive control advantages of bilingualism, may be domain specific (Babcock, Riontino & Vallesi, personal communication).

Clearly this issue necessitates further investigation. In particular, it would be very interesting and useful to get neuroimaging data using to the priming-free verbal and spatial Stroop tasks in order to localize the cortical areas involved in conflict resolution in the two domains and verify whether they are the same or not. Nevertheless the possibility that the involved cortical areas could be the same does not exclude the fact that the mechanism itself could be different with respect to the domain if the behavioural outputs are dissimilar.

To conclude, our results suggest that verbal and spatial conflict processes are regulated by different processes, and therefore cognitive control is not a general domain-independent mechanism, but rather it is likely to rely on different domain-specific mechanisms.

Table 5

	Verbal domain	Spatial domain
Congruency effect	Present	Present
Sequential congruency effects	Marginally present. Congruency effect is not modulated by previous trial congruency	Present. Congruency effect is modulated by previous trial congruency.
Repetition priming modulation	Increase of conflict adaptation for congruent trials	Increase of sequential congruency effects caused by intensification of conflict adaptation for congruent trials
Electrophysiological evidence (in younger)	Frontal N450 and parietal SP both modulated by current by previous trial congruency interaction	Frontal N450 and parietal SP both modulated by the separate effects of current and previous trial congruencies
Age-related effects [6]	General slowing. Specific increase of congruency effect (not sure) Absent a specific increase of sequential congruency effect similar ERP components modulation reflected by ERPs is different	General slowing. Absent a specific increase of congruency effect or sequential congruency effect similar ERP components modulation reflected by ERPs is different
Correlation with modulatory factors	Intelligence	Intelligence

[6] With respect to results relative to younger adults.

5.4. Limits of the project

Throughout this thesis we described some methodological compromises, criticism of the results and additional information that would be useful to get in order to have a clearer picture of the processes that we are investigating. In this section we try to make a critical analysis on the whole project by highlighting its limits.

Starting from the project design, it is clear that the choice of applying a cross-sectional approach facilitated the data collection in terms of time and difficulty. However it made it impossible to draw definitive conclusion about age-related *changes,* but permitted only to point out the differences between younger and older adults. This fact is linked with the problem of making inferences based on correlational analyses. Indeed, in order to verify the effect of a specific factor on a certain set of processes, such as conflict resolution, it would be more appropriate to directly manipulate the factor a priori. Unfortunately, this is not always possible, for practical and ethical reasons (cf., paragraph 5.2.2). Moreover, as specified in previous chapters, all the correlations that we calculated were not corrected for multiple comparisons. Therefore the correlational analyses reported here have to be considered as exploratory and causal inferences cannot be drawn from them.

Again at the theoretical level, we consider it important to point out that throughout the present project we attributed to the colour-word Stroop task the role of the verbal domain related task, drawing conclusions for the verbal domain on the basis of results on that task. It is clear that this classification is objectionable, since colour perception is not a pure verbal ability, however also the internal representation of colours is bound tightly to their verbal identity (colour naming), whereas this is not the case for the arrows indicating the direction in the spatial task. Of course the direction of the arrows also can be verbalized, but this is not automatic.

For what concerns the results, we pointed out that some of those are contradictory since are not consistent across the experiments (e.g., the increase of the verbal Stroop effect in older adults). This fact could be due to many reasons, as we discuss in paragraph 5.2.1. However the small sample size

surely contributed to such a discrepancy. Future studies should test the same effect with more robust sample sizes.

Finally it is important to point out that the ERP analysis presented here it is not exhaustive, but rather it should be considered as exploratory. Indeed, as explained in the introduction and data analysis sections of Experiments 4 and 7, we focused on those conflict-related markers that previous studies identified as relevant (i.e. N450 and SP). Therefore we selected the two time windows to analyse (400-500 and 600-800 ms) because they were supposed to contain the interesting markers. This does not mean that other time windows should not be explored and that the comparison of mean voltage would be the best approach. On the contrary, we are firmly convinced that a more powerful analysis should be done. Indeed, although we used only 9 electrodes here for the analysis, having collected data from 128 electrodes will permit us to further explore our data in many ways.

5.5. Proposals for future research

In order to partially overcome the limits pointed out in the previous section and to increase the relevance and the reliability of the findings that emerge from this thesis, there is further investigation at many levels that would be useful to carry out.

The starting point of the whole project was the need to investigate conflict resolution processes providing a proper repetition priming control, since previous studies only partially addressed this issue. In Experiments 1, 2 and 5 the repetition priming influences on the behavioural measures were highlighted, to clarify which effect was priming-dependent and which one was not, in order to make reasonable comparisons between findings from previous studies and the present ones. This has not been done for the ERP results. It would be worthwhile to make the same control with ERPs, by collecting electrophysiological data in a 4-AFC Stroop task that does not exclude priming and to a posteriori run separate analyses on the basis of priming level. This would clarify both the actual repetition priming effect on waveforms and where

the differences among our results and previous studies lie (e.g., Larson et al., 2009, Liotti et al., 2000; West, 2004; West & Alain, 2000a, 2000b; West & Moore 2005; West & Schwarb 2006).

The second aim was to investigate age-related effects on conflict resolution processes, but in the previous section the limits connected with a cross-sectional design were evidenced. Indeed, waiting until currently younger participants will get older would be clearly too time demanding, however it would be interesting to get a middle-aged sample (or more than one) in order to explore conflict-related differences with respect to different ages.

In paragraph 5.3 the existence of one or more cognitive control systems was argued, comparing conflict-related evidence belonging to the verbal domain with those belonging to the spatial one. We pointed out that our evidence suggests that cognitive control is not a general domain-independent mechanism, but the present project can rely on indirect measures only. Previous neuroimaging data indicated the ACC (Kerns et al., 2004; Pardo, Pardo, Janer, & Raichle, 1990) and the DLPFC as the areas involved in conflict resolution. However, in order to gain insights about a possible different location of a verbal versus a spatial cognitive control location, it would be necessary to directly compare two parallel tasks like the ones we used.

Furthermore, since both of the present Stroop tasks involved the visual modality, it would be therefore interesting to take advantage of the 4-AFC design structure (and relative benefits in terms of priming and sequential congruency control) to create and use new tasks involving stimuli belonging to others sensory modalities, such as the auditory or the tactile one. This would increase the evidence that will permit disentangling the issue of whether one or more cognitive control systems exist.

5.6. Conclusions

The present project has a multifaceted set of aims. A cognitive control mechanism was investigated using conflict-related measures such as congruency effects and sequential congruency effects as indices of cognitive control itself. This investigation was done paying particular attention to the repetition priming/binding influences that previous studies suggested are relevant in influencing conflict-related measures (e.g., Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003; Notebaert, Gevers, Verbruggen & Liefooghe, 2006). In order to be able to make comparisons between cognitive control involved in different domains, the project evolved in two parallel series of experiments conducted on the verbal and the spatial domains. Behavioural and electrophysiological evidence was gathered in order to explore conflict-related processes in younger and older ages. The findings illustrate that in the verbal domain the sequential congruency effects are reduced with respect to what previous findings reported (e.g., Kerns et al., 2004; Notebaert et al. 2006), whereas spatial sequential congruency effects are present even after the repetition priming exclusion. Repetition priming indeed resulted to differently influenced the processing of verbal and spatial stimuli.

ERPs showed that the two domains are partially comparable for what concerns conflict-related components, but that the modulation of those, reflecting the task sequential congruency conditions, is very different. Indeed the verbal Stroop task evidence demonstrates that conflict-related neural activity in frontal areas can reflect the interaction between current and previous trial congruency. However such modulation does not reflect the amount of conflict, as previously claimed (Liotti et al., 2000; Perlstein et al., 2006; West, 2003, 2004; West et al., 2005) but it rather detects the conflict level change in the present trial with respect to the just experienced one. This could then trigger the centro-parietal neural activity in order to appropriately regulate the attentional resources, exerting a direct influence on performance.

On the other hand the spatial Stroop task evidenced a modulation pattern compatible with the proactive inhibition account (Boulinguez et al., 2009; Criaud et al., 2012; Jaffard et al., 2008). Indeed, in this task the frontal negative

component reflects the congruency of the preceding trial and to increase its voltage for congruent with respect to incongruent trials. This suggests that a signal is generated to reduce the *default* inhibition that the high conflict level task required. The preceding trial congruency modulation flanks the current trial one without resulting in a reciprocal interaction, and probably leading to the presence of conflict sequential effect in the performance.

Our ERP results showed that the effect of *trial n* is not the only one modulating the conflict-related ERP components, but additionally the preceding trial effect and the interaction between the current and previous trials did modulate the ERPs. This suggests that limiting the analysis to the current trial would not only be less informative, but would also be misleading for drawing conclusions on the neural processes that underlie conflict resolution.

Older adults were impaired in the verbal domain only and limitedly to an increase in the verbal Stroop effect. However ERPs of older adults share with younger adults the main waveform components, but their modulation patterns with respect to the task congruency conditions are very different in both the verbal and spatial tasks. These asymmetries in the neural correlates of conflict, together with the reduced difference in performance between the two age-groups, point to a possible compensatory phenomenon. We suggest that the probable age-related decline of frontal areas (FLH, West, 1996) leads to the recruitment of different cortical substrates to cope with conflict, which implies also different sets of strategies and mechanisms as highlighted with the ERPs. Previous ERP studies investigated age-related effects mainly comparing the voltage difference between ERP modulations exerted by congruent and incongruent current trials in younger and older adults. Our results suggest that such comparisons could be misleading inasmuch as it is necessary to take into account the four sequential conditions instead of only the two congruency levels of the current trial. Indeed our results suggest that the fundamental difference between younger and older adults resides in the different way the sequential factors interact in aged people, not in a reduction in the power of a process similar to those of younger adults.

Nevertheless a reasonable discussion about the topographical rearrangement of cortical areas involved in conflict would not be possible without direct neuroimaging evidence.

The differences observed in the results concerning the two domains challenge the hypothesis of a supra-modal general cognitive mechanism. However further investigation is needed to strengthen the hypothesis of the existence of more domain-specific cognitive control mechanisms.

References

Albert, S.M., and Teresi, J.A. (1999). Reading ability, education, and cognitive status assessment among older adults in Harlem, New York City, *American Journal of Public Health, 89,* 95–97.

Alexander, G.E., Furey, M.L., Grady, C.L., Pietrini, P., Mentis, M.J., and Schapiro,M.B. (1997). Association of premorbid function with cerebral metabolism in Alzheimer's disease: Implications for the reserve hypothesis. *American Journal of Psychiatry, 154*, 165-172.

Andrés, P., Guerrini, C., Phillips, L.H., Perfect, T.J. (2008). Differential effects of aging on executive and automatic inhibition. *Developmental Neuropsychology*, *33*, 101-123. DOI: 10.1080/87565640701884212

Arenberg, D. (1978). Differences and changes with age in the Benton Visual Retention Test. *Journal of Gerontology*, *33*(4), 534-540.

Aron, A. R. (2007). The neural basis of inhibition in cognitive control. Neuroscientist, 13(3), 214–228.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M.D., Marsiske, M., …Willis, S. L. (2002). Effects of Cognitive Training Interventions With Older Adults: A Randomized Controlled Trial. *JAMA*, *288*, 2271–2281.

Belleville, S., Rouleau, N., Van der Linden, M. (2006). Use of the Hayling task to measure inhibition of prepotent responses in normal aging and Alzheimer's disease. *Brain and Cognition*, *62*, 113-119. DOI:10.1016/j.bandc.2006.04.006

Ben-David, B.M., Schneider, B.A. (2010). A sensory origin for color-word stroop effects in aging: simulating age-related changes in color-vision mimics age-related changes in Stroop. *Neuropsychol Dev Cogn B Aging Neuropsychol Cogn*, *17*, 730-746. DOI: 10.1080/13825585.2010.510553

Bergerbest, D., Gabrieli, J.D.E., Kim, H., Stebbins, G.T., Bennet, D.A., Fleischman (2009). Age-associated reduction of asymmetry in prefrontal function and preservation of conceptual repetition priming. *NeuroImage*, *45*, 237-246. DOI:10.1016/j.neuroimage.2008.10.019

Bialystok, E., Craik, F. I. M., Klein, R., and Viswanathan, M. (2004). Bilingualism, aging and cognitive control: Evidence from the Simon task. *Psychology and Aging, 19,* 290–303.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. Psychological Review, 108(3), 624–652.

Botvinick, M., Nystrom, L.E., Fissell, K., Carter, C.S., Cohen, J.D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature, 402*, 179-181.

Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D. (2001). Conflict monitoring and cognitive control. *Psychol Rev, 108*, 624-652. DOI: 10.1037/0033-295X.108.3.624

Boulinguez, P., Ballanger, B., Granjon, L., and Benraiss, A. (2009). The paradoxical effect of warning on reaction time: demonstrating proactive response inhibition with event- related potentials. Clin. Neurophys- iol. 120, 730–737.

Bowden, S. C., Cook, M. J., Bardenhagen, F. J., Shores, E. A., Carstairs, J. R. (2004). Measurement invariance of core cognitive abilities in heterogeneous neurological and community samples. *Intelligence*, *33*, 363-389. DOI: 10.1016/j.intell.2004.05.002

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews, 26,* 809–817. DOI:10.1016/S0149-7634(02)00067-2

Brown, M., & Besner, D. (2001). On a variant of Stroop's paradigm: Which cognitions press your buttons? Memory and Cognition, 29, 903–904.

Bugg, J. M., DeLosh, E. L., Davalos, D. B., & Davis, H. P. (2007). Age differences in Stroop interference: contributions of general slowing and task-specific deficits. *Neuropsychology, Development, and Cognition. Section B, Aging Neuropsychology and Cognition, 14*, 155–167. DOI: 10.1080/138255891007065

Burns, J. T. (1965). The effect of errors on reaction time in a serial reaction task. *PhD dissertation, University of Michigan* (unpublished).

Cabeza, R. (2002). Hemispheric Asymmetry Reduction in Older Adults: The HAROLD Model. *Psychology and Aging*, *17*, 85–100. DOI: 10.1037/0882-7974.17.1.85

Cabeza, R., Grady, C. L., Nyberg, L., McIntosh, A. R., Tulving, E., Kapur, S., et al. (1997). Age-related differences in neural activity during memory encoding and retrieval: A positron emission tomography study. *Journal of Neuroscience, 17,* 391–400.

Castel, A. D., Balota, D. A., Hutchison, K. A., Logan, J. M., and Yap, M. J. (2007). Spatial attention and response control in healthy younger and older adults and individuals with alzheimer's disease: evidence for disproportionate selection impairments in the simon task. *Neuropsychology*, *21*, 170-182.

Chiarello, C., Hoyer, W. (1988). Adult age differences in implicit and explicit memory: Time course and encoding effects. *Psychology and Aging, 3,* 358-366. DOI: 10.1037/0882-7974.3.4.358

Clark, J. E,, Lanphear, A.K., Riddick, C.C. (1987). The effects of videogame playing on the response selection processing of elderly adults. *Journal of Gerontology, 42,* 82-85. DOI: 10.1093/geronj/42.1.82

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., ... & Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *61*(11), 1166-1170.

Colcombe, S., Kramer, A.F. (2003). Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychological Science*, *14*, 125–130.

Cona, G., Arcara, G., Amodio, P., Schiff, S., & Bisiacchi, P. S. (2013). Does executive control really play a crucial role in explaining age-related cognitive and neural differences?. *Neuropsychology*, *27*(3), 378.

Cona, G., Bisiacchi, P. S., Amodio, P., & Schiff, S. (2013). Age-related decline in attentional shifting: Evidence from ERPs. *Neuroscience letters*, *556*, 129-134.

Connelly, S. L., Hasher, L., & Zacks, R. T. (1991). Age and reading: The impact of distraction. *Psychology and Aging, 6,* 533-541. DOI: 10.1037/0882-7974.6.4.533

Corbetta, M., Shulman, G.L. (2002). Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci. 3(3):201-15.

Criaud, M., Wardak, C., Hamed, S. B., Ballanger, B., & Boulinguez, P. (2012). Proactive inhibitory control of response as the default state of executive control. *Frontiers in psychology*, *3*.

Davidson, D.J., Zacks, R.T., Williams, C.C. (2003). Stroop interference, practice, and aging. *Aging, Neuropsychology and Cognition, 10,* 85–98. DOI: 10.1076/anec.10.2.85.14463

Davis, S.W., Dennis, N.A., Daselaar, S. M. Fleck, M. S., Cabeza, R. (2008), Qué PASA? The Posterior–Anterior Shift in Aging. *Cereb. Cortex, 18,* 1201-1209. DOI: 10.1093/cercor/bhm155

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. Journal of Experi- mental Psychology: Human Perception and Performance, 20, 731–750.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12,* 45-75. DOI:10.1016/0273-2297(92)90003-K

Dick, M.B., Kean, M.L., Sands, D. (1989). Memory for internally generated words in Alzheimer-type dementia: Breakdown in encoding and semantic memory. *Brain and Cognition, 9,* 88-108. DOI:10.1016/0278-2626(89)90046-8

Donohue, S. E., Liotti, M., Perez III, R., & Woldorff, M. G. (2012). Is conflict monitoring supramodal? Spatiotemporal dynamics of cognitive control processes in an auditory Stroop task. *Cognitive, Affective, & Behavioral Neuroscience*, *12*(1), 1-15.

Doyle, M. C., Rugg, M. D., & Wells, T. (1996). A comparison of the electrophysiological effects of formal and repetition priming. *Psychophysiology*, *33*(2), 132-147.

Drew, D., Waters, J. (1986). Video games: Utilization of a novel strategy to improve perceptual motor skills and cognitive functioning in the non-institutionalized elderly. *Cognitive Rehabilitation, 4,* 26-31.

Dustman, R.E., Emmerson, R.Y., Steinhaus, L.A., Shearer, D.E., Dustman, T.J. (1992). The effects of videogame playing on neuropsychological performance of elderly individuals. *Journal of Gerontology* , *47,* 168-171. DOI: 10.1093/geronj/47.3.P168

Dutzi, I. B., & Hommel, B. (2009). The microgenesis of action-effect binding. Psychological Research, 73, 425–435.

Dyer, F. N. (1973). The Stroop phenomenon and its use in the study of perceptual, cognitive, and response processes. Memory and Cognition, 1, 106–120.

Eisdorfer, C., Busse, E. W., & Cohen, L. D. (1959). The WAIS performance of an aged sample: The relationship between verbal and performance IQs. *Journal of gerontology*, *14*(2), 197-201.

Evans, D.A., Beckett, L.A., Albert, M.S., Hebert, L.E., Scherr, P.A., Funkenstein, H.H., Taylor, J.O. (1993). Level of education and change in cognitive function in a community population of older persons. *Annals of Epidemiology, 3,* 71-77. DOI:10.1016/1047-2797(93)90012-S

Eyler, L.T., Sherzai, A., Kaup, A. R., Jeste, D. V. (2011) A Review of Functional Brain Imaging Correlates of Successful Cognitive Aging. *Biological Psychiatry*, *70 ,* 115-122. DOI:10.1016/j.biopsych.2010.12.032

Fabiani, M., Low, K., Wee, E., Sable, J. and Gratton, G. (2006). Reduced suppression or labile memory? Mechanisms of inefficient filtering of irrelevant information in older adults. *J. Cognitive Neuroscience, 18,* 637-650. DOI:10.1162/jocn.2006.18.4.637

Fleischman, D.A., Gabrieli, J.D.E. (1998). Repetition priming in normal aging and Alzheimer's disease: A review of findings and theories. *Psychology and Aging*, *13,* 88-119. DOI: 10.1037/0882-7974.13.1.88

Floden, D., Vallesi, A., Stuss, D.T. (2011) Task context and frontal lobe activation in the Stroop task. *J Cogn Neurosci, 23*, 867-879. DOI:10.1162/jocn.2010.21492

Folstein, M.F., Folstein, S.E., McHugh, P.R. (1975). Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12,* 189-198. DOI: 10.1016/0022-3956(75)90026-6

Funes, M. J., Lupiáñez,J., and Humphreys, G. (2010). Sustained vs. transient cognitive control: Evidence of a behavioral dissociation. *Cognition, 114*, 338-347.

Gamboz, N., Russo, R., Fox, E. (2002). Age differences and the identity negative priming effect: An updated meta- analysis. *Psychology and Aging, 17,* 525–530. DOI: 10.1037/0882-7974.17.3.525

Gazzaley, A., Cooney, J.W., Rissman, J., D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience, 8,* 1298-1300. DOI:10.1038/nn1543

Gazzaley, A., D'Esposito, M. (2007). Top-down modulation and normal aging. *Ann n Y Acad Sci*, *1097,* 67-83. DOI: 10.1196/annals.1379.010

Gehring, W. J., & Knight, R. T. (2000). Prefrontal–cingulate interactions in action monitoring. *Nature neuroscience*, *3*(5), 516-520. doi:10.1038/74899

Gläscher, J., Tranel, D., Paul, L.K., Rudrauf, D., Rorden, C., Hornaday, A., Grabowski, T., Damasio, H., Adolphs, R. (2009). Lesion mapping of the cognitive abilities linked to intelligence. *Neuron, 61,* 681–691 DOI:10.1016/j.neuron.2009.01.026

Goldstein, J., Cajko, L., Oosterbroek, M., Michielsen, M., Van Houten, O., Salverda, F. (1997). Video games and the elderly. *Social Behavior and Personality*, *25,* 345-352.

Grady, C.L., McIntosh, A.R., Horwitz, B., Maisog, J.M., Ungerleider, L.G., Mentis, M.J., Pietrini, P., Schapiro, M.B., Haxby, J.V. (1995). Age-related reductions in human recognition memory due to impaired encoding. *Science*, *269,* 218-221. *DOI:* 10.1126/science.7618082

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. Journal of Experimental Psychology: General, 121(4), 480–506.

Gratton, G., Coles, M. G., and Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. *J Exp Psychol Gen, 121,* 480-506.

Gratton, G., Coles, M. G., Donchin, E. (1992). Optimizing the use of information: strategic control of activation of responses. *J Exp Psychol Gen, 121,* 480-506. *DOI:* 10.1037/0096-3445.121.4.480

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society*, *6*(6), 705-726.

Gutchess, A.H., Kensinger, E.A., Schacter D.L. (2007). Aging, self-referencing, and medial prefrontal cortex. *Social Neuroscience*, *2,* 117-133. DOI: 10.1080/17470910701399029

Habeck, C., Hilton, H.J., Zarahn, E., Flynn, J., Moeller, J.R., Stern, Y., (2003). Relation of cognitive reserve and task performance to expression of

regional covariance networks in an event-related fMRI study of non-verbal memory. *Neuroimage*, *20*,1723-1733. DOI:10.1016/j.neuroimage.2003.07.032

Hamberger, M., Friedman, D. (1992). Event-related Potential Correlates of Repetition Priming and Stimulus Classification in Young, Middle-aged, and Older Adults. *Journal of Gerontology*, *47,* 395-405. DOI: 10.1093/geronj/47.6.P395

Hartley, A.A. (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychology and Aging*, *8*, 371–379. DOI: 10.1037/0882-7974.8.3.371

Hasher, L., Chung, C., May, C. P., Foong, N. (2002). Age, time of testing, and proactive interference. *Canadian Journal of Experimental Psychology*, *56,* 200-207. DOI: 10.1037/h0087397

Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *J Exp Psychol Learn Mem Cogn*, *17,*163-169. DOI: 10.1037/0278-7393.17.1.163

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. *In: Gopher D, Koriat A, editors. Attention & Performance, XVII, Cognitive Regulation of Performance: Interaction of Theory and Application. MIT Press; Cambridge, MA*, 653–675.

Hasher, L., Zacks, R.T. (1988). Working memory, comprehension, and aging: a review and a new view. In: Bower, G.H. (Ed.), *The Psychology of Learning and Motivation, Vol. 22. Academic Press, New York,* 193–225.

Heckman, J. (1979) Sample selection bias as a specification error. *Econometrica*, 47, 153–61.

Hofmann, W., Schmeichel, B.J., Baddeley, A.D. (2012). Executive functions and self-regulation. Trends Cogn Sci. 16(3):174-80.

Hommel, B. (1998). Automatic stimulus-response translation in dual- task performance. Journal of Experimental Psychology: Human Perception and Performance, 24(5), 1368–1384.

Hommel, B. (2011). The Simon effect as tool and heuristic. Acta Psychologica, 136, 189–202.

Hommel, B., Proctor, R.W., and Vu, K.P. (2004). A feature-integration account of sequential effects in the Simon task. *Psychol Res*, *68*(1), 1-17.

Horn, J. L., and Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta Psychologica, 26,* 107–129.

Ikier S., Yang L., Hasher L. (2008). Implicit Proactive Interference, Age, and Automatic Versus Controlled Retrieval Strategies. *Psychological Science*, *19,* 456-461. DOI: 10.1111/j.1467-9280.2008.02109.x

Ince, P.G. (2001). Pathological correlates of late-onset dementia in a multicenter community-based population in England and Wales. *Lancet, 357,* 169-175.

Ishihara, S. (1962). *Tests for Color-blindness.* Tokyo: Kanehara Shuppan.

Jaffard, M., Longcamp, M., Velay, J.-L., Anton, J.-L., Roth, M., Nazarian, B., and Boulinguez, P. (2008). Proactive inhibitory control of movement assessed by event-related fMRI. Ne roimage 42, 1196–1206.

Java, R.I. (1996). Effects of age on state of awareness following implicit and explicit word-association tasks. *Psychology and Aging*, *11,* 108-111. DOI: 10.1037/0882-7974.11.1.108

Jiménez, L., & Méndez, A. (2013). It is not what you expect: Dissociating conflict adaptation from expectancies in a Stroop task. *Journal of experimental psychology: human perception and performance*, *39*(1), 271. DOI: 10.1037/a0027734.

Juncos-Rabadán, O., Pereiro, A. X., and Facal, D. (2008). Cognitive interference and aging: Insights from a spatial stimulus–response consistency task. *Acta Psychologica, 127*, 237–246.

Katzman R.(1993). Education and the prevalence of dementia and Alzheimer's disease. *Neurology, 43,* 13-20.

Katzman, R., Aronson, M., Fuld, P., Kawas, C., Brown, T., Morgenstern, H., Frishman, W., Gidez, L., Eder, H., and Ooi, W.L. (1989). Development of dementing illnesses in an 80-year-old volunteer cohort. *Annals of Neurology*, *25*, 317–324.

Kerns, J.G., Cohen, J.D., MacDonald, A.W., Cho, R.Y., Stenger, V.A., and Carter, C.S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023-1026.

Keys B.A. White, A.D. (2000). Exploring the relationship between age, executive abilities, and psychomotor speed. *Journal of the International Neuropsychological Society*, *6,* 76-82.

Kiefer, M. (2005). Repetition-priming modulates category-related effects on event-related potentials: further evidence for multiple cortical semantic systems. *Journal of cognitive neuroscience*, *17*(2), 199-211.

Koechlin, E., Ody, C., Kouneiher, F. (2003). The architecture of cognitive control in the human prefrontal cortex. Science 302(5648):1181-5.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: cognitive basis for stimulus-response compatibility—a model and taxonomy. Psychological Review, 97(2), 253–270.

Koss, E., Haxby, J. V., DeCarli, C., Schapiro, M. B., Friedland, R. P., & Rapoport, S. I. (1991). Patterns of performance preservation and loss in healthy aging. *Developmental Neuropsychology*, *7*(1), 99-113.

Kunde, W., and Wühr, P. (2006). Sequential modulations of stimulus-response correspondence effects depend on awareness of response conflict. *Memory and Cognition, 34* (2), 356-367.

La Voie, D., & Light, L. L. (1994). Adult age differences in repetition priming: A meta-analysis. *Psychology and Aging*, *9,* 539–553. DOI: 10.1037/0882-7974.9.4.539

Lavie, N., Hirst, A., de Fockert, J., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133,* 339-354. DOI: 10.1037/0096-3445.133.3.339

Leboe, L. C., & Mondor, T. A. (2007). Item-specific congruency effects in nonverbal auditory Stroop. *Psychological Research*, *71*(5), 568-575.

Lezak, M. D. (1995). *Neuropsychological assessment* (3rd ed.). New York: Oxford University Press.

Light, L.L., Albertson, S.A. (1989). Direct and indirect tests of memory for category exemplars in young and older adults. *Psychology and Aging*, *4,* 487-492. DOI: 10.1037/0882-7974.4.4.487

Light, L.L., Singh, A. (1987). Implicit and explicit memory in young and older adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13,* 531-541. DOI: 10.1037/0278-7393.13.4.531

Light, L.L., Singh, A., Capps, J.L. (1986). Dissociation of memory and awareness in young and older adults. *Journal of Clinical and Experimental Neuropsychology*, *8,* 62-74. DOI: 10.1080/01688638608401297

Liotti, M., Woldorff, M. G., Perez III, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, *38*(5), 701-711.

Lu, C. H., and Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin and Review, 2,* 174–207.

Ludwig, C., Borella, E., Tettamanti, M., & de Ribaupierre, A. (2010). Adult age differences in the Color Stroop Test: A comparison between an Item-by-item and a Blocked version. *Archives of Gerontology and Geriatrics, 51,* 135–142. DOI:10.1016/j.archger.2009.09.040

Lustig, C., May, C.P., Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology: General*, *130,* 199-207. DOI: 10.1037/0096-3445.130.2.199

MacLeod, C.M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–203. DOI: 10.1037/0033-2909.109.2.163

MacPherson, S. E., Phillips, L. H., & Della Sala, S. (2002). Age, executive function, and social decision making: A dorsolateral prefrontal theory of cognitive aging. *Psychology and Aging*, *17,* 598–609. DOI: 10.1037/0882-7974.17.4.598

Madden, D.J., Langley, L.K. (2003). Age-related changes in selective attention and perceptual load during visual search. *Psychology and Aging*, *18,* 54-67. DOI: 10.1037/0882-7974.18.1.54

Manly, J. J., Touradji, P., Tang, M.-X., Stern, Y. (2003). Literacy and memory decline among ethnically diverse elders. *Journal of Clinical and Experimental Neuropsychology, 5,* 680-690. DOI: 10.1076/jcen.25.5.680.14579

Mansouri, F.A., Buckley M.J., and Tanaka K. (2007). Mnemonic function of the dorsolateral prefrontal cortex in conflict-induced behavioral adjustment. *Science, 318* (5852), 987–990.

Mayas, J., Fuentes, L.J., Ballesteros, S. (2012). Stroop interference and negative priming (NP) suppression in normal aging. *Archives of Gerontology and Geriatrics, 54*(2), 333-338. DOI: 10.1016/j.archger.2010.12.012

Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. Nature Neuroscience, 6(5), 450–452.

Mayr, U., Awh, E., Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience, 6,* 450-452. DOI:10.1038/nn1051

McDowd, J.M., Oseas-Kreger, D.M. (1991) Aging, inhibitory processes and negative priming. *J Gerontology, 46,* 340–345. DOI: 10.1093/geronj/46.6.P340

McEvoy, C.L., Holley, P.E., Nelson, D.L. (1995). Age effects in cued recall: Sources from implicit and explicit memory. *Psychology and Aging*, *10,* 314-324. DOI: 10.1037/0882-7974.10.3.314

McLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. Psychological Bulletin, 109, 163–203.

Mitchell, D.B. (1989). How many memory systems? Evidence from aging. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15,* 31-49. DOI: 10.1037/0278-7393.15.1.31

Mitchell, K. J., Raye C. L., Johnson, M. K., Greene, E. J. (2006). An fMRI investigation of short-term source memory in young and older adults. *NeuroImage*, *30,* 627-633. DOI:10.1016/j.neuroimage.2005.09.039

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A.H., Howerter, A., Wager, T.D., (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. Cogn Psychol. 41(1):49-100.

Monti, L.A., Gabrieli, J.D.E., Reminger, S.L., Rinaldi, J.A., Wilson, R.S., Fleischman, D.A. (1996). Differential effects of aging and Alzheimer's disease on conceptual implicit and explicit memory. *Neuropsychology*, *10,* 101-112. DOI: 10.1037/0894-4105.10.1.101

Mordkoff, J. T. (2012). Observation: Three reasons to avoid having half of the trials be congruent in a four-alternative forced-choice experiment on sequential modulation. *Psychonomic bulletin & review*, *19*(4), 750-757. DOI: 10.3758/s13423-012-0257-3

Mortel, K.F., Meyer, J.S., Herod B., and Thornby, J. (1995). Education and occupation as risk factors for dementia of the Alzheimer and ischemic vascular types. *Dementia, 6,* 55-62.

Moscovitch, M. & Winocur, G. (1992). The neuropsychology of memory and aging. In F.I.M. Craik & T.A. Salthouse (Eds.), *The handbook of aging and cognition* (315–372). Hillsdale, NJ: Lawrence Erlbaum Associates.

Mutter, S.A., Naylor, J.C., Patterson, E.R. (2005). The effects of age and task context on Stroop task performance. *Memory & Cognition*, *33*, 514–530. DOI: 10.3758/BF03193068

Nasreddine, Z., S., Phillips, N., A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J., L., Chertkow, H. (2005). The Montreal Cognitive Assessment (MoCA): A Brief Screening Tool For Mild Cognitive Impairment. *Journal of the American Geriatrics Society*, *53,* 695-699. DOI: 10.1111/j.1532-5415.2005.53221.x

Neill, W.T. (1977). Inhibitory and facilitatory processes in attention. *Journal of Experimental Psychology: Human Perception and Performance*, *3,* 444-450. DOI: 10.1037/0096-1523.3.3.444

Nieuwenhuis, S., Forstmann, B. U., & Wagenmakers, E. J. (2011). Erroneous analyses of interactions in neuroscience: a problem of significance. *Nature neuroscience*, *14*(9), 1105-1107.

Nieuwenhuis, S., Stins, J. F., Posthuma, D., Polderman T. J. C., Boomsma, D. I., and de Geus, E. J. (2006). Accounting for sequential trial effects in the flanker task: Conflict adaptation or associative priming? *Memory and Cognition, 34*(6), 1260-1272.

Notebaert W, Gevers W, Verbruggen F, Liefooghe B. (2006). Top-down and bottom-up sequential modulations of congruency effects. *Psychon Bull Rev*. Feb;13(1):112-7.

Notebaert, W., & Soetens, E. (2003). The influence of irrelevant stimulus changes on stimulus and response repetition effects. *Acta Psychology (Amst), 112*(2), 143–156.

Notebaert, W., and Verguts, T. (2007). Dissociating conflict adaptation from feature integration: a multiple regression approach. *J Exp Psychol Hum Percept Perform, 33*(5), 1256-1260.

Notebaert, W., Gevers, W., Verbruggen, F., & Liefooghe, B. (2006). Top-down and bottom-up sequential modulations of congruency effects. Psychonomic Bulletin & Review, 13(1), 112–117.

Notebaert, W., Soetens, E., & Melis, A. (2001). Sequential analysis of a Simon task- evidence for an attention-shift account. Psychological Research, 65(3), 170–184.

Nucci, M., Mondini, S., and Mapelli, D. (2011). The Cognitive Reserve questionnaire (CRIq): a new instrument for measuring the cognitive reserve. *Aging Clin Exp Res.*

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., and Bäckman. L. (2012). Memory aging and brain maintenance. *Trends in Cognitive Sciences, 16*(5), 292–305.

Oldfield, R.C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9,* 97-113.

Pardo, J. V., Pardo, P. J., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. Proceedings of the National Academy of Sciences of the United States of America, 87(1), 256–259.

Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), Information Processing and Cognition: The Loyola Symposium (pp. 55–85). Hillsdale, NJ: Erlbaum.

Proctor, R. W., Pick, D. F., Vu, K.P. L., and Anderson, R. (2005). The enhanced Simon effect for older adults is reduced when the irrelevant location information is conveyed by an accessory stimulus. *Acta Psychologica, 119,* 21–40.

Rabbitt, P.M.A. (1979). How old and young subjects monitor and control responses for accuracy and speed. *British Journal of Psychology, 70, 305*-311. DOI: 10.1111/j.2044-8295.1979.tb01687.x

Riley, K.P., Snowdon, D.A., and Markesbery, W.R. (2002). Alzheimer's neurofibrillary pathology and the spectrum of cognitive function: findings from the Nun Study. *Ann*. *Neurol., 51*, 567–577.

Roberts, K. L., & Hall, D. A. (2008). Examining a supramodal network for conflict processing: a systematic review and novel functional magnetic resonance imaging data for related visual and auditory stroop tasks. *Journal of cognitive neuroscience*, *20*(6), 1063-1078.

Rocca, W.A., Bonaiuto, S., Lippi, A., Luciani, P., Turtu, F., and Cavarzeran, F., (1990). Prevalence of clinically diagnosed Alzheimer's disease and other dementing disorders: A door-to-door survey in Appignano, Macerata Province, Italy, *Neurology, 40,* 626-631.

Rush, B.K., Barch, D.M., Braver, T.S. (2006), Accounting for cognitive aging: Context processing, inhibition or processing speed. *Aging, Neuropsychology, and Cognition*, *13,* 588-610.
DOI:10.1080/13825580600680703

Rush, M. C., Panek, P. E., Russell, J. A. (1990). Analysis of individual variability among older adults on the Stroop Color Word Interference Test. *International Journal of Aging and Human Development*, *30,* 225–236.

Russell, E. W. (1972b). A WAIS factor analysis with brain damaged subjects using criterion measures. *Journal of Consulting and Clinical Psychology*, *39,* 133–139. DOI: 10.1037/h0033212

Rybash, J.M. (1996). Implicit memory and aging: A cognitive neuropsychological perspective. *Developmental Neuropsychology*, *12,* 127-179. DOI:10.1080/87565649609540644

Rypma, B., D'Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience*, *3,* 509-515. DOI:10.1038/74889

Salthouse, T.A. (1985). *A theory of cognitive aging.* Amsterdam: North Holland.

Salthouse, T.A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103,* 403-428. DOI: 10.1037/0033-295X.103.3.403

Salthouse, T.A., and Ferrer-Caja, E., (2003). What needs to be explained to account for the age-related effects on multiple cognitive variables? *Psychology of Aging, 18,* 91–110.

Salthouse, T.A., Babcock, R.L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology*, *27,* 763-776. DOI: 10.1037/0012-1649.27.5.763

Satz, P. (1993). Brain reserve capacity on symptom onset after brain injury: A formulation and review of evidence for threshold theory. *Neuropsychology, 7*, 273-295. DOI: 10.1037/0894-4105.7.3.273

Scarmeas, N., Levy, G., Tang, M.X., Manly, J., and Stern, Y. (2001). Influence of leisure activity on the incidence of Alzheimer's disease. *Neurology*, *57*, 2236–2242.

Schelstraete, M.A., Hupet, M. (2002). Cognitive aging and inhibitory efficiency in the Daneman and Carpenter's working memory task. *Exp. Aging Res*. *28,* 269-279. DOI:10.1080/03610730290080326

Scialfa, C.T., Esau, S.P. (1998). Age,target-distractor similarity, and visual search. *Experimental Aging Research, 24,* 337. DOI:10.1080/036107398244184

Simon, J. R., & Berbaum, K. (1990). Effect of conflicting cues on information processing: the 'Stroop effect'vs. the 'Simon effect'. *Acta psychologica*, *73*(2), 159-170.

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R.F., Mahncke, H. W. and Zelinski, E.M. (2009). A Cognitive Training Program Based on Principles of Brain Plasticity: Results from the Improvement in Memory with Plasticity-based Adaptive Cognitive Training (IMPACT) Study. *Journal of the American Geriatrics Society, 57*, 594–603. DOI: 10.1111/j.1532-5415.2008.02167.x

Snowdon, D.A., Greiner, L.H., Mortimer, J.A., Riley, K.P., Greiner, P.A., and Markesbery, W.R. (1997). Brain infarction and the clinical expression of Alzheimer disease. The Nun Study, *JAMA*, *277*, 813–817.

Spaniol, J. & Grady, C. (2012). Aging and the neural correlates of source memory: over-recruitment and functional reorganization. *Neurobiology of Aging. 33*, 425.e3–425.e18 DOI:10.1016/j.neurobiolaging.2010.10.005

Spapé, M. M., & Hommel, B. (2008). He said, she said: Episodic retrieval induces conflict adaptation in an auditory Stroop task. *Psychonomic Bulletin & Review*, *15*(6), 1117-1121.

Springer, M.V., McIntosh, A.R., Winocur, G., Grady, C.L. (2005). The relation between brain activity during memory tasks and years of education in young and older adults. *Neuropsychology*, *19,* 181-192. DOI: 10.1037/0894-4105.19.2.181

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society, 8,* 448-460. DOI: 10.1017.S1355617701020240

Stern, Y. (2009). Cognitive Reserve. *Neuropsychologia*, *47*, 2015-2028. DOI:10.1016/j.neuropsychologia.2009.03.004.

Stern, Y., Albert, S., Tang, M.X., and Tsai, W.Y. (1999). Rate of memory decline in AD is related to education and occupation: cognitive reserve? *Neurology, 53*, 1942–1947.

Stern, Y., Alexander, G.E., Prohovnik, I., Stricks, L., Link, B., and Lennon, M C. (1995). Relationship between lifetime occupation and parietal flow: implications for a reserve against Alzheimer's disease pathology. *Neurology*, *45,* 55-60.

Stern, Y., Gurland, B., Tatemichi, T.K., Tang, M.X., Wilder, D., & Mayeux, R. (1994). Influence of education and occupation on the incidence of Alzheimer's disease. *Journal of the American Medical Association*, *271,* 1004-1010. DOI:10.1001/jama.1994.03510370056032

Stern, Y., Tang, M.X., Denaro, J., Mayeux, R. (1995). Increased risk of mortality in Alzheimer's disease patients with more advanced educational and occupational attainment. *Annals of Neurology, 37,* 590-595. DOI: 10.1002/ana.410370508

Stroop, J.R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18,* 643–662. DOI: 10.1037/0096-3445.121.1.15

Strümer, B., Leuthold, H., Soetens, E., Schroter, H., and Sommer, W. (2002). Control over location-based response activation in the Simon task: behavioral and electrophysiological evidence. *J Exp Psychol Hum Percept Perform, 28*(6), 1345-1363.

Stuart-Hamilton, I. (1996). Intellectual changes in late life. In Woods, R. T. (Ed.) *Handbook of the clinical psychology of ageing.* Oxford, UK: Wiley.

Tipper, S. P., & Cranston, M. (1985). Selective attention and priming: Inhibitory and facilitatory effects of ignored primes. Quarterly Journal of Experimental Psychology A, 37(4), 591–611.

Tranter, L.J., and Koutstaal, W. (2008). Age and flexible thinking: an experimental demonstration of the beneficial effects of increased cognitively stimulating activity on fluid intelligence in healthy older adults. *Aging, neuropsychology, and cognition, 15,* 184–207.

Tucker-Drob, E. M., Johnson, K. E., Jones, R. N. (2009). The cognitive reserve hypothesis: A longitudinal examination of age-associated declines in reasoning and processing speed. *Developmental Psychology,* 45, 431-446. DOI: 10.1037/a0014012

Uttl, B., & Graf, P. (1997). Color-word Stroop test performance across the adult life span. *Journal of Clinical and Experimental Neuropsychology*, *19,* 405-420. DOI:10.1080/01688639708403869

Valenzuela, M.J., and Sachdev, P. (2006) Brain reserve and dementia: a systematic review. *Psychological Medicine*, *35*, 1–14.

Vallesi, A. (2011). Targets and non-targets in the aging brain: a go/nogo Event-related Potential study. *Neuroscience Letters*, *487,* 313-317. DOI:10.1016/j.neulet.2010.10.046

Vallesi, A., and Umiltà, C.A. (2009). Decay of stimulus spatial code in horizontal and vertical Simon tasks. *Journal of General Psychology, 136*(4), 1–24.

Vallesi, A., McIntosh, A.R., Stuss, D.T. (2009). Temporal preparation in aging: A functional MRI study. *Neuropsychologia*, *47,* 2876-2881. DOI:10.1016/j.neuropsychologia.2009.06.013

Vallesi, A., McIntosh, A.R., Stuss, D.T. (2011). Over-recruitment in the aging brain as a function of task demands: evidence for a compensatory view. *Journal of Cognitive Neuroscience, 23,* 801-815. DOI:10.1162/jocn.2010.21490

Vallesi, A., Stuss, D. T. (2010). Excessive sub-threshold motor preparation for non-target stimuli in normal aging. *NeuroImage*, *50,* 1251-1257. DOI:10.1016/j.neuroimage.2010.01.022

Vallesi, A., Stuss, D.T., McIntosh A.R., Picton, T.W. (2009). Age-related differences in processing irrelevant information: Evidence from event-related potentials. *Neuropsychologia*, *47,* 577-586.
DOI:10.1016/j.neuropsychologia.2008.10.018.

Van der Lubbe, R. H. I., and Verleger, R. (2002). Aging and the Simon task. *Psychophysiology, 39,* 100–110.

Van Ravenzwaaij, D., Brown, S., Wagenmakers E. (2011). An integrated perspective on the relation between response speed and intelligence. *Cognition*, *119,* 381-393. DOI:10.1016/j.cognition.2011.02.002

Verhaeghen, P. (2011). Aging and executive control: reports of a demise greatly exaggerated. *Current Directions in Psychological Science*, *20*(3), 174-180.

Verhaeghen, P., Cerella, J., Bopp, K.L., and Basak, C. (2005). Aging and varieties of cognitive control: A review of meta-analyses on resistance to

interference, coordination and task switching, and an experimental exploration of age-sensitivity in the newly identified process of focus switching. In: Engle RW, Sedek G, von Hecker U, McIntosh DM, editors. Cognitive Limitations in Aging and Psychopathology: Attention, Working Memory, and Executive Functions. Cambridge, UK: Cambridge University Press; 2005. Pp. 163-164.

Verhaeghen, P., Cerella, J.,Basak, C. (2006). Aging, Task Complexity, and Efficiency Modes: The Influence of Working Memory Involvement on Age Differences in Response Times for Verbal and Visuospatial Tasks. *Aging, Neuropsychology, and Cognition, 13,* 254-280. DOI:10.1080/138255890969267

Verhaeghen, P., De Meersman, L.D., (1998). Aging and the Stroop effect: a meta-analysis. *Psychology and Aging*, *13,* 120–126. DOI: 10.1037/0882-7974.13.1.120

Wechsler, D. (1944). The measurement of adult intelligence. Baltimore: Williams & Wilkins.

Wechsler, D. (1981). WAIS–R: Manual. New York: Psychological Corporation.

West, R. & Bell, M.A. (1997). Stroop color-word interference and electroencephalogram activation: Evidence for age-related decline in the anterior attention system. *Neuropsychology*, *11,* 421– 427. DOI: 10.1037/0894-4105.11.3.421

West, R., & Alain, C. (2000b). Effects of task context and fluctuations of attention on neural activity supporting performance of the Stroop task. *Brain research*, *873*(1), 102-111.

West, R., & Moore, K. (2005). Adjustments of cognitive control in younger and older adults. Cortex, 41(4), 570–581.

West, R., Alain, C. (2000a). Age-related decline in inhibitory control contributes to the increased stroop effect observed in older adults. *Psychophysiology, 37,* 179-189. DOI: 10.1017/S0048577200981460

West, R., Baylis, G.C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology and Aging*, *13,* 206-217. DOI: 10.1037/0882-7974.13.2.206

West, R., Moore, K. (2005). Adjustments of Cognitive Control in Younger and Older Adults. *Cortex*, *41,* 570-581. DOI:10.1016/S0010-9452(08)70197-7

West, R.L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120,* 272-292. DOI: 10.1037/0033-2909.120.2.272

Wilson, R.S., de Leon, C.F.M., Barnes, L.L., Schneider, J.A., Bienias, J.L., Evans, D.A., and Bennett, D.A. (2002) Participation in cognitively stimulating activities and risk of incident Alzheimer disease, *JAMA*, *287*, 742–748.

Wühr, P. (2005). Evidence for gating of direct response activation in the Simon task. *Psychonomic Bulletin and Review, 12*, 282-288.

Wühr, P., & Ansorge, U. (2005). Exploring trial-by-trial modulations of the Simon effect. Quarterly Journal of Experimental Psychology A, 58(4), 705–731.

Zeef, E. J., Sonke, C. J., Kok, A., Merel, B. M., Kenemans, J. L. (1996). Perceptual factors affecting age-related differences in focused attention: performance and psychophysiological analyses. *Psychophysiology*, *33,* 555–565. DOI: 10.1111/j.1469-8986.1996.tb02432.x

Zoccatelli, G., Beltramello, A., Alessandrini, F., Pizzini, F. B., & Tassinari, G. (2010). Word and position interference in Stroop tasks: a behavioral and fMRI study. *Experimental brain research*, *207*(1-2), 139-147. 10.1007/s00221-010-2433-x

Zysset, S., Muller, K., Lohmann, G., von Cramon, D. Y. (2001). Color-word matching stroop task: separating interference and response conflict. *Neuroimage, 13*, 29-36. DOI:10.1006/nimg.2000.0665.

Appendix

A comparison among Stroop task designs

As widely expressed in Chapter 2, we observed that considering two subsequent trials in a Stroop (or Stroop-like) task it is impossible to have complete alternation trials unless we don't use 4 levels of the features.

In Figure A1 we illustrate the comparison among a Stroop task that uses 3 targets and 3 distractors (3-AFC), a Stroop task that uses 3 targets and 4 distractors (3-AFC) and one that present 4 targets and 4 distractors (4-AFC).

We identified three types of trials according to their priming characterization: Repetition priming, NP-like and priming-free.

The pie graphs show the percentage of the three types of trial over the total of different stimuli allowed by each task design.

The histograms show the percentage in which the three types of trials compose the total number of each sequential congruency condition (with respect to the total amount of possible pairs of stimuli).

Clearly, in all the three design a random selection of stimuli would imply to have a strong majority of trials that present some kind of repetitions.

It is also important to notice that in 3 targets and 3 distractors task there are no priming free II sequences. Therefore even applying an *a posteriori* selection it is not possible to get a dataset that presents all the sequences without the priming confound. The 3 targets and 4 distractors and 4 targets and 4 distractors designs both permit to select a subset of trials that have all the four sequential conditions made of priming-free trials. However the 3 targets and 4 distractors design imply an imbalanced number of feature levels between target and distractor (3 vs 4), and moreover to have a odd number of response buttons, which carries the problem of which fingers or hand to use for giving the response.

Indeed the 4 targets and 4 distractors design result to be the simplest design that allows a proper conflict resolution free from priming confounds.

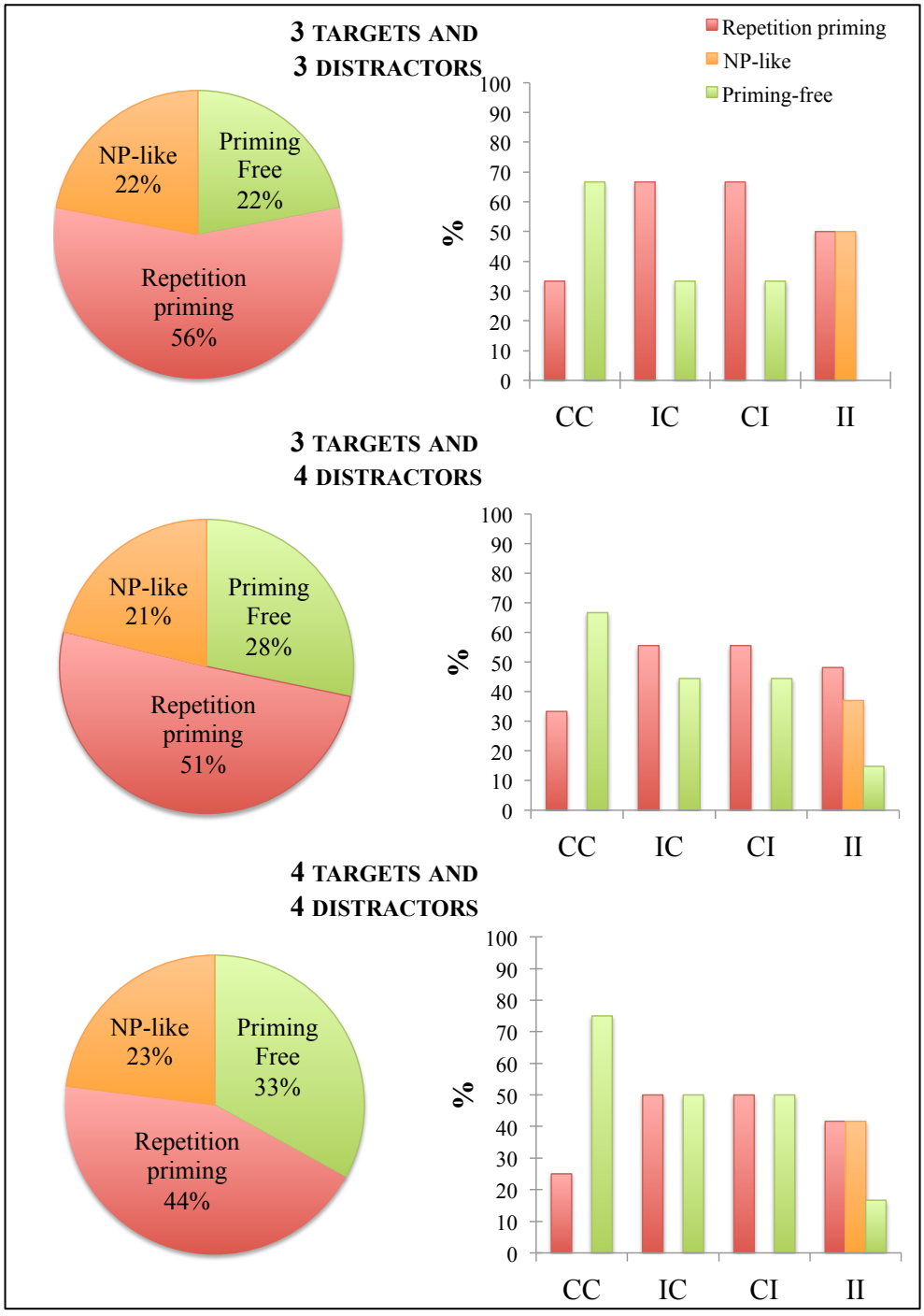
3 TARGETS AND
3 DISTRACTORS
NP-like
22%
Priming
Free
22%
Repetition
priming
56%
Repetition priming
NP-like
Priming-free
%
100
90
80
70
60
50
40
30
20
10
0
CC
IC
CI
II
3 TARGETS AND
4 DISTRACTORS
NP-like
21%
Priming
Free
28%
Repetition
priming
51%
4 TARGETS AND
4 DISTRACTORS
NP-like
23%
Priming
Free
33%
Repetition
priming
44%

Figure A1