Age-related changes in task switching: Effects of working memory on performance and electrical brain activity

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ABSTRACT

Philippe Goffaux

In our everyday lives, we are often confronted with having to do a number of different things at the same time. This makes doing any one thing much more difficult. This thesis examined how advancing age affects the ability to multitask (or task switch). It also examined how working memory affects age-related changes in task switching. To do this, both behavioural and electrophysiological brain responses were examined. It was found that compared to younger adults, older adults are slowed when responding in situations where a number of different tasks are presented in rapid succession. Consistent with our predictions, it was found that older adults with high working memory skills were preserved against this age-related change. This preserved ability (for older adults with high working memory) was accompanied by greater brain activity across prefrontal regions of the scalp (i.e., greater negative slow wave activity across left and right prefrontal leads). This is an important finding since the prefrontal cortex is deemed essential when actions have to be coordinated and planned. Greater prefrontal control was not found for younger adults, despite similarly fast reaction times. This suggests that older adults with high working memory recruit prefrontal control in order to compensate for the difficult task of switching between different response regimes. On the other hand, older adults with low working memory showed more posterior activity when preparing for a homogeneous target, suggesting that even when interference is absent, this group relied on external cues when preparing. Results are discussed in terms of recent task switching models.

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GENERAL INTRODUCTION

As we interact with the world that surrounds us, we are constantly performing behaviours that are guided in part by our surrounding environment and in part by our intention to act. In this way, we may decide to answer a ringing phone depending on our intention or desire to do so. Should we decide to answer the phone, a series of subgoals and subtasks are called upon to ensure efficient action. These subgoals and subtasks can be described at varying levels of abstraction. For example, we can consider answering the phone as series of sequential steps including: inhibition of the ongoing behaviour, walking to the phone, picking it up and saying "hello". These steps are called upon by the ringing phone and together make up a procedural response schema or task set. The way in which task sets are selected and executed is currently a matter of debate and has been the focus of a growing amount of research over the past decade. Of particular interest has been the investigation of task set selection under conditions which make it difficult to select the appropriate response. For example, it is becoming increasingly evident that task set selection is much more difficult when a stimulus evokes a competing response tendency or when multiple task sets are presented in a short period of time. The errors that follow under such conditions can sometimes lead to spectacular slips in action. Inspired by an anecdote involving the mathematician and Nobel Prize winner David Hilbert, Heckhausen and Beckmann (1990) describe how the simple act of removing one's tie can trigger an over-learned action schema which, if contextually inappropriate and left unchecked, can lead to undesired results:

> Shortly before the arrival of their dinner guests, Mrs. Hilbert noticed that her husband was not wearing a suitable

> tie. She sent him to the bedroom to change it. When she checked on him, because he failed to return, she found him in bed, undressed and fast asleep (pg.41).

As can be appreciated from this example, action schemas do not always facilitate the production of a desired behaviour. Since a given stimulus can trigger any number of alternative task sets, it becomes clear that intentional, executive control must sometimes be exercised to resist temptation or habit and ensure the accuracy of our actions.

In cognitive psychology, Norman and Shallice's (1986) Attention-to-Action (ATA) model is frequently cited as a useful framework from which to understand the role played by endogenous executive systems. According to this model, environmental stimuli can, in and of themselves, come to evoke specialized schemas or task-sets, which correspond to a desired or contextually appropriate response. This stimulus-evoked or bottom-up system accounts for the rapid production of purposeful behaviour in situations where environmental cues do not evoke competing responses. However, under conditions where response competition or uncertainty occurs, more than one response may be considered appropriate. To resolve this ambiguity and ensure the selection of a single appropriate response, an actively engaged and time consuming supervisory system is required. The ATA model posits that when environmental demands call-up more than one relevant response (as when multitasking) or when the context is novel or ambiguous, a supervisory system is needed to guide the appropriate selection of behaviour.

Depending on the environmental context that prevails, the use of executive control during task set selection may be a necessary ingredient. Slips of action that occur when the context is demanding may stem from failures in executive control. Failures in executive control may also explain the abnormal behavioural performance observed among frontal-lobe patients (Bechara & Van Der Linden, 2005) and elderly adults (Kramer et al., 1999; Rabbitt et al., 2001; Salthouse et al., 1998; Verhaeghen and Basak, 2005). To investigate the nature and timing of the processes engaged when reconfiguring the mind for a new task set, it is necessary to examine both the behavioural and brain correlates of performance. Unique populations, such as older adults also offer an opportunity to explore how changes in brain function predict age-impaired and age-invariant performance.

In the sections that follow, a review of the most pertinent studies on attentional control and task switching is first provided. This is followed by a review of the neural correlates underlying task set selection. Task switching performance is then discussed in the context of aging, focusing on the different theories advanced to explain the pattern of results often observed with advancing age. Particular attention is also given to recent age-related neuroimaging findings. An overview of the current experiments is then provided.

Task Set Switching: Paradigms, Costs and Controversies

In task switching experiments, participants are asked to attend to a target stimulus and respond to it according to a given set of instructions or rules. These instructions make up the task set while the associated behaviour makes up the response set. An example of this includes classifying a number as a function of its parity (odd or even) and selecting the appropriate response from a response pad. In this example, classifying along the parity dimension represents the task set and selecting the appropriate action to take (left button press if the number is odd, right button press if even) represents the response set. In task switching designs, most stimuli are also classified along a second (and sometimes third or fourth) dimension. So, in addition to classifying a number as a function of its parity, one could also be asked to classify this same number as a function of its relative ordinal value (for example, > or < 5) and to select the appropriate action (left button if < 5 and right button if > 5). The specific processing demands that are associated with any given stimulus can be learned ahead of time (always respond to the stimulus' parity) or it can be cued online (wait for the cue before the appropriate classification scheme can be selected). In either case, task switching designs always include trials where the task set repeats and trials where the task set switches. This allows for the logical comparison between repeat and switch trials and typically reveals larger response times and smaller accuracy scores on switch as opposed to repeat trials. This performance deficit or cost gives an index of the extra processing demands that are associated with having to reconfigure for a new task set on switch trials. In other words, reconfiguring the mind as one alternates between different task and response sets constitutes the predominant challenge in task switching designs.

Developed by Jersild in 1927, one of the earliest task switching experiments required that participants alternate rapidly between two reaction-time tasks (adding 3 to or subtracting 3 from numbers) in a single block of switch trials. Performance on this block of switch trials was then compared to the performance on a block of trials where only one task was presented (adding 3 for example). Jersild's results confirmed that performance suffered when participants had to perform within a mixed-task context. Unfortunately, the reaction time (RT) difference obtained when comparing performance in a block of repeat trials (a homogeneous block) to performance in a block of switch trials (a heterogeneous block) could not be exclusively tied to the cognitive control processes underlying the need to reconfigure. Important state differences including fatigue, motivation, and arousal could conceivably explain RT differences between homogeneous and heterogeneous blocks. In order to control for this, Rogers and Monsell (1995), as well as others, (Allport et al., 1994; Meiran, 1996; Meiran et al., 2000) compared repeat and switch trials when these occurred within the same block of mixed trials, thus minimizing block-related differences. They labeled this difference the *local switch cost*. The task switching paradigm designed by Rogers and Monsell (1995) consisted of a predictable sequence of repeat and switch trials arranged in a 2X2 presentation matrix which they called the alternate runs paradigm. During each block, runs of two successive trials of a given task alternated with runs of two successive trials of a different task. The first task required that, in a compound stimulus consisting of a letter and a number, the letter be classified as a consonant or a vowel while the second task required that the number be classified as odd or even. The same left versus right button press was used to distinguish between consonants and vowels and between even and odd numbers. Rogers and Monsell (1995) report the results of a number of different experiments, however, two of their findings had a particularly important impact in helping to understand how task sets are reconfigured. First, they showed that the ambiguity of the target stimulus had a large influence on the size of the local switch cost. During their alternate runs paradigm, each trial consisted of two characters, one relevant to the current task and one irrelevant. The irrelevant character was drawn either from the ensemble of characters of the non-current task or from a set of neutral characters (irrelevant to both task sets). Irrelevant characters that were drawn from the ensemble of characters of the non-current task either corresponded to keypresses that were correct (congruent) or incorrect (incongruent) for the current task. Their results showed that the presence of incongruent irrelevant characters induced the largest local switch cost, but that a local switch cost remained even when a neutral irrelevant character was presented. This suggests that interference at the stimulus identification level hinders performance but that even if the switch character is unambiguous the mere act of switching is sufficient to induce a local switch cost. It is important to point out that even when the switch stimulus was unambiguous, the same left versus right button press continued to be used in order to distinguish between consonants and vowels and between even and odd numbers. This continued ambiguity at the response level is also thought to be an essential feature of the local switch cost (Meiran 2000).

The second key finding reported by Rogers and Monsell (1995) was that prolonging the time period between the previous response and the current stimulus significantly reduced the local switch cost. In other words, when participants were given more time to prepare they improved their ability to reconfigure for a new task set. Unfortunately, improvements in performance leveled-off beyond 600 ms of preparation and a local switch cost remained. They labeled this remaining local switch cost the *residual switch cost.* On the basis of these results, Rogers and Monsell concluded that task set reconfiguration is completed in a two step process where at least part of the reconfiguration process can be accomplished under endogenous control, before stimulus onset. However, the remaining part of the reconfiguration process cannot be completed until exogenously triggered by stimulus attributes that are associated with the task. In a series of detailed experiments, Rubenstein, Meyer, and Evans (2001) showed that this target-triggered step was characterized by the executive retrieval of stimulus-response rules within working memory.

Assuming that more complex task rules are more difficult to engage within working memory, Rubenstein et al. (2001) predicted larger local switch costs for tasks that were associated with complex, as opposed to simple classification rules. The design involved classifying stimulus cards so that the shape, size, shading, and numerosity of geometric objects on them matched those of objects on corresponding target cards. This is similar to the task rules of the Wisconsin Card Sorting Test (WCST). Unlike the WCST, however, subjects knew when to switch from one task to the next. Importantly, Rubenstein et al. (2001) manipulated rule complexity such that in the low-complexity condition, cards had to be sorted along a single perceptual dimension (e.g., shape) while in the high-complexity condition cards had to be sorted along two perceptual dimensions (e.g., shape and numerosity). Consistent with their predictions, larger local switch costs were obtained for tasks that involved more complex rules.

The studies reviewed above suggest that the local switch cost reflects the extra time consumed by executive control functions engaged in anticipation of and during target presentation. However, instead of interpreting the local switch cost as an index of the control processes engaged when reconfiguring the mind, some authors have argued that the local switch cost is best explained as a proactive, interference phenomenon. Championed by Alan Allport (Allport, Styles & Hsieh, 1994; Allport & Wylie, 1999; Wylie & Allport, 2000), this interpretation essentially argues that the stimulus-response associations of the previous and now irrelevant task set are carried over to the new task set and interfere with performance. This account of the switch cost reflects *task priming* effects that are most apparent during target presentation and has been labeled the *task-set inertia* hypothesis. Anticipatory processes are effectively irrelevant in this model. Evidence in favour of the task set inertia model should show that the carry-over effects underlying task priming enhance the local switch cost. Three observations in support of task set inertia will now be described.

First, if task priming effects interfere with switch trial performance, then some form of inhibition must be applied to the previous task set in order to disengage from it and minimize interference on the switch trial. If this is true, then returning to this now inhibited task set should be more difficult. This means that responses should be slower on the last trial of the task sequence ABA than on the last trial of the task sequence CBA, where each letter represents a distinct task set. Slower performance on trials that have been recently abandoned is indeed observed, presumably because it takes more time to reactivate a recently inhibited task set (Arbuthnott & Frank, 2000a; Mayr, 2002; Mayr & Keele, 2000).

Second, proactive interference, and the inhibitory processes engaged to deal with it, interact with task difficulty to produce results that are hard to explain in terms of the duration of task set reconfiguration. For example, when one switches from a non-dominant to a dominant task, larger switch costs are observed (Allport, Styles & Hsieh, 1994). This is difficult for the endogenous activation model to explain, since it would predict that a dominant task set will take less (not more) time to reconfigure. A task set priming model, however, elegantly explains this observation. The paradoxical asymmetry of switch costs observed when switching between tasks of unequal strength was originally tested using Stroop stimuli. It has been known for quite a while now that incongruence between the ink colour in which a word is printed and the colour name it spells out interferes much more with ink naming than word reading (Stroop, 1935). For example, when the word "red" is spelled in green ink, it is much easier to read the word than it is to name the green ink colour. This asymmetry is attributed to the much stronger and more practiced word reading tendency and to the interference it provides during ink naming. The surprising increase in local switch cost size observed when switching from the non-dominant (ink naming) to the dominant (word reading) task set can be explained by the extra inhibition applied to the dominant task when switching to the less dominant task set. This extra inhibition needs to be overcome when the dominant task set is presented again and, therefore, slows down performance (Allport, Styles & Hsieh, 1994; Allport & Wylie, 1999). Inequality in the switch cost is explained, therefore, by an inequality in the response biases required when switching between task sets of unequal strength.

Problems with this account have been voiced and subsequent work has shown that the surprising asymmetry of switch costs can be reversed (Monsell, Yeung & Azuma, 2000; Yeung & Monell, 2003). Results showing a larger switch cost when switching to the dominant task are certainly valid, but this observation may be limited to special cases where there is an extreme inequality in the strength of stimulus-response pairings. Differences in task set difficulty that do not confound differences in the strength of the stimulus-response association should show results that are compatible with the endogenous activation model. If we take the Stroop task as an example, there is no reason to think that, in general, it is more difficult to name a colour than it is to read a word. The difficulty arises when the stimuli used for word reading and colour naming are exclusively words. In this case, the stimuli (i.e. words) are strongly associated to the reading response not the ink naming response. In this context, differences between word reading and ink naming are not tied to task difficulty *per se* but to differences in the strength of the stimulus-response association. When differences in stimulus-response associations are absent, the switch cost is indeed larger when switching to the less dominant task (Rubenstein et al., 2001; Yeung & Monell, 2003).

Finally, if task priming effects exist, then the carry-over effects of task set activation should dissipate with longer delays. In a direct test of this assumption, Meiran, Chorev and Sapir (2000) showed that, with preparation time kept constant, the local switch cost is reduced when the delay between task sets is prolonged. Meiran et al. (2000) used an externally cued task switching design and manipulated the time period between the response to the previous task and presentation of the next task's cue (the response-cue interval, RCI). All the while, the time period between the cue and the next target stimulus (the cue-target interval, CTI) was kept constant. Prolonging the RCI while keeping the CTI constant resulted in a reduced switch cost. The authors attributed this reduction to the greater time allotted for passive decay of the interference from the previous task. This finding suggests that a passive task-set dissipation is at play when reconfiguring for a new task. However, Meiran et al. (2000) showed that anticipatory preparation also plays a key role. This time, Meiran et al. (2000) kept the RCI constant and manipulated the length of the CTI. Prolonging the CTI while keeping the RCI constant also reduced the switch cost. It is important to acknowledge, then, that the local switch cost probably reflects both task priming effects and the time taken to prepare for the next task set; a point which is increasingly being acknowledged in the literature (Monsell, Yeung & Azuma, 2000; Sohn & Anderson, 2001; Wyllie, Javitt & Foxe, 2003).

The endogenous activation model and the task set inertia model offer potentially complementary explanations of the switch cost, however, alternative accounts have been advanced. For example, De Jong (2000) proposes that task set reconfiguration need not depend on both an endogenous and an exogenous target-triggered process. Instead, he argues that task set reconfiguration can be entirely completed in advance of the switch trial given sufficient time to prepare. According to De Jong's model, complete advanced reconfiguration is accomplished only on a proportion of switch trials, which explains why the switch cost can never be completely eliminated. Task set reconfiguration, therefore, would proceed in a probabilistic, all-or-none fashion rather than in a progressive, absolute manner.

A second alternative account of the local switch cost has recently been proposed by Logan and Bundesen (2003) in which the reaction time difference between repeat and switch trials has nothing to do with task set reconfiguration. The authors suggest that much of the local switch cost in cued paradigms actually comes from cue priming, not cued preparation. Their results show that changing the cue when repeating the same task reduced reaction time almost as much as a changing the task set itself. According to them, task switching does not actually require a switch between task sets. Rather, task switching costs are driven by a change in the cue, where the cue is used to disambiguate the relevant task from among all simultaneously held and activated task sets.

Finally, some authors have argued that the local switch cost itself is an incomplete index of cognitive control and that it does not adequately capture the entire set of processing constraints at play during task switching situations (Kray & Lindenberger, 2000; Mayr, 2001; Meiran, Gotler & Perlman, 2001). Evidence for this stems from the single versus mixed task block comparisons originally proposed by Jersild in 1927. When performance in a single-task block is compared to the performance in a mixed task block, a large difference in performance is observed, even, as it turns out, on trials that do not switch (see Meiran, Gotler & Perlman, 2001). This means that mixed task blocks include processing constraints that are not directly tied to the reconfiguration process. The increase in reaction time that is observed when comparing mixed and single task blocks is known as the *general switch cost*, whereas the increase in reaction time that is observed when specifically comparing repeat trials in mixed task blocks and single task blocks is known as the *mixing cost*. Both reflect conceptually similar costs, but the mixing cost is purer measure since it is uncontaminated by the increased reaction time associated with switch trial performance.

Since mixed task blocks require that multiple, competing task sets be maintained and co-ordinated, a large part of the mixing cost is thought to come from the extra demands placed upon working memory (Kray, Li & Lindenberger, 2002; Kray & Lindenberger, 2000). Competing stimulus-response associations are also believed to interfere with performance during target presentation, even on the repeat trials of mixed-task blocks (Los, 1999). Variables of interest in task switching research should include, therefore, the cost that arises during actual switch points and the cost associated with having to maintain and co-ordinate multiple task sets.

Brain Correlates of Task Switching

The use of task switching paradigms to decompose purposeful action into a combination of simpler cognitive functions has proven very useful in understanding when and to what extent endogenous control can be used to facilitate performance. However, decomposing purposeful action does not help address the way in which distinct ognitive processes are actually implemented neurally. In an attempt to explore this, recent neuroimaging studies have used functional scans to identify the brain activity underlying task set reconfiguration. The results of these studies show that when switching from one task to another the frontal cortex, the inferior frontal junction, the fronto-median cortex, the cingulate cortex and the parietal cortex are activated (Brass & von Cramon, 2002; Braver et al., 2003; Dove et al., 2000; Dreher et al., 2002; Gruber et al., 2006; Kimberg et al., 2000; MacDonald et al., 2000; Sohn et al., 2000). Regrettably, greater activation on switch as opposed to repeat trials does not allow us to appreciate the specific control process indexed by this greater activation. The extra activation observed on switch trials may be related to any number of control functions, including endogenous preparation, target-triggered activation, inhibition/disinhibition, conflict resolution, activation of working memory functions, activation of response rules or attending to specific target features. We are still far from being able to determine the specific functional role played by the different cortical regions active when performing a switch in task demand but research in this area is progressing rapidly. In this manner, recent studies have begun to isolate the specific neural activity underlying advanced preparation. In one of the first investigations on this issue, Sohn, Ursu, Stenger and Carter (2000) used an event-related fMRI study in which healthy young subjects were presented with a pair of tasks on every trial. Within each pair, subjects either repeated the same task or switched to a new task. Importantly, the authors manipulated foreknowledge such that subjects either knew or did not know ahead of time that the second task in a pair would repeat. In the latter situation, subjects had to wait until the target stimulus appeared to know which task to perform. Trials on which foreknowledge was provided were presented in blocks separate from trials on which no foreknowledge was provided. This design allowed the authors to compare repeat and switch trials and also allowed them to see how advanced preparation affects performance. Their results showed that advanced preparation (i.e., foreknowledge) improved RT for repeat and switch trials but that despite this, repeat trials remained faster than switch trials. Additionally, they found greater activity in the lateral prefrontal cortex and the superior parietal cortex when preparation was possible. However, only activation increases in the lateral prefrontal cortex predicted faster reaction times and only for switch trials. The authors conclude that the lateral prefrontal cortex plays a critical role in enabling advanced task set reconfiguration.

Unfortunately, Sohn et al. (2000) separated preparation-related activity from target-related activity by prolonging the preparation interval by as much as six seconds. Such a long delay might have triggered rehearsal processes not directly tied to the switching process. Using a different approach, Brass and von Cramon (2004) were able to isolate task set preparation from task execution without confounding memory (rehearsal) processes. They used a cued task switching paradigm for which the cue-target length was only 1200 ms. Importantly, they also included some trials where a cue but no target was presented (i.e., cue-only trials) and trials where the cue occurred simultaneously with the target (i.e., no-cue trials). By comparing cue-target trials and no-cue trials, the authors were able to isolate preparation related activity without having to use a long cue-target interval. On the other hand, comparing cue-target trials and cue-only trials revealed the cortical areas related to target processing and response execution. Their results showed that advanced task set preparation is strongly associated with inferior frontal junction and intraparietal sulcus activity whereas target specific processing is associated with pre-motor, primary motor and anterior cingulate cortex activity.

Together, the findings of Sohn et al. (2000) and Brass and von Cramon (2004) showed that the prefrontal and the parietal cortex are involved in task preparation. However, these findings are still based upon relatively slow hemodynamic changes (at best 1 second of temporal resolution) and, in spite of Brass and von Cramon's (2004) efforts, fMRI studies continue to provide a considerable degree of overlap between different event-related processes. Results derived from hemodynamic changes are not ideal when the goal is to capture the processes which underlie rapid variations in cognitive control. The tool of choice should have an excellent temporal resolution. By using electrophysiological recordings this objective can be met. In humans, non-invasive electroencephalographic recordings are used to track the subsecond timecourse and distribution of various cognitive control functions. When time-locked to the presentation of a specific event, electroencephalographic recordings produce an event-related brain potential (or ERP) which reflects the net electrical activity induced by the event. ERP differences in voltage strength, scalp distribution and timecourse are then used to reflect changes between different events. When applied to a task switching design, ERPs can be used to distinguish between cue- and target-triggered activities and between switch and repeat trials. The advantage of using ERPs is, of course, their excellent temporal resolution. However, ERPs also have a larger signal to noise ratio than the BOLD fMRI signal (Luck, 2005), which means that ERPs are much more sensitive to subtle changes in attention and cognitive control. In addition, ERPs measure the actual activity of neurons, unlike PET and fMRI scans which record changes in sugar or oxygen consumption (concentration) and have to assume that neuronal activity and haemodynamics are linked. Given the dependence of PET and fMRI signals on haemodynamic activity, they are also affected by differences in vasculature, blood flow, and blood volume. This means that strong inferences regarding neuronal activity should be tempered. Even though ERPs do not suffer from these limitations, they are limited in their ability to specify the exact neural sources responsible for cognitive control. This is because ERPs are recorded at the surface of the scalp, a certain distance away from the population of neurons which generated the electrical field. Notwithstanding this limitation, ERPs provide an excellent method for testing the inferences made by behavioural studies, especially with respect to the chronometric properties of task set reconfiguration.

Recently, a number of studies have used ERPs to look at performance changes in task switching and have shown specific activity differences between repeat and switch trials in both the pre-target and target-locked epochs (e.g., Barcelo, 2003; Brass et al., 2005; Hsieh & Chen, 2006; Hsieh & Yu, 2003; Karayanidis et al., 2003; Kieffaber & Hetrick, 2005; Lorist et al., 2000; Nicholson et al., 2005; Poulsen et al., 2005; Rushworth et al., 2002; Sinai & Phillips, 2002; Swainson et al., 2006; Wylie et al., 2003). More specifically, these studies show that when having to switch rapidly between alternating task sets, pre-target processes produce a large negative slow wave, distributed over posterior scalp regions. Importantly, larger negative slow waves are observed prior to repeat trials than prior to switch trials, which suggest a processing difference between these two trial types. Negative slow waves, or stimulus preceding negativities (SPNs), typically develop between two task relevant stimuli where the first one conveys information that facilitates preparation for a second, imperative stimulus (Brunia & van Boxtel, 2001). Consequently, larger posterior negativities on repeat as opposed to switch trials suggest differences in the ability to anticipate and prepare for an impending target stimulus. In an attempt to better understand the functional significance of the repeat versus switch negativity difference, Karayanidis et al. (2003) manipulated the degree of preparation time available in advance of the target. Their results show that when more time for advanced preparation is given, the amplitude of the repeat versus switch posterior negativity difference is resolved prior to target presentation. This is accompanied by a reduced RT local switch cost. Their data supports the idea that posterior negative slow wave differences between repeat and switch trials reflect differences in endogenous task preparation. It is important to point out, however, that some task switching studies also show repeat versus switch differences in prefrontal cortex activity. This is precisely the case of a recent task switching study conducted by Brass et al. (2005). The authors discovered that prefrontal cortex activity precedes posterior negativity differences between repeat and switch trials. Using dipole modeling of their cue-locked ERP waveforms in combination with fMRI results, Brass et al. (2005) found that posterior negative slow wave activity differences between repeat and switch trials follow activity differences in the prefrontal cortex. Specifically, the ERP findings reveal that prior to the beginning of negative slow wave activity, switch trials showed a negative going-deflection peaking 470 ms after cue onset. Dipole modeling indicates that the early parts of this negative deflection resulted from left and right inferior frontal activity while the later part resulted from right intraparietal sulcus activity. The results of this study indicate that prefrontal cortex activity precedes parietal cortex activity during endogenous preparation. Regarding this temporal order of activation, it has been proposed that parietal regions receive biasing signals from the prefrontal cortex; a process which is thought to be involved in isolating a relevant task goal from among multiple candidate goals (Tomita et al., 1999). Based on these results, it is interesting to note that posterior negative waveforms recorded in ERP studies are sometimes accompanied by a negative shift in the cue-locked activity recorded over frontal regions (Lorist et al., 2000; Poulsen et al., 2005; Poulsen et al., 2001). More precisely, greater negativities are recorded in anticipation of switch trials than in anticipation of repeat trials. Recently, Falkenstein et al. (2003) showed that frontal negative slow waves develop only during effortful performance. In their study, Falkenstein et al. (2003) had participants respond to one of four letters by pressing the appropriate key on a keypad. Their design also included a cue, presented 1200 ms ahead of the target letter. Importantly, on some trials, the cue called for the investment of extra effort (i.e., it changed colours indicating that participants had to try and respond especially fast). The authors found that on extra effort trials, large negative slow waves developed across frontal regions of the scalp (Fz & FCz). Falkenstein et al. (2003) interpreted this change as evidence of greater resource allocation and better executive control over the assignment of control functions used to perform their task. This interpretation of frontal activity is very similar to the one advanced by Tomita et al. (1999) and again suggests that frontal regions of the cortex help regulate (enhance or fine tune) the activity of other regions involved in task execution.

The stream of neuronal activity described above suggests that when preparing for an impending switch target, a fronto-parietal circuit is activated. This activity precedes target evaluation and, according to Rogers and Monsell's two-step model, is indicative of endogenously driven control processes. However, once the target stimulus appears, a late positive deflection or P3b wave is typically observed across parietal scalp regions. Previous ERP studies on task switching indicate that this activity is larger for repeat targets than for switch targets (Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2005; Sinai & Phillips, 2002; Wylie et al., 2003). The nature of the functional significance of the P3b waveform is debated, with theories ranging form the contextual updating of task relevant information in working memory to the resolution of stimulus-response competition. Despite this, there is general agreement that the P3 is an index of memory access (Kok, 2001). In this way, larger positivities on repeat as opposed to switch trials may suggest that attentional networks and working memory resources are more easily accessible on repeat than on switch trials. In this thesis, a direct comparison between repeat, switch, and homogeneous trials will be carried out. Comparing these three different trial types within the same study has never been done.

Age Effects on Task Switching: Adjustments in Cognitive Control

As we grow older, changes in cognitive control often begin to appear. This is typically observed as an over-proportional deficit in response speed and response accuracy on tasks where information needs to be coordinated or protected from interference (Kramer et al., 1999). Senescence, therefore, seems to affect executive control (even when psychomotor slowing has been accounted for). Atrophy and metabolic change in frontal regions of the cortex also accompany these age-related differences and are in keeping with the frontal lobe hypothesis of cognitive aging (West, 1996). This hypothesis specifies that, of all the regions of the cortex, the frontal lobe is the most vulnerable to neurobiological aging which explains why older adults have greater deficits on tasks that involve executive control (Verhaeghen & Cerella, 2002). Unfortunately describing age-related deficits in terms of executive loss provides only a general and undifferentiated account of cognitive aging. Simply referring to a loss in executive control is far from sufficient if the goal is to better understand how adjustments in cognitive functioning vary with advancing age. The vagueness of the construct does, however, provide a strong incentive for the development of more precise accounts of cognitive aging. Recently, data from work on the task switching paradigm has provided promising new insights on the possible nature of age-related deficits and on the dynamic control of behaviour. In the sections that follow, a review of the most pertinent findings on age differences in task switching is given. Since cognitive aging is predominantly a biological process, a preference will be given to studies that also discuss the neural basis of task switching and aging.

Effect of Aging on Task Switching: Behavioural and Neural Markers

An important question in the context of aging and task switching concerns the degree to which advancing age affects performance during set-selection situations. In one of the earliest investigations of aging and task switching performance, Kray and Lindenberger (2000) compared the performance of 118 adults ranging from 20 to 80 years of age. The authors used an alternate runs design where participants had to switch task every two trials without the aid of an external task cue. This was compared to the performance on a single task block where only one task was ever possible. A few key findings should be noted. First, a general switch cost and a local switch cost were differentiated into two related but distinct factors. Second, older adults (61-80 years old) had larger RT general switch costs than younger adults (20-40 years old) but equal RT local switch costs. Finally, structural equation modelling showed that better working memory capacity predicted smaller local switch costs (r=-.22) but not smaller general switch costs (r=-.01) for the young whereas it predicted smaller local switch costs (r=-.27) and smaller general switch costs for the old (r=-.27). These results suggests that older adults have a difficult time when performing in a situation where more than one task set is relevant and that working memory may be an important predictor. Similar conclusions have also been reported by Mayr (2001), Meiran et al. (2001) and Kray et al. (2004). It is possible that aging impairs the organization of cognitive processes within working memory, which leads to larger performance deficits when older adults have to perform in mixed-task blocks. This interpretation is consistent with a large body of literature showing that working memory capacity declines with advancing age (see Craik & Jennings, 1992).

In cognitive psychology, working memory is a theoretical framework that defines the processes used for the short-term storage and manipulation of information. Its origins can be traced back to the early 1960's when the prevailing ideology was to link cognitive processes to computer models. In 1974, Baddley and Hitch introduced the first multi-component model of working memory. Their model essentially contained maintenance subsystems (the articulatory loop for verbal information and the visuo-spatial sketchpad for visual and spatial information) and a central executive system. The latter was described as being responsible for directing attention and for co-ordinating the cognitive processes that must be applied to the information held in temporary storage. Together, storage and executive subsystems are thought to comprise an integrated whole called working memory. Neuroimaging studies that have focused on working memory reveal that the dorsolateral prefrontal cortex becomes active when information must be retrieved or manipulated whereas the ventrolateral prefrontal cortex becomes active when information must be maintained for a short period of time (see Rajah & D'Esposito, 2005 for a review). Given reports that older adults seem to have a particularly difficult time manipulating information in working memory (Craik & Jennings, 1992), neuroimaging studies of working memory should reveal large age-related changes in the dorsolateral but not the ventrolateral prefrontal cortex. Interestingly there is evidence to support this claim. Recently, Rypma and D'Esposito (2000) showed that, compared to younger adult older adults have less activity in the dorsolateral prefrontal cortex region of the brain during working memory retrieval. Importantly, this reduced activity for older adults was associated with reduced retrieval success. On the other hand, during working memory maintenance, older and younger adults showed similar levels of activation across the ventrolateral prefrontal region of the brain.

In the section that follows a review of the theories often advanced to explain age-related changes in mixed task performance is given. As we shall see, these theories can be understood in terms of an age-related change in working memory capacity (either because of a change in working memory maintenance or because of a change in working memory retrieval). At this stage, it is important to keep in mind that a combination of the elements proposed by each theory is certainly possible when explaining why the general switch cost increases during old age.

The first and most often cited hypothesis suggests that declining working memory capacities (especially declining retrieval functions) affect the general switch cost because it forces older adults to adopt a more conservative task set bias during mixed-task blocks. In other words, since switching is difficult, older adults may prefer to stay switch-ready at all times. Therefore, unlike younger adults, older adults may engage in task set reconfiguration for every trial (as a sort of default operating mode), despite the fact that task sets may actually repeat on occasion (Mayr, 2001; De Jong, 2001). The result is that older adults are primed for switching but unlikely to profit from repetition, which leads to an enhanced RT on repeat trials. When the mixing cost contrast is computed, larger cost scores are obtained for older adults. Evidence that age-related changes have a strategic origin is very difficult to provide. Nevertheless, De Jong (2001) recently showed that the larger mixing costs of older adults may have a strategic basis. De Jong used a time-band procedure (Wickelgren, 1977) which forced his older adults to respond very quickly, within a narrow time band. The goal of this procedure was to force older adults to drop any possible conservative response strategy. In his experiments, De Jong forced his older adults to respond within the same narrow time period for both mixed and single task blocks, thus equating response speed across blocks. The variable of interest in this design was response accuracy. De Jong's results showed that under conditions where only a narrow response window is allowed, older adults have the same response accuracy rate during single and mixed-task blocks. In other words, the large RT mixing cost usually seen among older adults was not transformed into large accuracy mixing costs by the time band procedure, which would have been expected if the processing capacity of older adults were somehow compromised. The results were interpreted by De Jong as evidence that much of the age-related increase in RT mixing cost stems from the adoption of conservative response strategies, strategies that are forcibly dropped by using time-band testing procedures.

The conservative strategy hypothesis supposes that much of the age-related mixing cost comes from older adult's unnecessary use of task updating strategies, even on repeat trials. Although this interpretation is appealing, there is some evidence to suggest that younger adults also adopt conservative response strategies in mixed-task blocks and that this also affects their repeat RT performance. For example, Monsell et al. (2003) recently tested younger adults and showed that under randomly alternating conditions, the cost of switching was found even on the second and third repeat trial after a switch. In other words, response speeds continued to be slow and only reached levels that were comparable to those found in single-task blocks after four repeat trials. This pattern of results was not found when switching was fully predictable (i.e., using an alternate runs design). When switching was predictable, the cost of switching occurred only on the first repeat trial after a switch. Monsell et al. (2003) argued that the use of retrieval processes on repeat trials is modulated by expectations regarding the probability of a further task switch. This means that, in randomly alternating mixed-task blocks, it may be useful to stay switch-ready simply because a switch trial is likely to occur at any moment[1]. So if younger adults also adopt conservative response strategies, especially under randomly alternating mixed-task conditions, what might account for the age-difference in mixing cost RT? One possibility is that younger adults are simply better than older adults at retrieving task sets, whether it is for repeat or switch trials. This would be consistent with the working memory retrieval data reviewed above (see Rypma and D'Esposito, 2000). A second possibility is that older adults may simply have a difficult time maintaining the active representation of an already loaded task set (West 1999; West, 2004; Kray et al., 2005). If task set representations quickly fall out of focus for older adults, then mixed-task situations where the cue disappears well before the target appears should be particularly problematic. In a direct investigation of this assumption, West (2004) and Kray et al. (2005) tested younger and older adults in a dual task context where each cue-target pair was separated by a blank screen for at least 1000ms. Both investigators used Stroop stimuli to test for age differences in task switching and both found significantly larger mixing cost RTs for older adults than for younger adults. This means that, older adults responded more slowly than younger adults in situations where they had to alternate between colour naming and word reading and where the cue was not always present. West (2004) and Kray et al. (2005) also recorded the ERP responses of their participants and found that during mixed-task blocks, but not single-task blocks, older adults showed large cue-locked negative slow wave activity across frontal leads.

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[1] Probability effects were thought to be driven by changes in the predictability of the switching sequence (i.e., the difference between predictable and random switching designs). However, in Monsell et al.'s (2003) experiment, there were twice as many switch trials in the random switching paradigm than in the predictable switching paradigm. It is conceivable that a greater probability of switch trials in the random switching paradigm also explained why conservative response strategies were adopted in the random switching paradigm. It is likely, therefore, that both predictability and probability effects contributed to the adoption of switch-ready strategies in Monsell et al.'s (2003) study.

Younger adults did not show this pattern of activity. Since the cue disappeared well before the target appeared, both investigators interpreted this effect as evidence of an age-related difficulty in the ability to maintain task context over time. According to the authors, the greater frontal activity of older adults simply reflected the greater control that they had to exert in order to deal with task maintenance difficulties. Unfortunately, the results described by West (2004) and Kray et al. (2005) cannot rule out the possibility that age-related differences in task set retrieval functions are also present and may also explain part of the age-related increase in mixing cost RT. This is because they did not also test for age differences by using a design where the cue remained on screen for the entire cue-target interval. If the larger general switch cost of older adults is indeed the result of a change in their ability to retrieve context information but not the result of a change in their ability to maintain this information, then performance in mixed task blocks should suffer even if the cue (i.e. context information) remains present during the entire preparatory period.

Interestingly, there is some evidence in favour of this explanation. Both Mayr (2001) and Meiran et al. (2001) used a cued, randomly alternating task switching design where the cue was present during the entire cue-target interval and both found a larger general (or mixing) cost for older adults than for younger adults. Since the task cue was always present, their results could not have reflected a deficit in the ability of older adults to maintain task set representations over time. More likely, their results are consistent with the idea that older adults have a difficult time retrieving task set information. Unfortunately, neither study explored how age-related changes in working memory might affect this process or which brain region might be responsible for mediating it. Given the available data on age-related changes in working memory (i.e., poorer working memory retrieval for older adults and reduced dorsolateral prefrontal cortex activity during retrieval), one might expect that older adults should have a difficult time with retrieval functions and that, as a consequence, performance in mixed-task blocks should suffer. This should be particularly evident for older adults with poor working memory skills and should be accompanied by reduced patterns of activity across frontal regions of the cortex.

Although the link between age, working memory capacity and task switching performance has not been investigated much (however see Kray & Lindenberger, 2000), some authors, using different paradigms, confirm that advancing age predominantly affects memory retrieval (Daselaar et al., 2006; Grady et al., 2002; Hogan et al., 2006; Spaniol et al., 2006; Swick et al., 2006). Mostly using episodic memory paradigms, this type of research reveals that older adults depart from the typical pattern of left lateralized prefrontal cortex activity during memory encoding and right lateralized prefrontal cortex activity during memory retrieval (Babiloni et al, 2006; Düzel et al., 1999; Tulving et al.,1994). Instead, older adult tend to show greater bilateral activation across prefrontal regions (Cabeza et al., 1997; Cabeza, 2002; Dolcos et al., 2002). This change in activity pattern seems to be related to functional compensatory processes, since greater bilateral activity during recall of mnemonically stored information is seen only in older adults who maintain response accuracy rates that are comparable to those of younger adults. This type of compensatory activity has been observed in a variety of different cognitive domains, including working memory (Reuter-Lorenz et al., 2000), inhibitory control (Nielson et al., 2002) and source memory retrieval (Cabeza et al., 2002). As it pertains to task switching, however, little is known about the cortical regions that are affected by advancing age. In one of the first and only papers to investigate this, Di Girolamo et al. (2001) found that older adults had slower RTs when responding to both mixed and single task situations and that they recruited greater prefrontal cortex activity (dorsolateral prefrontal and medial frontal) during single-task conditions. On the other hand, Smith et al. (2001) found that older adults are impaired only when performing in mixed-task conditions and that, unlike younger adults, they recruited extra prefrontal cortex activity (left dorsolateral prefrontal) when responding to mixed-task conditions. This extra activity within the left prefrontal cortex is consistent with the idea that older adults compensate for retrieval difficulties by recruiting additional brain regions. So Di Girolamo et al. (2001) found that the largest age difference occurred during single task blocks whereas Smith et al. (2001) found that the largest age difference occurred during mixed-task blocks. Design differences between the two studies may account for these discrepant results, especially if we consider that one study used multivalent stimuli and recorded brain activity using fMRI scans (Di Girolamo et al., 2001) while the other used univalent stimuli and recorded brain activity using PET scans (Smith et al., 2001).

It is interesting to note, that in the Smith et al. (2001) study, the pattern of brain activity recorded among older adults were the same as the ones observed among poorly performing young adults. In their study, Smith et al. (2001) tested younger and older adults on a dual task that involved simultaneously encoding target words and evaluating the accuracy of simple mathematical equations. Each trial consisted of five consecutive word-equation pairs. At the end of each trial, the target words that had just been shown were presented again, but in a particular sequence. Participants had to decide whether or not the probe sequence corresponded to the actual presentation sequence they had seen. Performance on the dual task was compared to the performance on each of the two constituent tasks (math-alone and memory-alone). Results showed that, when compared to the memory-alone condition, the dual task condition reduced the ability to recognize whether or not the probe sequence was correct. Importantly, the dual task condition increased the decision time (response latency when judging the accuracy of the probe sequence) of older adults much more than it did for younger adults. This suggests that older adults are disproportionately impaired compared to younger adults when having to perform in a dual task situation. PET scan activity obtained during testing also showed that older adults recruited additional left frontal activity when performing in a dual task context; activity which was not present during the memory-alone or math-alone task. When they divided younger adults into high and low dual task performers, the same left frontal activity was obtained for poor task-performing younger adults. This finding is particularly interesting because it suggests that additional prefrontal cortex activity may be required in those subjects who find mixed-task blocks demanding (poor young performers and older adults). This finding also suggests that the activity change observed in older adults can occur at any age (since it was also found in poor young performers) and must, therefore, be linked to some aspect of cognitive control which is affected by the aging process but not unique to it. We will argue in this thesis that working memory capacity (in particular working memory retrieval) is a likely candidate to explain the emergence of such results.

In sum, the above review suggests that older adults are impaired when responding in mixed-task situations, resulting in larger RT mixing costs than younger adults. Age-related changes in working memory retrieval seem to relate to this change but it is not clear why the local switch cost should be preserved. After all, working memory appears to be involved in various aspects of the reconfiguration process[2]. Why then, should older adults, who are thought to show deficits in working memory capacity, not show larger locals witch costs? As reviewed above, this unexpected finding may occur because the repeat versus homogeneous contrast is more sensitive to the updating operations that have to be applied in mixed-task situations than the repeat versus switch contrast. In other words, the local switch cost may be a more ambiguous indicator of executive control demands in set-selection situations because all mixed-task trials (repeat and switch) are sensitive to stimulus ambiguity, response ambiguity and the need for advanced preparation. As a result, the mixing cost may actually be a more fundamental index of executive control demands (see Mayr, 2001 for a similar argument).

Overview of Project

The task switching and aging literature reviewed above suggests that older adults are impaired in their ability to respond to situations where tasks alternate frequently. Although age-related decline in working memory capacity is assumed to mediate this change in performance, it is still unclear how working memory comes to affect the task set reconfiguration process. Does it affect the ability to retrieve a relevant task set from among multiple, competing candidates? Does it affect the ability to classify ambiguous

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[2] For example, when a change in task set becomes necessary, working memory retrieval functions have to be triggered in order to recover the new task set. Second, the newly retrieved information has to be maintained until a response is required. Inhibitory functions may also need to be applied in order to prevent the return of previously relevant, but currently irrelevant task rules. Finally, evaluating the target stimulus and pairing it with its appropriate response requires that the information that has been retrieved and maintained in advance of the target be manipulated. It is clear, therefore, that working memory includes concepts that should account for the processes triggered when alternating between different tasks.

targets? Are there age-related changes in the pattern of neuronal activity associated with target preparation and classification? Does working memory capacity change the nature of these patterns? To answer these questions we used a randomly alternating, cued task switching design and recorded the behavioural and electrophysiological (ERP) responses of younger adults, older adults with poor working memory skills and older adults with high working memory skills. Since task switching lends itself well to the subtractive methodology of electrophysiological research, the current study was also able to chart the pattern of cortical activity specific to the local switch cost contrast and to the mixing cost contrast.

The methodology and the different findings of the current project are detailed in the next three Chapters. These Chapters are presented in manuscript format. Manuscript 1 has already appeared as Goffaux, Phillips, Sinai, and Pushkar (2006) and Manuscript 2 has been submitted for journal publication. Manuscript 3 is currently being formatted for journal publication and will be submitted shortly. The first Chapter reports the findings collected among young adults only. In this Chapter, the event-related activation (ERPs) of trials that occur in mixed-task blocks (switch and repeat trials) and single task blocks (homogeneous trials) were recorded and compared. To our knowledge, this is the first time that the pattern of electrophysiological activity underlying local and mixing costs are measured in the same study and among the same subjects. Chapter 1, therefore, explored the change in cortical activity which accompanies task set reconfiguration (i.e., the local switch cost) and multitasking in general (i.e., the mixing cost). An additional goal of Chapter 1 was to capture the specific neuronal signature underlying task-set reconfiguration. To achieve this, the electrophysiological activity of repeat and switch trials were compared, but only after they were equated on RT. This gave an unbiased index of the processes underlying task set-reconfiguration (i.e., unbiased by trial-type differences in RT).

Chapter 2 adds to the findings reported in Chapter 1 by comparing the results also obtained from older adults. The importance of working memory capacity in predicting age-related changes in task switching were also explored. This was achieved by separating older adults into high and low working memory groups. Furthermore, since the task switching design used in this study included an external task cue which was present for most of the cue-target interval, any age-related change in cue-locked activity was assumed to reflect a change in the ability of older adults to retrieve task set information. This design differs from previously published methodologies that tested for age differences in cue-locked activity using a briefly presented cue (Kray et al., 2005; West, 2004). Not surprisingly, age-related changes in cue-locked activity obtained under these circumstances were interpreted as a deficit in the ability to maintain task set representations. Departing from this assumption, it was hypothesized that older adults would have a difficult time retrieving task set representations (not just a difficult time maintaining them) and that working memory capacity would be important in explaining this result. If correct, group differences in cue-locked activity should be seen even if the cue remains visible during most of the cue-target interval. The use of behavioural and electrophysiological responses allowed us to test this hypothesis and allowed us to explore how brain-behaviour relationships change with advancing age.

Finally, Chapter 3 complements the findings reported in Chapter 2 by looking at the relationship between task switching and the performance on various executive control measures. Chapter 3 looks only at the data from older adults and so provides an index of the attentional control measures which continue to show changes in late life. The goal in Chapter 3 was to see if the mixing cost and the local switch cost would load uniquely on three executive processes that have previously been described as discrete components of executive functioning. These processes are 1) the ability to execute task alternations, 2) the ability to inhibit non-relevant information during the retrieval process, and 3) the ability to exercise restraint over strong response tendencies. Importantly, the results obtained in Chapter 3 should help us to interpret the age and WM results obtained in Chapter 2. In Chapter 2, our findings were interpreted as WM differences, however, a number of different interpretations can also be advanced to explain the results. This is because WM (the cognitive mechanism used to separate older adults into high and low WM groups in Chapter 2) includes a number of different components, in particular a central executive component which is responsible for a wide range of different functions (Stoltzfus et al., 1996). WM differences, therefore, may reflect differences in rote recall, differences the ability to manipulate information, or even differences in the ability to keep all stored information active and free form interference. Results from Chapter 3 should help in determining the functional significance of age, task switching and WM interactions.

MANUSCRIPT 1

Abstract

In order to understand how the brain prepares for and executes a switch in task demand, we measured reaction time (RT), accuracy, and event-related brain potentials associated with performance in single and mixed-task blocks using a cued design. Our results show that trials which repeat in a mixed-task block (repeat trials) were more demanding than trials which repeated in a single-task block, as reflected by the presence of a RT mixing cost and by the presence of a smaller target-locked positivity (P3b) on repeat trials. Within a mixed-task block, repeat and switch trials also differed, where repeat trials showed evidence of greater preparation (larger cue-locked negativity), more efficient target processing (larger target-locked P3b), and shorter RTs. In addition, the cue-locked negativity difference remained despite equating repeat and switch trials on RT, suggesting that this negativity difference is specific to the switching process. Our results are discussed in light of existing models of task switching.

Behavioural and electrophysiological measures of task switching during single and mixed-task conditions

Multitasking has recently become a hot topic for empirical research, perhaps partly because we are increasingly required to work in such a way. As our workdays increasingly require that we execute multiple tasks (for example, when we must answer the phone while writing an e-mail), our attention must be diverted from one task to another and it is logical that our performance comes to suffer. In fact, recent research shows that switching frequently between different tasks takes a toll on efficiency as measured by reaction time (RT) tasks (e.g., see Rogers & Monsell, 1995; Meiran et al., 2000; and Rubinstein et al., 2001). The decrement in efficiency observed when one is multitasking is believed to come, in large part, from the need to shift attention and implement changes in cognitive routines, both of which require conscious, effortful control.

The goal of this study was to explore behavioural and electrophysiological measures of multitasking using a task switching paradigm. In the following paragraphs, we provide a brief overview of task switching and of the different associated costs. Following this, we review some of the most pertinent neurophysiological studies of task switching that have been published.

In one of the first of the recent generation of studies, Rogers and Monsell (1995) argued that effective switching requires the reconfiguration of task set. This, in turn, entails shifting attention and retrieving and implementing relevant stimulus-response action rules (Rubinstein et al., 2001). Rogers and Monsell (1995) had participants alternate tasks predictably on every second trial in a given block of trials, such that a participant had to either repeat the same task or switch to a different task. This design, known as the alternate runs paradigm, allowed Rogers & Monsell (1995) to isolate transient cognitive control processes and show that it takes longer to switch between competing task-demands than it does to repeat the same task, a phenomenon labelled the local switch cost. They also showed that the local switch cost decreases when the time prior to a predictable switch trial increases, indicating that one can engage in advanced preparation to facilitate the reconfiguration of the task set. However, no matter how much preparatory time was given, it remained more costly to switch between tasks than it did to repeat a task, which suggests that advanced preparation alone is not sufficient to complete task set reconfiguration. The local switch cost that remains despite a long preparatory interval is known as a residual switch cost. Rogers and Monsell concluded that although the active or endogenous control processes engaged during a long preparatory interval allow a participant to complete part of the task set reconfiguration process in advance, the presentation of the target stimulus is necessary to complete this process. This latter phenomenon reflects externally driven, target-triggered processes. In short, Rogers and Monsell proposed a two-step model where both preparatory, pre-target, endogenously controlled processes and target-driven, exogenous processes contribute to the reconfiguration of task sets under goal-directed conditions.

Rogers and Monsell's alternate runs paradigm stood in contrast to the way multitasking had been investigated up to that point. Previous work on task switching (Jersild, 1927; Spector & Biederman, 1976) had compared RT performance between blocks of trials which continually repeated (i.e., homogeneous or single-task blocks) and blocks which contained only switch trials (i.e., heterogeneous or mixed-task blocks). This comparison revealed larger RTs for heterogeneous task blocks than for homogeneous task blocks, but could not be exclusively tied to the cognitive control processes underlying the switch cost. Important state differences including fatigue, motivation, and arousal could conceivably explain RT differences between homogeneous and heterogeneous blocks. In order to control for this, Rogers and Monsell, as well as others, (Allport et al., 1994; Meiran, 1996; Meiran et al., 2000) compared repeat and switch trials when these occurred within the same block of mixed trials, thus minimizing block-related differences. However, a comparison between performance on homogeneous and heterogeneous blocks remains interesting. Indeed, unlike homogeneous blocks, heterogeneous blocks require that multiple, competing task sets be maintained and co-ordinated in working memory (Kray & Lindenberger, 2000). Competing task sets are believed to interfere with performance, even on heterogeneous repeat trials that require no switch in task set (Los, 1999). The cognitive control processes exerted to deal with this interference is captured by comparing homogeneous RTs to heterogeneous repeat RTs and is defined as the mixing cost (Meiran, 2000; Meiran et al., 2001). Notwithstanding potential block differences in arousal and motivation, the homogeneous versus heterogeneous repeat RT difference is believed to capture an important task switching difference in sustained cognitive control processes and continues to be a useful index of task switching.

Although RT and accuracy are sensitive measures of changes in task set, they do not provide information on how the brain prepares for and responds to these changes. To adequately observe the cortical activity related to switching between tasks and repeating tasks, the neuroimaging technique of choice should be sensitive to processing changes evoked over very short periods of time. Given their high temporal resolution, electroencephalographic recordings are ideally suited to capture these changes. When time-locked to the presentation of a stimulus event and averaged across trials, electroencephalographic recordings reflect voltage variation in cortical activity associated with specific events. Known as event-related brain potentials (ERPs), these time-locked voltage changes are defined according to their polarity (positive or negative), latency (in milliseconds), amplitude (in μV), and topographic scalp distribution. To date, only a handful of studies have used ERPs to examine control processes involved in task switching and all have used different task switching designs. For example, some studies used an alternate runs paradigm (Karayanidis et al., 2003; Lorist et al., 2000; Wylie et al., 2003) while others used an externally cued paradigm (Brass et al., 2005; Poulsen et al., 2005; Poulsen et al., 2001; Rushworth et al., 2002; Sinai & Phillips, 2002). Task set difficulty also varied, ranging from either simple classification tasks (e.g., categorizing a number as either even or odd) to more complex tasks (e.g., categorizing a word as either living or non-living). Finally, some task switching designs varied stimulus-response mappings rather than the tasks themselves (Rushworth et al., 2002). Although the studies cited above involve task switching, their designs were quite different, making it difficult to observe a consistent picture from their findings.

Nevertheless, two findings do appear to emerge from many of these studies. The first is the presence of a larger negative slow wave obtained over posterior scalp regions during the period preceding a repeat target, as opposed to a switch target. This is possibly a stimulus preceding negativity (SPN), which is believed to reflect the anticipatory activity sustained by a network involving thalamo-cortical pathways. According to Brunia and van Boxtel (2001), these pathways activate both frontal and parietal regions when preparing for a forewarned or predictable task. Brunia and van Boxtel (2001) argue that negativity observed at frontal scalp regions indexes the ongoing control exerted over attentive processes, while negativity observed over parietal regions indexes anticipation of task relevant stimuli. The posterior negativities observed prior to predictable task repetitions in the task switching studies reported above (Brass et al., 2005; Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2005; Poulsen et al., 2001; Rushworth et al., 2002; Sinai & Phillips, 2002) suggest facilitated processing during repeat as opposed to switch trials. As for switch- and repeat-related frontal negativities, task switching studies have not provided consistent results. Some authors report larger frontal negativities on switch trials (Lorist et al., 2000; Poulsen et al., 2005; Poulsen et al., 2001) while others report large frontal negativities on repeat trials (Rushworth et al., 2002). Still others report no differences between the frontal negativities of repeat and switch trials despite posterior negativity differences (Karayanidis, et al., 2003; Sinai & Phillips, 2002). It is not yet clear what can account for these discrepant findings but methodological differences among these studies are at least one probable cause. In spite of these differences, what is needed is a functional understanding of the negativities elicited during task preparation. We attempt to provide this in the present study by conducting within-subject analyses of the relationship between negative slow waves and the local switch cost when RT for repeat and switch trials are equated. That is, one of our goals was to determine whether the negative slow wave discriminates between repeat and switch trials. To do so, we compared repeat and switch trials equated for RT to be able to evaluate task-specific differences independent of RT differences.

The second consistent electrophysiological finding observed among ERP task switching studies is a larger P3b-like waveform following the presentation of a repeat as opposed to a switch target (Karayanidis et al., 2003; Lorist et al., 2000; Poulsen at al., 2001; Rushworth et al., 2002; Sinai & Phillips, 2002). The P3b component is a late (300 -~800 ms), posteriorily distributed positive deflection linked to target evaluation. Its amplitude is believed to increase proportionally as target processing is facilitated, a process affected by working memory resources (Johnson, 1984; Kok, 2001; Kramer & Spinks, 1991). Thus, a larger target-locked positivity on repeat as opposed to switch trials may indicate a greater amount of available working memory resources with which to process repeat targets.

To date, no study has examined the electrophysiological correlates of mixing and local switch costs in the same study. The present study used ERP recordings to investigate both preparatory and target-driven processes engaged during a cued task switching paradigm. The presence and functional significance of mixing and switch costs was investigated by analysing RT, accuracy, and ERP data. Given the results obtained by previous studies, it was expected that trials that offered the opportunity for facilitated pre-target preparation should show faster RT, higher accuracy scores, and larger pre-target posterior negativities. Thus we expected to find greater preparatory effects on homogeneous trials, less on repeat trials, and lesser still on switch trials. Furthermore, we examined within-subject differences in repeat and switch waveforms when these were equated for overall RT. Observing a larger negativity for repeat as opposed to switch trials despite similar RTs would indicate that the negativity is associated with specific local switch cost differences over and above general response speed.

Also expected was a larger post-target positive deflection (P3b) distributed over posterior scalp regions on trials where target evaluation is facilitated. Thus, we expected to see greater post-target target processing effects (larger P3bs) on homogeneous trials, followed by repeat trials, and then by switch trials respectively. We also wanted to know if target-locked P3b differences between repeat and switch trials persist when their RTs are equated. By exploring both the cue- and target-locked activity of repeat and switch trials when these have the same RTs, we will be able test whether or not repeat-switch differences persist throughout target-triggered processes when time to prepare is afforded.

Method

Participants

Twenty young adults (6 men and 14 women; mean age =24.5, SD=3.4) participated in this study. Eighteen reported being right handed and 2 reported being left handed. All participants were recruited from either the Concordia University student population or through word of mouth and all reported being in good health. Informed consent was obtained from all participants and each was remunerated $20 for his/her participation.

Materials and Apparatus

The target stimuli consisted of 16 concrete nouns (*beetle, nail, worm, stone, apple, marble, banana, ladder, tank, boulder, hippo, train, snake, bear, pencil, tree*) for which the participant performed one of three semantic classification tasks: (A) an existence judgement (is it living or non-living?), (B) a size judgement (is it large or small?) or (C) a breadth judgement (is it wide or narrow?) on any given trial. For each classification task, 50% of the stimuli were associated with each dichotomous response (e.g., for the existence classification task, 8 nouns required a living response and the other 8 required a non-living response). Using the psycholinguistic database available at the University of Western Australia's website (http://www.psy.uwa.edu.au/MRCDataBase/uwa_mrc.htm), each set of 8 nouns assigned to the two possible categories (e.g., the 8 living and 8 non-living sets) were matched for concreteness, imageability, and frequency (all Fs<3.37 and ps>.05).

Each experimental trial consisted of a cue-target sequence (see Figure 1). The same target words were used for each semantic classification task (e.g., "pencil" was categorized as small, narrow, or non-living) and responses were mapped to the same two buttons for all tasks (e.g., the left button was pressed for living, large, and narrow judgements while the right button was pressed for non-living, small, and wide judgements). These task-response mappings were counterbalanced across participants. Each of the 16 nouns (and the three cue words "Existence", "Size", or "Breadth") were presented in a white, 24-point font and appeared on a black background computer screen.

Procedure

Each participant provided informed consent and then completed a demographic and health questionnaire. Given that this experiment was part of a larger study, participants completed both the task switching experiment and a series of neuropsychological tests in the same session, although the details of the latter are not relevant to the present study. Participants were tested individually in a single session which took approximately 2 hours for the task switching experiment, followed by 1 ½ hours for the neuropsychological tests. Short breaks were given when necessary.

Participants were seated one meter away from a computer monitor and instructed to read silently each of the stimuli presented. Instructions informed the participants that cue-target pairs were to be presented and that the cue would inform them as to which semantic classification task to perform on the subsequent target word. Each cue word was presented on-screen for 1s and was followed by a target (one of the 16 concrete nouns) 1180 ms afterwards. This period of time represented the cue-target interval (CTI). The period of time between the response and the presentation of the cue for the next trial (i.e., the response-cue interval: RCI) was either 200 ms following a correct response or 800 ms following an incorrect response. A short 200 Hz tone (100 ms duration) was presented following incorrect responses and, combined with the increased RCI, allowed participants to monitor and optimize their performance on following trials. Participants were instructed to respond as accurately and as quickly as possible. Target words were kept onscreen for a maximum of 5 seconds or until a response was given. So as to minimize electrophysiological artefacts, participants were also instructed not to move, talk, or blink during the presentation of the stimuli.

Participants first learned the target-response pairings for each of the three semantic tasks (existence, size, and breadth) in separate homogeneous blocks. Each of the three homogeneous blocks consisted of 160 trials of cue-target pairs for a single semantic task. By definition, then, each homogeneous trial was a repeat trial. The first 80 trials of each block were to learn and practice the response-key assignments. The remaining 80 trials were experimental trials on which behavioural and ERP data were collected. Ordering of the three task blocks was randomized across participants. Following the three homogeneous blocks, participants completed two heterogeneous blocks consisting of trials randomly sampled with equal frequency from each of the three different semantic tasks. These two blocks contained 260 trials each plus 10 warm-up trials at the beginning of each block. Each trial within a heterogeneous block was either a repetition of the previous semantic task or a switch to another semantic task. Heterogeneous block trials were defined as a function of the task performed on one (n-1) or two (n-2) trials previously. Repeat trials consisted of a trial where the same semantic task was performed only twice in a row (e.g., A in an BAA trial sequence). Switch trials consisted of a trial where the participant switched from performing one semantic task to another, without having performed that task on trial n-2 (e.g., A in a CBA trial sequence). None of the 16 target words were repeated within any three-trial sequence in homogeneous or heterogeneous blocks. This minimized stimulus-response associations (i.e., negative priming) from interfering with the task-response associations. Finally, repeat trials (as defined above) accounted for 20% of all trials within a heterogeneous block, whereas switch trials (as defined above) accounted for 26%. The remaining 54% were trials that did not follow the specific triplet pattern defined above and included runs of repeat trials (e.g., AAA) or switch trials where the task had been performed recently (e.g., A in an ABA trial sequence); however, these were outside the focus of the current report.

Electroencephalogram (EEG) Recordings

EEG recordings were obtained from a nylon cap fitted with tin electrodes (Electro-Cap International). The EEG signal was obtained from six midline sites (FPz, Fz, FCz, Cz, CPz, Pz) and 22 lateral sites over the left and right hemisphere, respectively (prefrontal: FP1, FP2; frontal: F3, F7, F4, F8; frontocentral: FC3, FC4; frontotemporal: FT7, FT8; central: C3, C4; centroparietal: CP3, CP4; temporal T5, T6; temporoparietal: TP7, TP8; parietal: P3, P4, and occipital: O1, O2). A forehead location was used as ground. All EEG electrodes were referenced to the left ear during acquisition and re-referenced offline to a linked ear reference. The electoroculogram (EOG) was recorded bipolarly from electrodes placed at the outer canthi of both eyes (horizontal EOG) and above and below the left eye (vertical EOG). EOG artefacts were corrected off-line for all participants using a regression algorithm (Gratton, Coles & Donchin, 1983). EEG activity was sampled continuously at 100 Hz and amplified using Neuroscan Synamps in a DC-30 Hz bandwidth.

Rational for Hypothesis Testing

In order to assess the different executive abilities involved in task switching, two different cost analyses were carried out. The mixing cost is presumed to reflect demands of keeping more than one task active in working memory and was investigated by comparing the average behavioural and ERP measures of trials within a homogeneous block from repeat trials within a heterogeneous block. ERP mixing cost contrasts were analysed during both the pre-target (i.e., cue-locked) and post-target (target-locked) periods. The local switch cost is presumed to measure task set reconfiguration. It was investigated by comparing the average behavioural and ERP measures of repeat trials within a heterogeneous block from switch trials within a heterogeneous block. Here, too, the local switch cost contrast was analysed during both the pre-target and post target periods.

Results

Behavioural Data Reduction

Prior to any cost analyses, RTs were trimmed for each of the five blocks such that RTs greater than or smaller than 2.5 standard deviations of the block mean or less than 200 ms were eliminated. This represented no more than a 7.4% loss of trials in any given block. RT data were analysed only for correct trials that followed at least two correct responses. In order to pool data, two analyses of variance (ANOVAs) were conducted to determine whether mean RT and accuracy scores for repeat and switch trials could be collapsed across the three semantic tasks (existence, size and breadth) and across both heterogeneous blocks. These, and all other analyses reported below, were conducted using SPSS v.11.0 statistical software. Greenhouse-Geisser corrections for non-sphericity are applied where appropriate. A task (existence, size, breadth) by block (heterogeneous block 1 and 2) by cost type (local switch cost, mixing cost) ANOVA was first conducted on RT and accuracy scores to test whether cost types differed as a function of block and/or semantic task. To ascertain this, only interactions involving cost type are described. The RT and accuracy analyses failed to show any significant interaction with cost type (all $\underline{F}$s<1.05 and all $\underline{p}$s>.05), indicating that the switch and mixing costs did not differ as a function of block or semantic task. We consequently collapsed RT, accuracy, and ERP measures across all three semantic tasks and across both heterogeneous blocks for the analyses reported below.

Behavioural Results

Average RT data (see Table 1) revealed a significant mixing cost, such that participants were faster to respond to repeat trials within a homogeneous block than to repeat trials within the heterogeneous blocks, t (19)=-10.72, p<.001. A significant local switch cost was obtained, revealing that in heterogeneous blocks participants responded more quickly to repeat trials than to switch trials, t (19)=-4.89, p<.001.

When performance accuracy was analysed (Table 1), there were no significant effects for the mixing cost, t (19)=0.82, p=.42, or the local switch cost, t (19)=1.42, p=.17.

ERP Data Reduction

Correct trials analysed for RT effects were also analysed for ERP effects. Epochs for both cue-locked and target-locked waveforms were time-locked to the presentation of the cue and spanned over 2400 ms. Epochs for cue-locked waveforms were baseline corrected between 0 and 100 ms after the cue's onset (see Figure 2)[3]. Epochs for target-locked waveforms were baseline corrected between 980 and 1180 ms after the cue's onset (i.e., 200 ms prior to target onset, see Figure 3). Setting the cue-locked epoch to span a timeframe long enough to include the waveforms associated with both the cue and the target (i.e., 2400 ms) allowed us to appreciate the cortical activity across the whole cue-target period.

Both cue-locked and target-locked waveforms were analysed as a function of scalp region. Mean waveform amplitudes were computed as a function of anteriority (anterior:

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[3] We had originally chosen a -200 to 0 ms pre-cue baseline period. However, this baseline appeared to include the negative-going resolution of the P300 activity associated with the preceding trial. By baseline correcting from 0 to 100 ms into the cue period, we were able to reduce the influence of the negative-going resolution of the preceding P300 component.

F3, Fz, F4, FC3, FCz, FC4; central: C3, Cz, C4; and posterior: CP3, CPz, CP4, P3, Pz, P4) and laterality (left: F3, FC3, C3, CP3, P3; midline: Fz, FCz, Cz, CPz, Pz; and right: F4, FC4, C4, CP4, P4). Cue-locked waveforms were also analysed as a function of time interval. Cue-locked mean amplitudes were examined in the 400-800 ms, and 800-1180 ms post-cue intervals whereas target-locked P3b activity was examined through peak scoring (i.e., . the amplitude and latency of the most positive point obtained in the 300-800 ms post-target interval). Figures 2 and 3 show the grand average waveforms collapsed across subjects for each of the three different trial types (homogeneous, repeat, and switch trials) as a function of laterality and anteriority for both cue-locked and target-locked waveforms, respectively. Cue-locked waveforms show a negative going deflection for both heterogeneous conditions observable at posterior scalp regions and evident at the later intervals (starting at approximately 600 ms), whereas the homogeneous condition exhibits a flattening of the waveform in the later portion of the cue-target interval. Target-locked waveforms show that all conditions were characterized by a P300 deflection observable over the posterior half of the scalp, which varied in amplitude as a function of condition.

ERP Results

In order to verify the presence of mixing cost and local switch cost effects in the cue-locked waveforms, trial type differences were analysed as a function of scalp region and time interval using a series of four-way repeated measures ANOVAs (trial type X laterality X anteriority X time). Cost effects in the target-locked waveforms were analysed as a function of scalp region using a series of three-way repeated measures ANOVAs (trial type X laterality X anteriority) for both peak P3b amplitude and latency scores. Main effects of trial type are reported, followed by significant higher-order interactions with time and/or scalp regions. If present, the higher-order interaction is described and followed-up with either a three-way and/or two-way repeated measures ANOVA and/or paired-sample t-tests. Significant contrasts not germane to our hypotheses are not reported (e.g., a time X scalp region interaction). Bonferroni corrections were applied to both ANOVAs and t-tests where appropriate. The reported post-hoc findings include only the significant paired-sample t-tests' results.

Cue-locked Data

Mixing Cost

As shown in Figure 2, during the second half of the cue interval, repeat trials show a negative slow wave potential which becomes progressively larger by the time the target appears and which is absent from the homogeneous condition. A trial type (homogeneous versus repeat) by anteriority (anterior, central, posterior) by laterality (left, midline, right) by time (400-800 ms, 800-1180 ms) ANOVA revealed a significant main effect of trial type, *F* (1, 19)=23.99, *p*<.001, as well as a significant trial type by anteriority by time interaction, *F* (2, 738)=26.88, *p*<.001, ε=.638. Post-hoc comparisons indicated that repeat trials had larger negative amplitudes than homogeneous trials across anterior, *t* (19)=6.07, *p*<.001, central *t* (19)=9.40, *p*<.001, and posterior scalp regions *t* (19)=7.51, *p*<.001. This was observed only during the 800 to 1180 ms interval. These results confirm that repeat trials have a larger negative amplitude than homogeneous trials in the late cue-locked period.

Local switch cost

Cue-locked ERP waveforms presented in Figure 2 also show a late negative slow wave for switch trials, although less pronounced than that of repeat trials. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) by time ANOVA revealed a significant trial type by anteriority interaction, F (2, 38)=14.45, p<.001, ε=.576. Post-hoc comparisons indicated that repeat trials showed larger negative amplitudes than switch trials over the posterior region, t (19)=-2. 17, p<.02. These results indicate that the repeat-switch negative slow wave difference observed throughout the 400-1180 ms interval is more pronounced over the posterior scalp region.

To examine whether this negative slow wave reflects a specific repeat versus switch processing difference or a non-specific reaction time difference favouring repeat trials, additional cue-locked waveforms were computed for repeat and switch trials when these trials were equated for reaction times. In other words, a subset of the fastest switch trials (M=636.88 ms, SD=102.86) were selected such that their average RT was equal to a subset of repeat trials (M=636.55 ms, SD=102.43; t (19)=0.96, p=.348). This allowed us to determine if changes in the negative slow wave could be confidently related to differences in processing repeat versus switch trials while controlling for non-specific speed effects.

Figure 4 shows a larger late negative slow wave for repeat as opposed to switch trials in the posterior part of the scalp. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) by time ANOVA revealed a significant trial type by anteriority interaction, F (2, 38)=12.20 p<.001, ε=.609. Post-hoc comparisons indicated that, compared to switch trials, repeat trials showed larger negative amplitudes over the posterior part of the scalp, t (19)=2.39, p<.03. These results suggest that even when trial types are equated for RT, cue-locked negative slow wave activity is still larger prior to a repeat trial than a switch trial and that the effect is not reducible to a mere difference in speed of responding.

Target-locked Data

Mixing Cost

Target-locked ERP waveforms presented in Figure 3 show a large homogeneous versus repeat difference noticeable throughout the 300-600 ms post-target interval and across the entire posterior half of the scalp. A trial type (homogeneous versus repeat) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b amplitude scores revealed a significant main effect of trial type, F (1, 19)=19.58, p<.001, as well as a significant trial type by anteriority interaction, F (2, 38)=9.68, p<.002, ε=.684. Post-hoc comparisons indicated that, compared to repeat trials, homogeneous trials showed larger positive amplitudes across central, t (19)=-4.06, p<.001, and posterior regions, t (19)=-5.74, p<.001. A trial type (homogeneous versus repeat) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b latency scores did not reveal a significant main effect of trial type (F<4.03, p>.05) nor any interaction with trial type (all Fs<1.62, all ps>.05). Together, the results indicate a larger P300 deflection for homogeneous trials than repeat trials at all electrode sites distributed in the posterior half of the scalp.

Local switch cost

Target-locked ERP waveforms presented in Figure 3 also show a large repeat versus switch difference observed at the posterior half of the scalp and throughout the

300-600 ms interval. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b amplitude scores revealed a significant main effect of trial type, F (1, 19)=13.37, $p<.005$, as well as a significant trial type by anteriority interaction, F (2, 38)=4.39, $p<.05$, $\varepsilon=.645$. Post-hoc comparisons indicated that as compared to switch trials, repeat trials showed larger positive amplitudes across central, t (19)=-3.487, $p<.001$ and posterior regions, t (19)=-4.24, $p<.001$. A trial type (repeat versus switch) by anteriority (anterior, central, posterior) by laterality (left, midline, right) ANOVA conducted on peak P3b latency scores did not reveal a significant main effect of trial type ($F<3.68$, $p>.05$) nor any interaction with trial type (all Fs<2.06, all ps>.05).

Peak P3b comparisons between RT-equated repeat and switch trials were also conducted. These analyses were restricted to midline sites only. A trial type (repeat versus switch) by anteriority (Fz vs FCz vs Cz vs CPz vs Pz) ANOVA conducted on peak P3b amplitude scores and again on peak P3b latency scores revealed no difference between repeat and switch trials (all Fs<4.15, all ps>.05) nor any interaction with trial type (all Fs<1.13, all ps>.05)[4]. This indicates that the repeat-switch processing difference that was observed in preparation of a target stimulus when repeat and switch trials were RT equated does not persist during target processing itself, at least not when 1180 ms of preparation was afforded.

Inter-block differences in P3b jitter

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[4] The similar peak P3b amplitudes of RT-matched repeat and switch trials can be appreciated by looking at Figure 4. Although this figure depicts cue-locked waveforms it is clearly apparent that repeat and switch trials did not differ immediately prior to target onset nor in their peak P300 activity. Target-locked waveforms did not differ from these cue-locked waveforms and so were not included.

As can be appreciated in Table 1, the RTs were more variable in the heterogeneous block than in the homogeneous block. Since the peak latency of the P3b component is, in part, sensitive to variation in response time (Christensen et al., 1996; Verleger, 1997), greater response variability in the heterogeneous condition might yield greater variability in the P3b peak latency from trial to trial. Such intra-subject variability in P3b latency could result in a smeared and reduced peak amplitude when trials are averaged together for each subject and could explain our repeat versus homogeneous P3b amplitude difference. In order to eliminate this possibility, we computed peak-aligned averages for each condition by identifying the latency of the maximum positive peak in single EEG trials in a 350 to 750 ms window. New EEG epochs were computed from 200 ms before and 200 after the peak latency for each trial and were then averaged together as a function of condition (homogeneous, repeat and switch trials). This was performed for each participant using data from the Pz because it corresponds to the scalp location where the P3b waveform is most pronounced. Importantly, a sizeable and significant amplitude difference remained between the peak-aligned conditions having controlled for RT variability. Paired samples t-tests confirmed that homogeneous trials were more positive (25.1 μV) than repeat trials (21.8 μV), $\underline{t}$ (19)=6.91, $\underline{p}$<.0001 and that repeat trials were more positive than switch trials (19.4 μV), $\underline{t}$ (19)=5.90, $\underline{p}$<.0001.

Discussion

Behavioural Data

As expected, RT data revealed significant mixing and local switch costs, indicating that homogeneous trials were responded to more quickly than repeat trials, which in turn were responded to more quickly than switch trials. Accuracy was uniformly high and did not differ between trial types. Our behavioural results are largely consistent with past findings. That is, performance is poorer when having to switch between different tasks (Karayanidis et al., 2003; Meiran et al., 2000; Rogers & Monsell, 1995) or when having to repeat the same task in alternation with switch trials (Los, 1999; Meiran et al., 2001).

Electrophysiological Waveforms

An interesting difference in morphology was evident between the cue-locked activity in homogeneous trials and heterogeneous repeat and switch trials. The heterogeneous repeat and switch trials were characterised by a negative slow wave late in the cue interval which was absent from the homogeneous trials[5]. Moreover, the late negative slow wave was larger on repeat trials than switch trials. In the discussion that follows, we will argue that the late negative slow wave reflects trial-by-trial task set preparation which is necessary during heterogeneous blocks only (and is therefore absent from homogenous block trials) and is enhanced on repeat trials compared to switch trials. We will then discuss the target-locked activity.

Mixing Cost

Cue-locked averages showed that repeat trials were characterized by a late negative slow wave which became progressively larger over the last portion (800-1180

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[5] The negative slow wave we obtained in our waveforms may be similar to the negativity reported by Brunia and van Boxtel (2001), which they term "SPN". However, since our experimental paradigm differs markedly from the ones reported in Brunia and van Boxtel , we will continue to employ the neutral term negative slow wave.

ms) of the cue-target interval. Homogeneous trials, on the other hand, failed to show the presence of negative slow wave activity. By the time the target appeared, then, repeat trials displayed a larger negativity than homogeneous trials.

What cognitive functions might underlie our cue-locked homogeneous versus repeat differences? One possibility involves sustained non-specific arousal or motivational differences across homogeneous and heterogenous task blocks. Although non-cognitive factors such as arousal and motivation might have contributed to the mixing cost, recent neuroimaging data suggest that the mixing cost reflects differences in effortful cognitive control. Braver et al. (2003) found that specific brain regions (prefrontal and cingulate cortex) to be more active during mixed task blocks than single-task blocks and that this difference related to the magnitude of RT mixing costs on a trial-by-trial basis.

In our data, a cognitive account of the mixing cost also seems appropriate, especially given the nature of the waveform components driving our electrophysiological difference. As mentioned above, one of the most striking differences between our repeat and homogeneous trials can be found in the morphology of their respective cue-locked waveforms. Whereas repeat trials showed the presence of a late negative slow wave, homogeneous trials showed a flattening of the waveform throughout the late cue-target interval. Since late negative slow waves are evoked in preparation of an imperative stimulus (Brunia & van Boxtel, 2001) and since a substantial negativity was obtained on repeat trials, it is logical to conclude that repeat cues were important in helping participants prepare for a repeat target stimulus. Homogeneous cues, on the other hand, failed to elicit a negative slow wave. This is not altogether surprising since cues in the homogeneous block were not necessary to predict the upcoming task. Homogeneous blocks involved only one relevant task-set which, in all likelihood, facilitated attention monitoring and the maintenance of the task set in working memory. A homogeneous cue, therefore, probably served a different purpose than did a heterogeneous cue, perhaps helping only to maintain an already prepared task set rather than to provide information that guides advanced preparation.

As mentioned above, cognitive control accounts of the mixing cost argue that a large part of this cost is associated with the added difficulty of having to maintain multiple task sets. Since multiple task sets are thought to compete during the selection of appropriate stimulus-response rules, target-locked differences should also be observed during the mixing cost contrast. Examination of our target-locked positivity (P3b) supports this prediction. We found significantly larger P3b amplitudes for homogeneous targets than for repeat targets. The P3b waveform is believed to be a sensitive index of target-triggered evaluation within working memory (Kok, 2001). In and of itself, this electrophysiological index says nothing about the specific nature of the processes active within working memory, such as rule activation, resolution of response competition, intentional task set implementation, or template matching and updating. However, it is generally well accepted that the amplitude of the P3b waveform reflects processing capacity and mental workload (see Kok, 2001 for a review). Our P3b results suggest, therefore, that greater target-triggered working memory demands are central to the mixing cost contrast, probably resulting from the need to co-ordinate multiple stimulus-response associations during heterogeneous trials. The functional significance we attribute to our target-locked P3b wave (be it for homogeneous or repeat trials) is in line with the interpretation of Rubinstein et al. (2001). From their behavioural experiments, Rubinstein et al. (2001) conclude that the processes engaged during target identification relate to rule activation and involve the selective engagement of response-rules in working memory. It is logical, therefore, to interpret our mixing cost results as reflecting, at least in part, differences between mixed and single-task blocks in the selection and maintenance of task-rules within working memory.

We were able to rule out another alternative explanation of our P3b findings, namely that smaller P3b amplitudes on repeat trials were a by-product of greater intra-subject latency-jitter due to more variable response times on heterogeneous blocks compared to homogeneous blocks. Significant amplitude differences remained between the conditions even after we computed waveforms time-locked to the peak positivity in individual trials. Inter-block variance in latency jitter could not have explained this difference. This finding is consistent with the idea that the P3b amplitude is a sensitive index of stimulus evaluation and intensity of processing (Kok, 1990; Polich & Kok, 1995; Johnson, 1984).

Local switch cost

Cue-locked averages also showed evidence of negative slow wave activity for switch trials. However, as can be appreciated in Figure 2, the amplitude of the late negativity in the posterior part of the scalp was greater for repeat trials than for switch trials. This suggests that by the end of the cue-target interval, repeat cues helped participants anticipate repeat targets to a greater extent than switch cues helped participants anticipate switch targets (Brunia & van Boxtel, 2001).

The idea that the repeat versus switch negativity difference might reflect preparation/anticipation differences is supported by Karayanidis et al. (2003). In their study, repeat versus switch differences in negativity varied as a function of preparatory time (longer response-target intervals) and, importantly, related to RT variations in the local switch cost. In other words, when preparation time was increased, the repeat versus switch negativity difference decreased and was followed by a reduction in the size of the RT local switch. In our study, the fact that repeat and switch slow waves were still different by the end of the CTI suggests that our local switch cost RT difference reflected preparation differences between our repeat and switch trials. Although we believe our cue-locked negativity difference reflected a difference in advanced preparation between repeat and switch trials, it could have also reflected a non-specific speed effect. To better understand the functional significance of our pre-target negativity, we looked at the negativity difference between our repeat and switch trials when these trials were equated for RT. Our results showed that despite similar RTs, repeat trials still had a greater negativity in the posterior part of the scalp than switch trials, suggesting that differences in preparation were still present. Our negative slow waves, therefore, were sensitive to specific advanced processing differences between repeat and switch trials which were not merely a by-product of RT. This means that we can be confident in interpreting our posterior negativity difference as reflecting a true difference in the neural mechanism responsible for preparation during a switch in task demand. Although others have reported larger negativities and faster responses on repeat as opposed to switch trials (Brass et al., 2005; Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2005; Poulsen et al., 2001; Rushworth et al., 2002; Sinai & Phillips, 2002), our demonstration that the posterior negativity distinguished repeat from switch trials, even when differences in RT were controlled, strengthens the functional interpretation of the negative slow wave. Posterior negative slow waves, therefore, appear to reflect the cognitive control processes triggered when preparing to switch to a new task. Finally, the dissociation we observed between posterior negative amplitudes and reaction time is also consistent with findings from Travis and Tecce (1998), which showed that negative slow wave amplitude varied as a function of attention-related processes, not response time.

An alternative interpretation, not tied to task set preparation, may be raised to explain part of our switch cost. Logan and Bundesen (2003) proposed that much of the local switch cost in cued paradigms comes from cue priming, not cued preparation. This means that it is the repetition of the cue, not the task set itself, which facilitates response time on repeat trials. Indeed, our local switch cost contrast involved repeat trials which confounded cue repetition with task repetition. Brass et al. (2005) recently obtained a significant local switch cost in a cued task switching study which did not confound cue-encoding with task-encoding, indicating that local switch costs are not entirely accounted for by a cue-priming confound. Nevertheless, this present study and many in the literature did not control for cue repetition; therefore, it is possible that a cue-priming contribution remains. However, we argue that one would not expect to see cue priming effects appearing as late in the cue interval as where we observed our repeat-switch differences.

In our study, cue-locked differences between repeat and switch negativities were also followed by target-locked P3b waveform differences. Larger posterior positivities were obtained following repeat targets, indicating that target evaluation was facilitated on repeat trials (Kramer & Spinks, 1991; Barceló, 2003). However, given the presence of a significant repeat-switch difference in cue-locked negativity prior to the presentation of the target, it is possible that our target-locked period continued to reflect differences in preparation and not target-triggered differences. To answer this question, it is important to know whether changes affecting pre-target processing affected both the pre- and post-target waveforms. Karayanidis et al. (2003) varied the length of the pre-target interval and found that shorter pre-target intervals increased the repeat-switch difference in pre-target negativity and also increased the amplitude and latency of the post-target positivity difference. Since the pattern of our pre- and post-target results are similar to those described by Karayanidis et al. (2003) in their short interval, part of our repeat versus switch difference in P3b amplitude may be due to insufficient preparation. However, even when long pre-target intervals were given, Karayanidis et al. still obtained a repeat-switch difference in target-locked positivity, suggesting that the target-locked P3b difference also reflected target-triggered processes. Our reduced target-locked P3b on switch trials, therefore, likely reflects a combination of sub-optimal pre-target preparation and the extra processing required to retrieve the new set of stimulus-response rules.

Although this two-step cue- and target-driven reconfiguration process nicely accounts for the way switching might occur, De Jong (2000) recently proposed an intention activation model where task-set reconfiguration follows an all-or-none process. De Jong argued that allowing more time for advanced preparation does not necessarily mean that every switch trial will become better prepared. Instead, he argued that advanced preparation allows for a larger proportion of switch trials (but not all) to be completely prepared or reconfigured prior to the presentation of the target. The crucial point here is that for those switch trials that are completely reconfigured in advance, the RT difference between repeat and switch trials should disappear. Since we compared repeat and switch trials equated for RT, we created a comparison in which repeat and switch trials should have been equally prepared, according to De Jong's argument. Thus, the cue-locked neural activity should differ between repeat and switch trials given their differing need for reconfiguration, but should not differ during target processing if the switching process was completed in advance of the target[6]. Interestingly, our results support this claim since we continued to find a significant difference between RT-matched repeat and switch trials during the cue-locked interval with respect to the negative slow wave activity but not during the target-locked interval (i.e., the P3b activity). These findings are consistent, therefore, with the idea that, at least on some trials, task set reconfiguration follows a discrete all-or-none process. However, a recent study by Nieuwnehuis & Monsell (2002) showed that even under conditions that encourage complete advanced preparation (i.e., use of a payoff system), a robust residual switch cost remained. These authors suggest that for a certain number of switch trials, some form of exogenous, target-driven process may remain necessary when reconfiguring for a new task set. A progressive, endogenous task set reconfiguration model may still be pertinent when explaining what takes place when preparing for a switch target. Future work is needed to explore the testing conditions under which task set reconfiguration proceeds in a probabilistic rather than in a progressive absolute fashion.

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[6] This should be the case only when sufficient time for preparation is afforded; otherwise, the all-or-none reconfiguration process would be completed during the target period and electrophysiological differences would be expected only for target-locked contrasts.

Finally, it is possible that the greater P3b on repeat versus switch trials reflects differences in the frequency of occurrence of these events and not in the cognitive resources related to switching. Given the difficulty associated with having to perform in a mixed task context, it is possible that our participants kept themselves ready for a switch in task demand at all times. This means that repeat trials, when they occurred, may have been unexpected. Past findings have shown that the size of the P3 component increases when expectation violations occur (Johnson, 1986, 1993; Verleger et al., 1994). Thus, our repeat versus switch P3b difference might reflect nothing more than a mismatch between expectation and experience. However, it is important to remember that it was the task set which repeated, never the target word itself; thus, we think it is unlikely that the P3b activity measured at the target reflected the frequency of the repetition of tasks in general (which had been cued nearly 1200 ms previously).

Summary and Future Directions

This study has documented electrophysiological differences on trials which vary in the degree to which they call on sustained and transient shifts in cognitive control processes. Moreover, the ability to examine neural activity during pre- and post-target intervals separately has allowed us to further fractionate previous behavioural results. We were able to show that repeat trials were more easily prepared for than switch trials and obtained larger cue-locked negativities, which preceded significant differences in RT. Interestingly, repeat versus switch trial differences in negativity remained even after equating for RT, ruling out a general speed effect. We also showed that homogeneous trials were not characterized by negative slow wave activity which, when compared to repeat trial activity, likely reflects single versus mixed task block differences in task set maintenance and cue processing. RT differences between homogeneous and repeat trials confirmed that participants performed more efficiently during single-task blocks than during mixed-task blocks.

Target-locked differences between our trial types were also obtained. We found the largest target-locked positivities (P3b) for homogeneous trials, followed by repeat trials, and switch trials, respectively. We interpret this finding as reflecting a difference in the target evaluation process, a process likely reflecting inter-trial differences in available working memory resources. Interestingly, we did not obtain a target-locked positivity difference between our RT-matched repeat and switch trials which suggests that, on some occasions at least, the reconfiguration process can be completed in advance of the switch trial target.

Finally, these findings reflect the way young, healthy adults prepare for and respond to task changes. We are currently examining how ERPs associated with anticipatory and post-target processing during task switching are influenced by advanced age. By examining performance and age-related changes in signal strength and topography, future studies will be able to explore how the aging brain multitasks.

Acknowledgements

A portion of these data was reported previously at the Eight International Conference on Cognitive Neuroscience (ICON8), Porquerolles Island, France, September 9-15, 2002. This study was supported by a grant awarded to N.A. Phillips from NSERC (Natural Sciences and Engineering Research Council of Canada). We would like to thank S. Gagnon, T.S. Choy and L. Ingenito for their assistance in subject testing, data processing and graphical processing. We are grateful to our study participants for their time and effort.

Table 1

Mean (Standard Deviation) for Reaction Time (ms) and Accuracy (%) Scores

	Trial Type				Cost	
	Homogeneous		Repeat		Mixing Cost	
Reaction Time	550.0	(59.7)	748.2	(113.5)	198.2*	(82.7)
Accuracy	96.2	(3.2)	95.6	(3.3)	-.06	(3.2)
	Repeat		Switch		Local switch cost	
Reaction Time	748.2	(113.5)	836.6	(180.1)	88.4*	(80.8)
Accuracy	95.6	(3.3)	94.2	(3.9)	-1.4	(4.5)

*p<.001

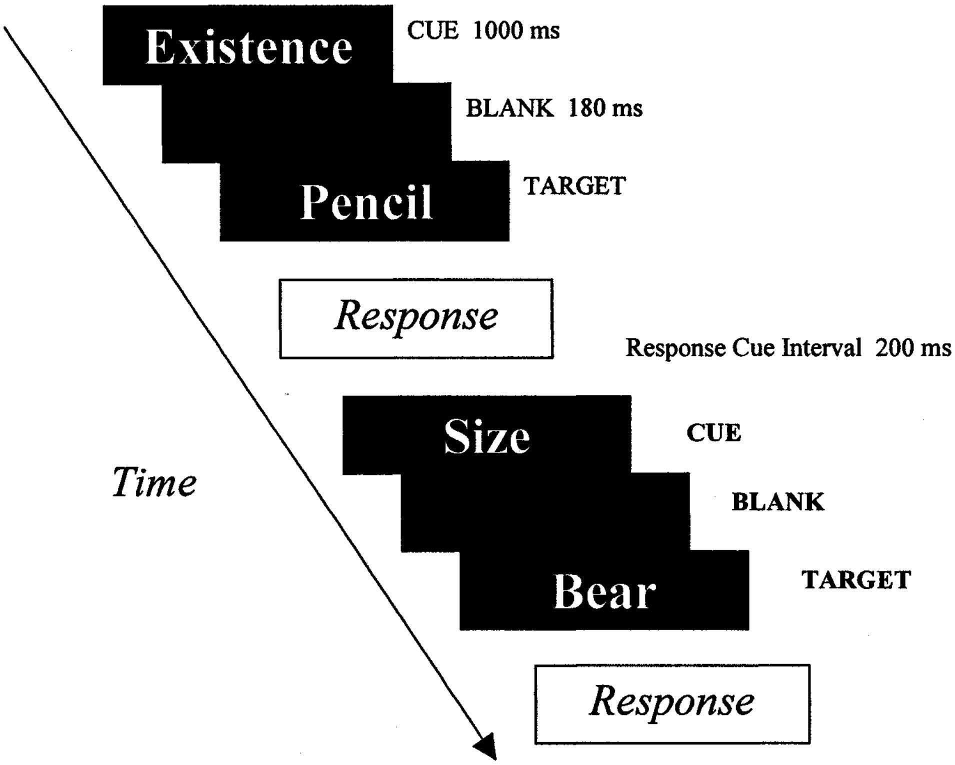

Figure 1. Example of the cue-target sequencing and timing used in our design.

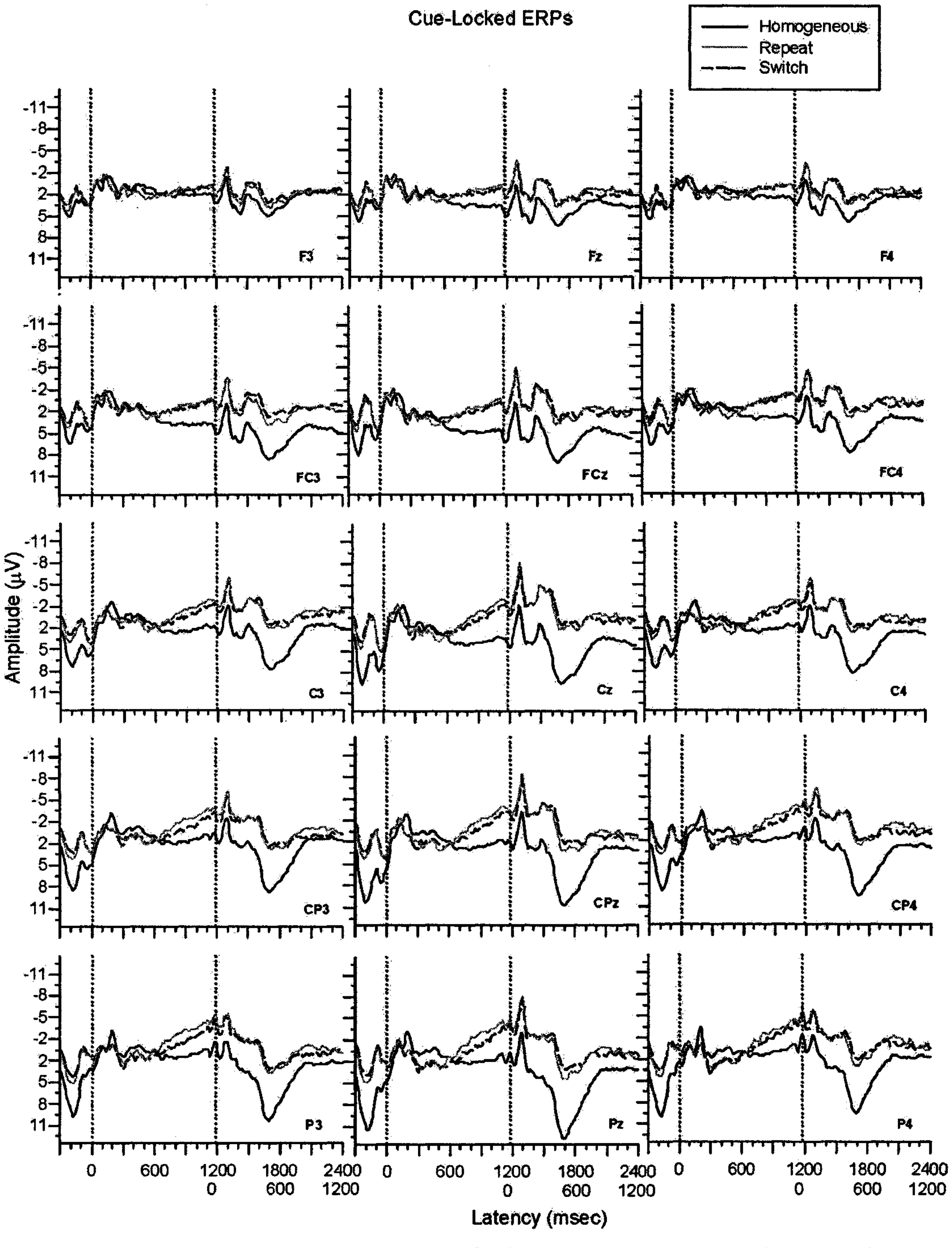

Figure 2. Cue-locked grand average waveforms for homogeneous, repeat and switch trials. ERP activity is shown over the entire cue-target interval, however, the waveform was baseline corrected from 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue, while the lower X-axis time scale indicates latency referenced to the onset of the target. Waveforms recorded at anterior (F3, Fz, F4, FC3, FCz, FC4), central (C3, Cz, C4) and posterior (CP3, CPz, CP4, P3, Pz, P4) electrode locations are shown.

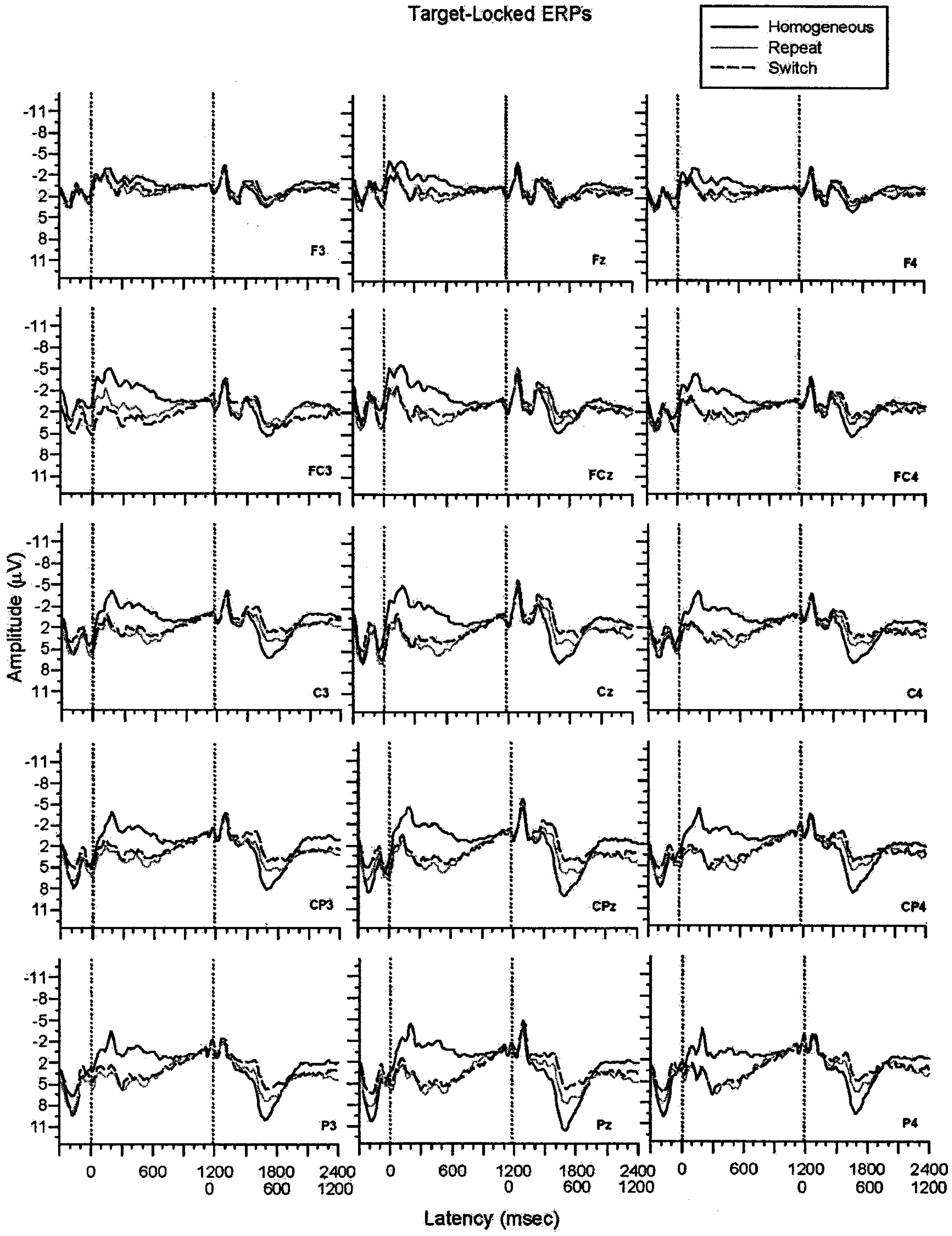

Figure 3. Target-locked grand average waveforms for homogeneous, repeat and switch trials. ERP activity is shown over the entire cue-target interval, however, the waveform was baseline corrected 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue, while the lower X-axis time scale indicates latency referenced to the onset of the target. Waveforms recorded at anterior (F3, Fz, F4, FC3, FCz, FC4), central (C3, Cz, C4) and posterior (CP3, CPz, CP4, P3, Pz, P4) electrode locations are shown.

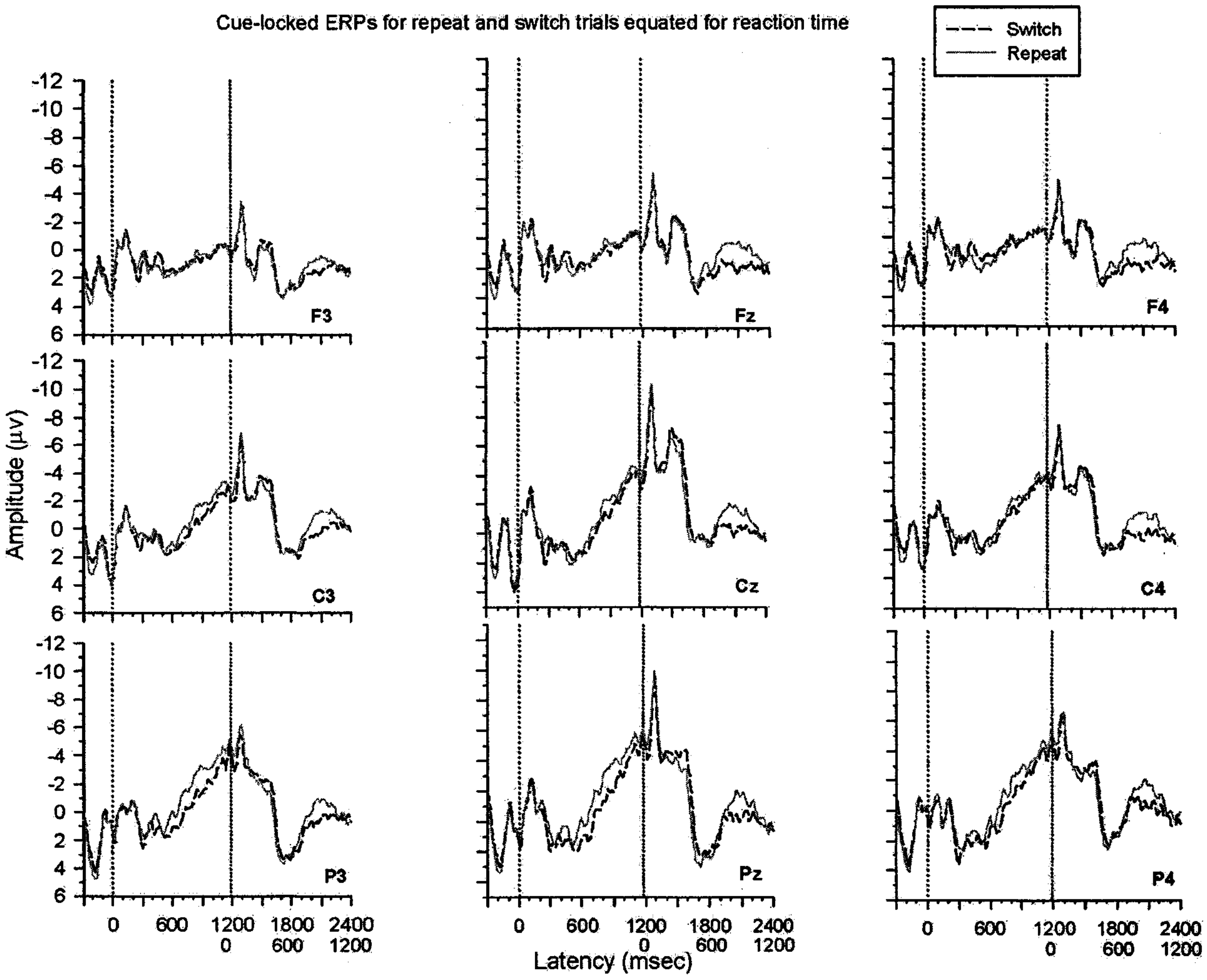

Figure 4. Cue-locked grand waveforms averaged for repeat trials and switch trials equated for RT. ERP activity is shown over the entire cue-target interval with the waveform baseline corrected from –200 ms to 0 ms prior to cue-onset. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue stimulus, while the lower X-axis time scale indicates latency referenced to the onset of the target stimulus. Selected waveforms recorded at anterior (F3, Fz, F4), central (C3, Cz, C4) and posterior (P3, Pz, P4) electrode locations are shown.

MANUSCRIPT 2

Abstract

Age-related changes in task switching were investigated using behavioural measures and event-related brain potentials (ERPs). We tested younger and older adults and separated older adults into high (Old-High) and low (Old-Low) working memory groups. All participants responded more slowly in mixed than single task blocks (RT mixing cost). Younger adults and Old-High participants had equivalent RT mixing costs and showed larger posterior negative slow waves when preparing for mixed than for single task trials, suggesting that mixed task trials needed trial-to-trial preparation. Old-High participants also showed frontally-distributed activity on mixed-task trials, suggesting their use of executive control to offset age-related changes in mixed-task preparation. In contrast, Old-Low participants had large RT mixing costs and large posterior ERP negativities during single task trials, suggesting that they prepare during single and mixed-task blocks.

Neurophysiological measures of task set switching:

Effects of working memory and aging

The cognitive aging literature is now rich with examples showing an association between increasing age and decreasing executive functions (for reviews see West, 1996; Raz, 2000). However executive control processes do not represent a homogeneous construct and identifying the different subcomponents of executive control is a continuing challenge in cognitive neuroscience. Recently, the task switching paradigm has proven useful in characterizing some of these subcomponents (see Monsell, 2003 for a review).

In the current investigation, we used the task switching paradigm to explore age-related changes in executive function. Specifically, we examined whether older adults with better working memory capacities would show task switching performance that was comparable to that of younger adults. This was investigated using behavioural measures and electrophysiological responses (i.e., event-related brain potentials). In the paragraphs that follow we briefly review the relevant task switching literature (behavioural and electrophysiological studies) and examine how advancing age affects the ability to multi-task.

One of the reasons why studying task switching has gained in popularity is because it allows cognitive researchers to decompose performance into specific between-trial effects. Studies that have focused on between trial effects indicate that, when performing in a block where multiple task sets are active, both transient and sustained forms of cognitive control are required (Braver et al., 2003; Meiran et al., 2001). It is possible to isolate transient and sustained forms of cognitive control by contrasting different types of trials across different types of task blocks. In this manner, comparing the performance on repeat and switch trials when these alternate within the same block of trials (known as a heterogeneous or mixed task block) isolates transient forms of control. This comparison is referred to as the local switch cost and is thought to index the processes triggered when reconfiguring the mind for a new set of task goals and response rules. In contrast, comparing the performance on repeat trials that occur within the context of a mixed task block to repeat trials that occur within the context of a single task block (known as a homogeneous block) isolates sustained cognitive control processes. This comparison is referred to as the mixing cost and is thought to index the engagement of extra working memory processes needed to maintain the instructions for all relevant task settings (Meiran et al., 2000).

If we look at the literature on aging and task switching we are informed that elderly adults have larger RT mixing costs than younger adults but equal RT local switch costs (Kray, & Lindenberger, 2000; Mayr, 2001; Meiran et al., 2001). This suggests that aging hinders performance when multiple task sets have to be maintained in working memory, but not when actively switching between task sets (but see Kramer et al., 1999 and Hahn et al., 2004). In order to better understand the nature of this age-related change, it is possible to measure the electrical neural activity generated when performing an externally cued task switching experiment. This was achieved in the current study by recording the event-related brain potentials (ERPs) triggered by either the presentation of a cue or a target stimulus. ERPs have an excellent temporal resolution and are ideally suited to capture rapid voltage variations associated with the onset of different cognitive control processes. The few studies that have looked at ERPs and task switching have mostly been conducted among the young and have shown that multitasking can be fractionated into distinct waveforms associated with either pre-target epochs, target-locked epochs, or both (Goffaux et al., 2006; Karayanidis et al., 2003; Kieffaber & Hetrick, 2005; Lorist et al., 2000; Poulsen et al., 2005; Rushworth et al., 2002). The results of these studies indicate that when having to switch rapidly, pre-target processes elicit a large negative slow wave, distributed over posterior scalp regions. Importantly, larger negative slow waves are observed prior to repeat trials than prior to switch trials, which suggest a processing difference between these two trial types.

In addition to the cue-locked electrophysiological differences observed during local switch cost contrasts, we recently showed that the mixing cost contrast was associated with a difference in the cue-locked activity of homogeneous and repeat trials (Goffaux et al., 2006). Repeat trials showed a negative-going deflection in the later part of the cue-locked interval, starting at approximately 600 ms, whereas the homogeneous condition exhibited an absence of the waveform during this period. In mixed-task contexts, but not single task contexts, environmental cues might signal a task change at any moment, and so these cues must necessarily be processed (Braver et al., 2003), which explains why repeat cues were characterized by negative slow wave activity whereas homogeneous cues were not.

Studies that have used ERPs to investigate the neuroelectric indices of task switching also report a large target-locked posterior positivity (P3b wave) that occurs approximately 300-800 ms after target onset and varies as a function of target type (Karayanidis et al., 2003; Lorist et al., 2000; Poulsen et al., 2005). Larger P3b amplitudes have been obtained following homogeneous, repeat, and switch targets, respectively (Goffaux et al., 2006). Theoretical formulations concerning the functional significance of the P3b waveform suggest that this electrical potential reflects the end-product of cognitive functions active when evaluating a target stimulus, be they template matching, resolution of response competition, or context updating (Kok, 2001). In this manner, P300 differences between trials reflect condition differences in the cognitive resources required or available when evaluating targets.

Age-related studies that have examined ERPs and task switching have been rare; however, Kray et al. (2005) and West (2004) recently found that older adults have an enhanced negativity when they prepare for mixed as opposed to single task blocks (most evident at frontal electrode leads). Both studies interpreted the larger negativity of their older adults as evidence of an age-related difficulty in the ability to maintain a currently relevant task set under mixed-task conditions. This interpretation was motivated by the fact that, in both studies, the cue disappeared well before the target stimulus appeared. However, it is unknown whether older adults would still show larger negative slow waves if the cue was present during most of the preparation interval. If older adults continue to show this pattern when the cue is present, this would suggest an age-related change in task set activation or retrieval rather than task set maintenance. The importance of working memory capacity in explaining this age-related change also remains to be explored. We examine these possibilities in the present study.

The goal of the present study was to examine age differences in task switching performance using behavioural (RT and accuracy) and electrophysiological (cue- and target-locked) measures. Because it was difficult to know from past studies whether age differences were due to problems in maintaining the task in working memory or due to incomplete preparation, we used a cued task switching paradigm with a relatively long preparation interval (almost 1,200 ms) during which the cue remained visible. This allowed our participants to potentially maximize their preparation and minimized task set maintenance demands. Thus, our study was designed to isolate age differences in task set preparation. In addition, we also examined whether differences in working memory capacity could explain age-related differences in task switching performance and neuroelectric activity. To achieve this, we separated older adults into two groups according to their performance on a working memory task (the WAIS-III Letter-Number Sequencing task, LNS)[7]. Older adults included in the Old-High group performed as well as younger adults on the LNS task, whereas older adults included in the Old-Low group performed more poorly than younger adults and Old-High participants. If working memory affects target preparation and response, then we should find group differences in cue and target electrophysiological activity and in behavioural measures.

Method

Participants

Twenty young adults (6 men and 14 women; mean age =24.5, SD=3.4; range= 21-33) and twenty-seven older adults (8 men and 19 women; mean age =75.8, SD=4.4; range= 70-86) participated in this study. Young adults were the same as those tested in

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[7] As might be expected, younger adults did not vary greatly in their working memory performance. Preliminary analyses conducted with the young adults separated into high and low working memory groups did not reveal any differences with respect to their mixing and local switch costs (RT & accuracy). This contrast, therefore, is not discussed in the present study. Because we were interested in how working memory affected task switching performance in older adults, only older adults were separated into high and low working memory groups.

Manuscript 1. Eighteen younger adults and twenty-five older adults reported being right-handed. All other participants were left-handed. Younger adults were recruited from either the Concordia University student population or through word of mouth. Younger adults included in this study were the same participants described in Goffaux et al. (in press). All participants reported being free of neurological or cardiovascular diseases based on their responses to an extensive health questionnaire. None of our participants were taking medications that might affect central nervous system function or cardiovascular tone. Older adults consisted of community-dwelling volunteers, recruited by telephone contact from a list of participants previously tested in the lab. Informed consent was obtained from all participants and each was remunerated $20 for his/her participation. Younger adults had more years of formal education (young mean=18.7, SD=2.3; old mean=15.6, SD=2.9; p<.001) but did not differ from older adults on vocabulary (WAIS-III vocabulary subtest; Wechsler, 1997; young mean=53.7 SD=9.8; old mean=56.4, SD=9.4; p>.05). This suggests comparable general intellectual abilities across groups.

Performance on a measure of working memory (raw score on the Letter Number Sequencing subtest-LNS, Wechsler, 1997) was used to separate older adults into high and low working memory participants. This was done by dividing older adults according to the median of their group performance on the LNS subtest. As a result, 13 older adults were included in the Old-Low group (3 men and 10 women; mean age =75.1, SD=3.7) and 14 older adults were included in the Old-High group (5 men and 9 women; mean age =76.4, SD=5.0). Importantly, Old-High participants and younger adults had similar LNS scores (Old-High mean =13.1, SD=1.7 and young mean =14.1, SD=2.9, p=.22) and both were significantly higher than those of low working memory older adults (Old-Low mean = 9.5, SD=0.7; both ps<.001).

Materials and Apparatus

The target stimuli consisted of 16 concrete nouns (*beetle, nail, worm, stone, apple, marble, banana, ladder, tank, boulder, hippo, train, snake, bear, pencil, tree*) for which the participant performed one of three semantic classification tasks: (A) an existence judgement (is it living or non-living?), (B) a size judgement (is it large or small?) or (C) a breadth judgement (is it wide or narrow?) on any given trial. For each classification task, 50% of the stimuli were associated with each dichotomous response (e.g., for the existence classification task, 8 nouns required a living response and the other 8 required a non-living response).

Each experimental trial consisted of a cue-target sequence (see Figure 1). The same target words were used for each of the three semantic classification tasks (e.g., *pencil* could be categorized as small, narrow, or non-living) and responses were mapped to the same two buttons for all tasks (e.g., the left button was pressed for living, large, and narrow judgements while the right button was pressed for non-living, small, and wide judgements). These task-response mappings were counterbalanced across participants. Each of the 16 nouns (and the three cue words *Existence*, *Size*, or *Breadth*) were presented in a white, 24-point font and appeared on a black background computer screen.

Procedure

Each participant provided informed consent and then completed a detailed demographic and health questionnaire. Participants first completed the task switching experiment and then the LNS and vocabulary subtests of the Wechsler Adult Intelligence

Scale-III. Participants were seated one meter away from a computer monitor and instructed to read silently each of the stimuli presented. Instructions informed the participants that cue-target pairs were to be presented and that the cue would inform them as to which semantic classification task to perform on the subsequent target word. Each cue word was presented on-screen for 1s and was followed by a target (one of the 16 concrete nouns) 1180 ms afterwards. This period of time represented the cue-target interval (CTI). The period of time between the response and the presentation of the cue for the next trial (i.e., the response-cue interval: RCI) was either 200 ms when following a correct response or 800 ms when following an incorrect response. A short 200 Hz tone (100 ms duration) was presented following incorrect responses and, combined with the increased RCI, allowed participants to monitor and optimize their performance on following trials. Participants were instructed to respond as accurately and as quickly as possible. Target words were kept onscreen for a maximum of 5 seconds or until a response was given. So as to minimize electrophysiological artefacts, participants were also instructed not to move, talk or blink during the presentation of the stimuli.

Participants first learned the target-response pairings for each of the three semantic tasks (existence, size, and breadth) in separate homogeneous blocks. Each of the three homogeneous blocks consisted of 160 trials of a single semantic task and each trial therein was, by definition, a repeat trial. The first 80 trials of each block were practice trials. The remaining 80 trials were experimental trials on which behavioural and ERP data were collected. Ordering of the three homogeneous task blocks was randomized across participants. Following the three homogeneous blocks, participants completed two heterogeneous or mixed trial blocks consisting of randomly presented trials sampled with equal frequency from each of the three different semantic tasks. These blocks contained 260 trials each plus 10 warm-up trials at the beginning of each block. Each trial within a heterogeneous block was either a repetition of the previous semantic task or a switch to another semantic task. Heterogeneous block trials were defined as a function of the task performed on one (n-1) or two (n-2) trials previously. Repeat trials consisted of a trial where the same semantic task was performed only twice in a row (e.g., A in an BAA trial sequence). Switch trials consisted of a trial where the participant switched from performing one semantic task to another, without having performed that task on trial n-2 (e.g., A in a CBA trial sequence). None of the 16 target words were repeated within any three-trial sequence in homogeneous or heterogeneous blocks. This prevented short term stimulus-response associations (i.e., negative priming) from interfering with the task-response associations. Repeat trials (as defined above) accounted for 20% of all trials within a heterogeneous block, whereas switch trials (as defined above) accounted for 26%. The remaining 54% were trials that did not follow the specific triplet pattern defined above and included runs of repeat trials (e.g., AAA) or switch trials where the task had been performed recently (e.g., A in an ABA trial sequence); however, these were outside the focus of the current report.

Electroencephalogram (EEG) Recordings

EEG recordings were made using a nylon cap fitted with tin electrodes (Electro-Cap International). The EEG signal was obtained from six midline sites (FPz, Fz, FCz, Cz, CPz, Pz) and 22 lateral sites over the left and right hemisphere, respectively (prefrontal: FP1, FP2; frontal: F3, F7, F4, F8; frontocentral: FC3, FC4; frontotemporal: FT7, FT8; central: C3, C4; centroparietal: CP3, CP4; temporal T5, T6; temporoparietal:

TP7, TP8; parietal: P3, P4, and occipital: O1, O2). A forehead electrode was used as ground. All EEG electrodes were referenced to the left ear during acquisition and re-referenced offline to a linked ear reference. The electrooculogram (EOG) was recorded bipolarly from electrodes placed at the outer canthi of both eyes (horizontal EOG) and above and below the left eye (vertical EOG). EOG artefacts were corrected off-line for all participants using a regression algorithm (Gratton, Coles & Donchin, 1983). EEG activity was sampled continuously at 100 Hz and amplified using Neuroscan Synamps in a DC-30 Hz bandwidth.

Results

Behavioural Data Reduction

Prior to any cost analyses, RTs were trimmed for each of the five blocks such that RTs greater than 2.5 standard deviations of the block mean or less than 200 ms were eliminated. RT data were analysed only for correct trials that followed at least two correct responses. In order to pool data, two analyses of variance (ANOVAs) were conducted to determine whether RT and accuracy data for repeat and switch trials could be collapsed across the three semantic tasks (existence, size and breadth) and across both heterogeneous blocks. These, and all other analyses reported below, were conducted using SPSS v.11.0 statistical software. Greenhouse-Geisser corrections for non-sphericity are applied where appropriate. A task (existence, size, breadth) by block (heterogeneous block 1 and 2) by cost type (local switch cost, mixing cost) ANOVA was first conducted on RT and accuracy scores to test whether cost types differed as a function of block and/or semantic task. This analysis was conducted independently for younger adults, Old-Low participants and Old-High participants in the event that there were subtle group differences that would not be detected by a test for a higher order interaction. To verify if cost type differed as a function of block and/or semantic task, only interactions involving cost type are described. The RT and accuracy analyses failed to show any significant interaction involving cost type for younger adults (All Fs<1.05 and all ps>.05), Old-High participants (All Fs<2.74 and all ps>.05) and Old-Low participants (All Fs<1.20 and all ps>.05), indicating that for all three groups, the local switch and mixing costs did not differ as a function of block or semantic task. We consequently collapsed RT and accuracy data across all three semantic tasks and across both heterogeneous blocks for the analyses reported below.

Behavioural Results

Before comparing our groups on the relative size of their mixing and local switch costs, we verified that Old-High, Old-Low, and younger participants showed the presence of mixing and local switch costs. Comparisons made using raw RT data (see Table 1) revealed a significant mixing cost for all three groups, F (1, 44)=176.78, p=.001, such that participants were faster to respond to repeat trials within a homogeneous block than to repeat trials within heterogeneous blocks. A significant local switch cost was also obtained for all groups, F (1, 44)=67.06, p=.001, revealing that, within heterogeneous blocks, participants responded more quickly to repeat trials than to switch trials.

To see if the size of the mixing and local switch cost differed between groups, we compared logarithmically transformed cost scores. Log transformations were used to minimize group differences in baseline performance. Our results showed that Old-Low participants had larger RT mixing costs than younger adults (p<.02), whereas Old-High participants and younger adults had similar RT mixing costs (p=.31). Old-High and Old-Low participants had similar RT mixing costs (p=.32). All participants had similar RT local switch costs (all ps>.21).

Results for performance accuracy (Table 1), revealed the presence of group differences, F (4, 88)=10.02, p=.001, ε=.777. Whereas younger adults did not show the presence of an accuracy mixing or local switch cost (both ps>.81), Old-High and Old – Low participants responded more accurately to homogeneous trials than to repeat trials, (all ps<.001), and more accurately to repeat trials than to switch trials, (all ps<.01). High and low working memory older adults also had a bigger accuracy mixing costs than younger adults (all ps<.001). All three groups had comparable accuracy local switch costs (all ps>.05).

ERP Data Reduction

Correct trials analysed for RT effects were also analysed for ERP effects. Epochs for cue-locked waveforms were time-locked to the presentation of the cue and epochs for the target-locked waveforms were time-locked to the presentation of the target. Epochs for cue-locked waveforms were baseline corrected between 0 and 100 ms after the cue's onset (see Figures 2, 3, & 4). This post-cue baseline allowed us to reduce the influence of the negative-going resolution of the P300 component associated with the response to the target on the previous trial. As noted in Goffaux et al. (2006), there was potentially an overlap between the late target-locked activity and early cue-locked activity when a short response cue interval is used. Applying a baseline correction after the onset of the cue successfully corrects for this overlap and allows the activation differences which occur later in the cue-target interval to be accurately measured. Epochs for target-locked waveforms were baseline corrected between 980 and 1180 ms after the cue's onset (i.e., 200 ms prior to target onset, see Figure 6). Setting the cue-locked epoch to span a timeframe long enough to include the activity associated with both the cue and the target (i.e., 2400 ms) allowed us to appreciate changes that might have occurred across the whole cue-target period.

Both cue-locked and target-locked waveforms were analysed as a function of scalp region. Mean waveform amplitudes were computed as a function of anteriority and laterality (*left anterior*: F3, FC3; *mid-anterior*: Fz, FCz; *right anterior*: F4, FC4; *left central*: C3; *mid-central*: Cz; *right central*: C4; *left posterior*: CP3, P3; *mid-posterior*: CPz, Pz; *right posterior*: CP4, P4). Cue-locked waveforms were also analysed as a function of time interval. To capture the build-up of slow negative wave activity that gradually developed in the later stages of the cue-target interval, we calculated cue-locked mean amplitude across the 400-800 ms and 800-1180 ms post-cue epochs. Target-locked P300 activity was examined through peak scoring (yielding the amplitude and latency of the most positive point obtained in the 300-800 ms post-target interval).

ERP Results

In order to verify the presence of mixing and local switch cost effects and to test for group differences in the cue-locked waveforms, group and trial type differences were analysed as a function of scalp region and time interval using a series mixed-design ANOVAs. For all cue-locked analyses, data from lateral electrode sites were tested separately using a five-way mixed design ANOVA (trial type X group X anteriority X laterality X time). For midline sites, a four-way mixed design ANOVA (trial type X group X anteriority X time) was used. Cost and group effects in the target-locked waveforms were analysed on midline sites using a three-way mixed design ANOVA (trial type X group X anteriority) separately for peak P3b amplitude and latency scores. The anteriority factor in these ANOVAs included five levels (Fz, FCz, Cz, CPz, Pz) and was limited to midline sites where the P300 component was largest, which is consistent with past task-switching studies (Karayanidis et al., 2003, Lorist et al., 2000, Goffaux et al., 2006). Significant main effects of trial type and group are reported, followed by significant higher-order interactions with any of the other factors. If present, the higher-order interaction is described and decomposed using simple effects with Bonferroni-corrected pairwise comparisons.

Cue-locked Data

Mixing Cost

As illustrated in Figures 2, 3, & 4, for heterogeneous conditions, younger adults showed a negative slow wave potential which became progressively larger by the time the target appeared and which was absent from the homogeneous condition. Both older adult groups, however, showed negative slow wave activity for homogeneous, repeat and switch trials. Negative slow wave activity on homogeneous trials was most striking in the Old-Low group. The ANOVA results conducted to test for cue-locked homogeneous versus repeat differences at midline sites revealed a significant main effect of trial type, F (1, 44)=6.78, p=.01, indicating that repeat trials were more negative than homogeneous trials. A significant main effect of group, F (2, 44)=8.30, p=.001 was also found. Post hoc analyses showed that younger adults had smaller negative amplitudes than either high or low working memory older adults (all p's<.005), whereas the latter two groups did not differ (p>.05). A significant trial type by time interaction, F (1, 44)=45.95, p=.001 was also found. Post hoc analyses revealed that repeat trials were more negative than homogeneous trials but only during the 800-1180 ms interval (p<.001). We are cautious, however, when interpreting this finding since a trial type by group interaction nearly met conventional levels of significance, F (2, 44)=2.86, p=.068 and suggests group differences in the cue-locked mixing comparison. This was confirmed by the analyses conducted for lateral sites.

The ANOVA results for lateral sites revealed a significant main effect of trial type, F (1, 44)=5.21, p=.03, and group, F (2, 44)=8.63, p=.001. A significant trial type by group by anteriority by time interaction, F (4, 88)=2.69, p=.04, ε=.641 was also obtained. Simple effects conducted on the interaction to test for trial type differences indicated that younger adults had larger negative amplitudes for repeat trials than for homogeneous trials across frontal, central and posterior scalp regions during the 800-1180 ms interval (all p's<.01). Old-High participants also showed larger negative amplitudes for repeat than for homogeneous trials across central and posterior scalp regions during the 800-1180 ms interval (all p's<.02). Low working memory seniors, however, did not show this difference (all p's>.05). To understand the locus of the mixing cost pattern difference observed for Old-Low participants, we conducted simple effects to test for group differences on repeat and homogeneous trials separately. Results revealed that Old-Low participants failed to show a mixing cost because their homogeneous negativities, recorded over central and posterior regions, were larger than that of the other two groups (all ps<.05; compare the solid lines of Figures 2, 3, & 4), not because their repeat negativities were smaller (repeat negativities at central and posterior regions were comparable across groups; all ps>.05). Repeat negativities did however differ between groups at fronto-lateral sites (e.g., electrodes F3 and F4). As shown by the repeat surface potential map illustrated in Figure 5, this was most obvious for Old-High participants. Repeat slow waves were reliably more negative for Old-High participants than for younger adults (p<.02 throughout the entire 400-1180 ms interval), whereas Old-Low participants and younger adults did not differ (all ps>.05). In fact, as can be appreciated in Figure 5, fronto-lateral negative slow wave activity was less pronounced in Old-Low participants and almost absent in younger adults. Among older adults, then, those with high working memory exhibited greater fronto-lateral slow wave activity on repeat trials.

Local switch cost

Cue-locked ERP waveforms presented in Figures 2, 3, & 4 show that switch trials were also characterised by posterior negative slow wave activity, although it appeared to be less pronounced than that of repeat trials. The ANOVA results for midline sites revealed a significant main effect of trial type, F (1, 44)=9.15, p=.004, indicating that repeat trials were more negative than switch trials. A significant trial type by group by anteriority by time interaction, F (4, 88)=8.07, p=.0001, ε=.715 was also found. Simple effects conducted on the interaction to test for trial type differences revealed that repeat trials were more negative than switch trials at posterior sites for all three groups. This was observed between 800-1180 ms for younger adults (p<.03) and between 400-1180 ms for Old-Low and Old-High participants (p<.03).

The ANOVA results for lateral sites revealed a significant main effect of trial type, F (1, 44)=4.47, p=.04, and group, F (2, 44)=3.20, p=.05. A significant trial type by group by anteriority by time interaction, F (4, 88)=7.02, p=.001, ε=.575 was also obtained. Simple effects conducted to test for trial type differences indicated that repeat trials were more negative than switch trials at posterior sites between 800-1180 ms for younger adults (p<.03), between 400-1180 ms for Old-High participants (p<.05) and between 400-800 ms for Old-Low participants (p<.03)[8]. Among all three groups, then, a repeat versus switch difference in posterior negative slow wave activity was observed. Simple effects conducted to test for group differences on repeat and switch trials separately also showed that during the 800-1180 ms interval, Old-High participants obtained larger repeat and switch negativities than younger adults at fronto-lateral sites (all ps<.05). Old-Low participants and younger adults did not differ (p>.05).

Target-locked Data

Mixing Cost

Target-locked ERP waveforms presented in Figure 6 show a larger P300 potential for homogeneous trials than for repeat trials. This difference is most noticeable at electrode Pz for all three groups and is present throughout the 300-700 ms post-target interval. The ANOVA results for peak P3 amplitude scores revealed a significant trial type by anteriority interaction, F (4, 176)=7.88, p=.0001, ε=.557. No main effect of group, F (2, 44)=0.83, p=.44 or trial type, F (1, 44)=1.02, p=.32 were found. Simple effects conducted on the interaction to test for trial type differences showed that,

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[8] For Old-Low participants, repeat trials were also more negative than switch trials during the 800-1180 ms interval but only on left posterior electrode sites (p<.05). Insufficient power likely prevented us from observing this left versus right amplitude differences during the late cue-locked epoch (i.e., non-significant trial type by group by anteriority by laterality by time interaction, F (4, 88)=1.87, p=.13, ε=.812).

compared to repeat trials, homogeneous trials had larger positive amplitudes but only at electrode Pz (p<.005). A significant group by anteriority interaction, F (8, 176)=7.20, p=.0001, ε=.389 was also found. Simple effects conducted to test for anteriority differences showed that, for younger adults, P300 amplitudes became progressively larger when moving from anterior to posterior electrode sites (all p's<.02). This was not observed for Old-Low and Old-High participants, who both showed equally large positivites across all electrode sites (all p's>.05).

The ANOVA results for peak P3 latency scores revealed a significant main effect of group, F (2, 44)=8.02, p=.001. Post-hoc comparisons indicated that younger adults had shorter P300 latencies (mean=559.9 ms, SD=102.4) than either Old-High (mean=675.5 ms, SD=102.5; all p's<.01) or Old-Low participants (mean=686.5 ms, SD=102.3), while the latter two groups did not differ (p>.05).

Local switch cost

Target-locked ERP waveforms presented in Figure 6 also show a P300 repeat versus switch difference noticeable throughout the 300-700 ms interval. The ANOVA results for peak P3 amplitude scores revealed a significant main effect of trial type, F (1, 44)=10.06, p=.003, indicating that repeat trials were more positive than switch trials. A significant group by anteriority interaction, F (8, 176)=4.91, p=.002, ε=.438 was also found. Simple effects conducted on the interaction to test for anteriority differences showed that, for younger adults, P300 amplitudes were larger at posterior sites than at frontal and central sites (all p's<.005). For high and low working memory seniors, P300 amplitudes were equally large across all electrode sites (all p's>.05). Together these results indicate that all three groups have a similarly large P300 local switch cost, albeit the topography of the P300 was distributed equivalently across the scalp among the old.

The ANOVA results for peak P3 latency scores revealed a significant main effect of trial type F (1, 44)=10.05, p=.003. This means that repeat P3 amplitudes had a shorter latency (mean=639.6 ms, SD=133.7) than switch P3 amplitudes (mean=685.1 ms, SD=159.7). A non-significant trend towards an effect of group was found, F (2, 44)=2.73, p=.08.

Discussion

When we compared older adults as a function of working memory it was clear that they performed very differently. In line with our hypotheses, we found that older adults with better working memory capacities performed as well as younger adults with respect to the RT mixing cost whereas older adults with poor working memory had larger RT mixing costs than younger adults. The older adults with high working memory and older adults with poor working memory did not differ reliably, although the difference in their mixing costs was large (over 100 ms, favouring high working memory older adults). Nevertheless, the brain activation revealed marked and reliable differences between the two groups, suggesting that older adults with high working memory and those with low working memory are doing something quite different when they multitask. The ERP results reviewed below show how differences in working memory capacity affect the aging brain when preparing for and responding to a target stimulus.

Cue-Locked ERP Effects

For homogeneous cues, younger adults did not show any negative slow wave activity whereas the older adults did. In fact, the posterior negative slow wave activity recorded for homogeneous cues was larger for older adults with poor working memory than for the other two groups. Since posterior negative slow waves develop when a task cue is used to prepare for an upcoming target, posterior negativities are likely associated with context monitoring and the retrieval of task relevant attributes (Johansson & Mecklinger, 2003; Goffaux et al., 2006). Given the group differences we observed during our single-task condition, this would suggest that older adults with poor working memory have to rely on the external context provided by the cue to prepare for homogeneous targets. Older adults with poor working memory capacities may have to use the cue to continually retrieve the current goal even if the task is entirely predictable. Recent data collected by DiGirolamo et al. (2001) also suggest that older adults continually retrieve the algorithms necessary for task set selection during single-task contexts. The authors found that, contrary to younger adults, older adults failed to show an fMRI activation difference when performing in mixed as opposed to single task contexts. Importantly, the lack of a significant difference in activation between mixed and single task conditions for older adults resulted from a greater activation of the cortical regions underlying single-task performance, not from a diminished activation of the cortical regions underlying mixed-task performance. The authors concluded that advancing age obligates the use of similar neural control when performing in both single and mixed-task contexts. This study, however, did not take into account the effects of working memory capacity on age-related changes in performance. As shown in the present study, when working memory capacity is taken into consideration, it is clear that only low working memory seniors needed to exert trial-to-trial preparation during single-task contexts.

In the present study we also observed a significant difference in ERP scalp topography between groups. At frontal sites, older adults with high working memory had larger negative slow waves than younger adults for both repeat and switch trials. Most obvious was the enhanced fronto-lateral negativity (at electrodes F3 & F4) of Old-High participants. Although we cannot assume a direct relationship between ERP topography and brain localization, larger negative slow wave activity at frontal sites is thought to reflect the activity of frontal executive processes triggered when effortful control is invested (Falkenstein et al., 2003; Lorist et al., 2000). In our case, the large negativity of Old-High participants suggests that they are capable of exercising greater executive control when preparing for mixed-task targets since their RT costs were similar to those of younger participants. Age-related increases in bilateral frontal activity have previously been reported in a variety of cognitive domains, including episodic memory retrieval (Grady et al., 2002), working memory function (Reuter-Lorenz et al., 2000) and inhibitory control (Nielson et al., 2002). Bilateral activation of homologous frontal regions has been attributed to a general mechanism of compensatory processing (Cabeza et al., 2004). Evidence for this has recently been provided in a PET study, where the brain activity of younger and older adults was recorded as they performed a difficult working memory task (Cabeza et al., 2002). High-performing older adults performed as well as younger adults but continued to show greater DPFC activity than younger adults. Such findings support the idea that greater fronto-lateral activation is related to compensatory processing. Given that we obtained enhanced activity over fronto-lateral scalp regions and a small RT mixing cost for our Old-High participants (equal to that of younger adults), we surmise that they responded to the mixed-task condition by compensating for the increased difficulty that occurs when having to respond in conflicting situations. We believe that this compensatory activity facilitated task set retrieval for Old-High participants.

Interestingly, there is evidence that bilateral prefrontal regions play a key role in the retrieval of stored information, especially in competing situations. For example, Bunge et al. (2002) found greater bilateral prefrontal cortex activity when their participants retrieved S-R associations in the presence of incongruent targets but not in the presence of congruent targets (i.e., in the presence or absence of competing flanker cues). Using fMRI BOLD signals, Rypma and D'Esposito (2000) found that cued retrieval of target items from a memory set was associated with a distinct pattern of (mostly dorsolateral) prefrontal cortex activity. Further, they found that the nature of the association between retrieval-related activity and performance varied as a function of age. For younger adults, slower subjects showed greater dorsolateral prefrontal cortex activity than faster subjects. For older adults, slower subjects showed less dorsolateral prefrontal cortex activity than faster subjects. This suggests that the prefrontal cortex is recruited to help retrieve stored information, especially if one is young and poor at it or old and good at it.

In contrast to Kray et al. (2005) and West (2004) who surmised that there was a task set maintenance problem with advancing age because the cue disappeared well before the target appeared (at least 1000 ms earlier), we suggest that age-related changes in task set preparation are also associated with task set retrieval differences. Since our cue was available through the cue-target interval, differences in cue-locked neural activity recorded over frontal regions (i.e., larger fronto-lateral negative slow waves for Old-High than for younger adults) probably reflect task set retrieval processes.

One potential limitation of our study is worth noting. We used a long cue-target interval because we wanted to evaluate older adults' ability to prepare when given an adequate amount of time. This resulted in a lengthy test session. As a consequence, we were compelled to use a short response-cue interval (i.e., 200 ms) to reduce testing time and avoid fatigue, particularly in our older participants. However, it can be argued that a short response-cue interval may allow persisting task activation from a preceding trial which may interfere with preparation for the subsequent trial. This type of competition is known as proactive interference and its effects dissipate gradually as the delay between the response and the cue increases (Meiran et al., 2000). Interestingly, Meiran et al. (2001) and Cepeda et al. (2001) reported that such proactive interference dissipates more slowly for older adults than for younger adults. This means that when a short response cue interval is used, age differences in RT may be seen. However, this problem only holds for contrasts involving the local switch cost since proactive interference occurs only when the preceding trial is a different task from the current one. In fact, when a task repeats, the previous trial should generate proactive facilitation. Thus, in the current study, if the proactive effects of previous tasks dissipate more slowly for older adults, then we should have seen a larger local switch cost and a smaller mixing cost compared to younger adults. Since we did not find this pattern of results, we do not think that our short response-cue interval penalized our older adults in this paradigm. Moreover, our decision to extend the baseline for the ERP averages into the cue-interval eliminated any carry-over of the response to the previous trial on the current trial. Nevertheless, our future research will manipulate response-cue and cue-target intervals in order to fully investigate their effects.

Target-Locked ERP Effects

Unlike younger adults, older adults showed greater equipotential P3 distribution across the scalp for all trial types which suggest that younger and older adults do not recruit the same neural circuits when classifying target stimuli. This finding is often reported (e.g., Anderer et al., 1996; Iragui et al., 1993; Pfefferbaum et al., 1984; Friedman, 2003) and supports the idea that advancing age is associated with a redistribution of the cortical generators underlying P300 activity. In addition, older adults showed an overall delay in peak P3 latencies which is consistent with the hypothesis that advancing age decreases overall stimulus classification speed.

Nevertheless, for all groups, peak P300 amplitudes were larger for homogeneous trials followed by repeat, and then switch trials, respectively. In the present study, homogeneous versus repeat and repeat versus switch trial differences in P300 amplitude did not vary as a function of group membership. One way of explaining this finding is to view target-evaluation as an obligatory process that persists even after ample preparation time has been allotted. Such obligatory processes might follow low-level processing streams that are insensitive to differences in higher-order control functions (see Mayr & Keele, 2000 for a similar argument). In our case, this would explain why differences in working memory capacity did not change the size of the P300 mixing and local switch cost. Other factors that affect cognitive control functions, such as mental fatigue and caffeine consumption also fail to affect the P300 mixing (Tieges et al., 2006) and local switch cost (Tieges et al., 2006; Lorist et al., 2000). Fatigue and caffeine consumption do, however, affect the frontal negative slow wave that develops during the preparation interval. Together with our results, this suggests that variations in cognitive control specifically affect preparatory process, not target evaluation *per se*.

Summary

The use of ERPs in a cued task switching design has allowed us to chart the time course of cognitive control functions as they lead up to and follow specific target events. In combination with behavioural results we were able to record cue- and target-locked waveforms and detail an age-related change in cognitive control functions. In the present study, older adults with lower working memory capacities had large posterior negativities when preparing for homogeneous targets, suggesting that they need to rely on external cues even when preparing for single task targets. This ERP activity was not observed for Old-High participants and young adults. In contrast, older adults with high working memory capacities showed greater negative slow wave activity over fronto-lateral scalp regions when preparing for mixed task trials and obtained small RT mixing costs. This suggests that better working memory capacities in old age facilitate the mobilization of frontal control which helps to offset declining performance during mixed-task contexts.

Finally, age and working memory did not affect inter-trial differences (homogeneous versus repeat and repeat versus switch) in P300 amplitude. We believe this indicates an obligation to activate low-level processes during target evaluation; an obligation which all participants had to satisfy in order to successfully classify the target events.

Acknowledgements

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Table 1

Mean and Standard Deviation of Untransformed Reaction Time (ms), Transformed Reaction Time (log ms) and Accuracy (%)

	Trial Type						Cost			
Young Participants	Homogeneous		Repeat		Switch		Mixing Cost		Local Switch Cost	
Raw Reaction Time	550.0	(59.7)	748.2	(113.5)	836.6	(180.1)	198.2	(82.7)	88.4	(80.8)
Transformed Reaction Time	2.74	(.05)	2.87	(.07)	2.91	(.09)	.13	(.05)	.04	(.04)
Accuracy	96.2	(3.2)	95.6	(3.3)	94.2	(3.9)	-.58	(3.2)	-1.4	(4.5)
Old-High Participants	Homogeneous		Repeat		Switch		Mixing Cost		Local Switch Cost	
Raw Reaction Time	723.5	(67.8)	1051.7	(174.5)	1202.5	(269.8)	328.2	(209.0)	150.8	(141.9)
Transformed Reaction Time	2.86	(.04)	3.02	(.07)	3.07	(.10)	.16	(.09)	.05	(.05)
Accuracy	98.0	(2.6)	92.0	(7.6)	86.9	(12.9)	-6.0	(5.8)	-5.1	(7.1)
Old-Low Participants	Homogeneous		Repeat		Switch		Mixing Cost		Local Switch Cost	
Raw Reaction Time	776.6	(129.4)	1212.0	(199.2)	1398.9	(222.2)	435.4	(196.4)	186.9	(133.8)
Transformed Reaction Time	2.89	(.07)	3.08	(.08)	3.14	(.08)	.19	(.08)	.06	(.04)
Accuracy	97.8	(2.2)	88.6	(5.1)	83.3	(5.8)	-9.2	(5.2)	-5.3	(5.8)

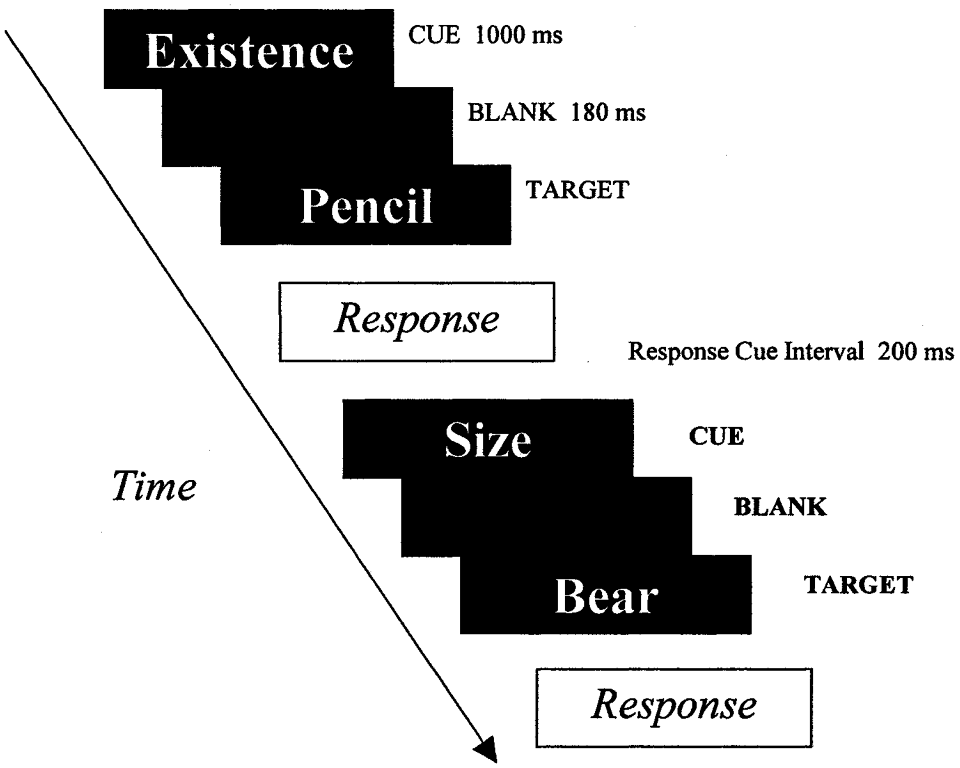

Figure 1. Example of the cue-target sequencing and timing used in our design.

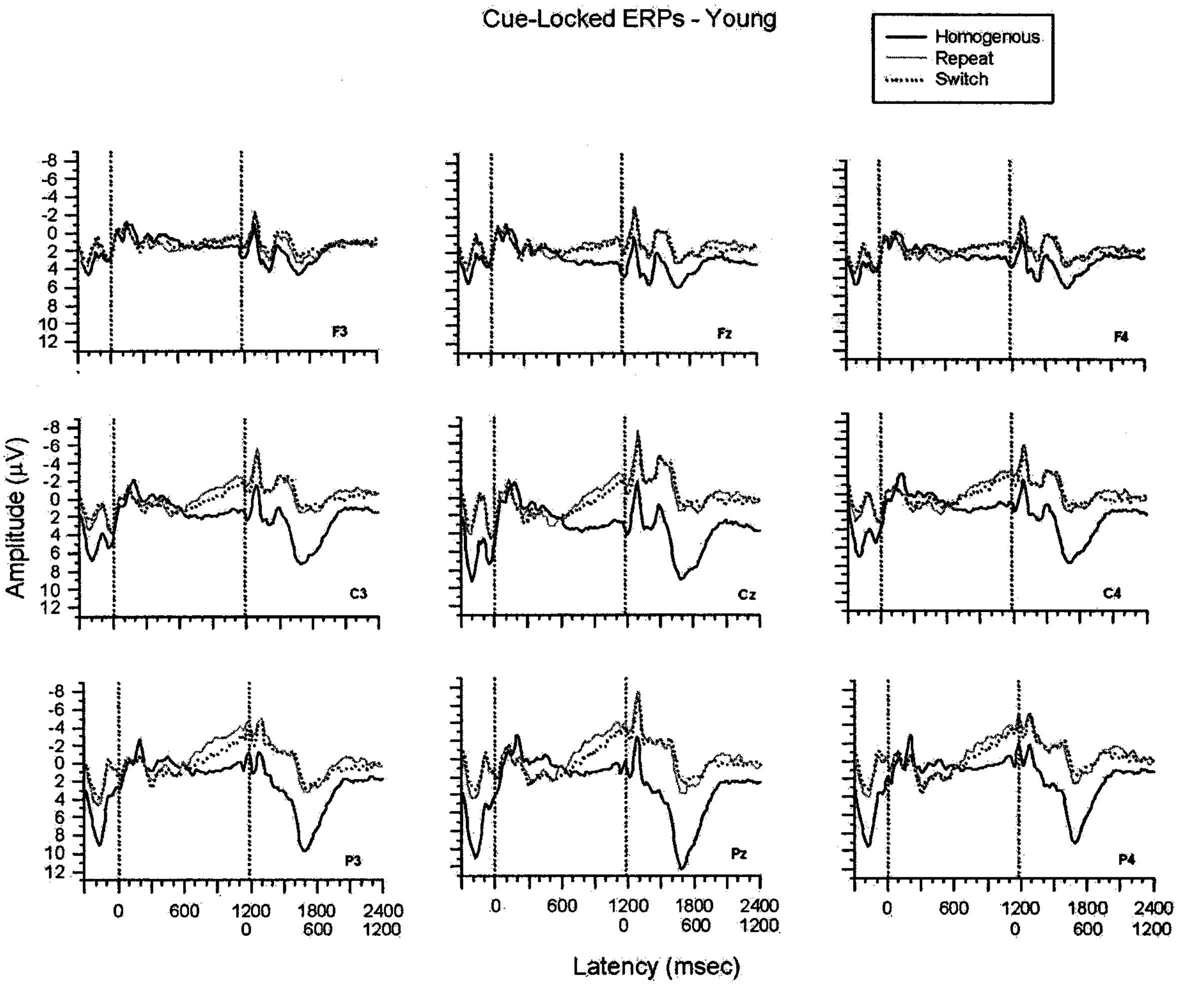

Figure 2. Younger adults' cue-locked grand average waveforms for homogeneous, repeat and switch trials. ERP activity is shown over the entire cue-target interval, however, the waveform was baseline corrected from 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue, while the lower X-axis time scale indicates latency referenced to the onset of the target. Selected waveforms recorded at anterior (F3, Fz, F4), central (C3, Cz, C4) and posterior (P3, Pz, P4) electrode locations are shown.

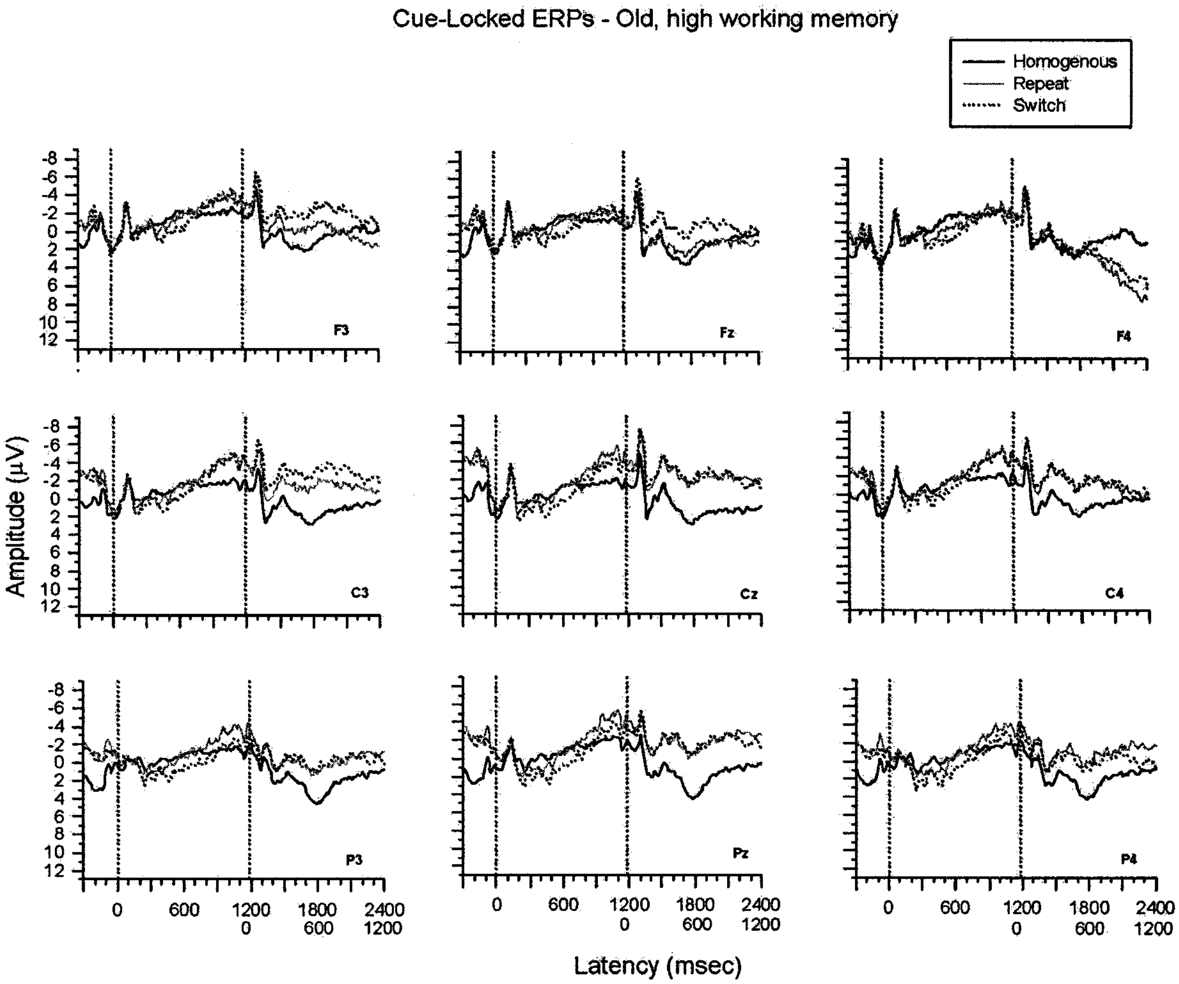

Figure 3. High working memory older adults' cue-locked grand average waveforms for homogeneous, repeat and switch trials. ERP activity is shown over the entire cue-target interval, however, the waveform was baseline corrected from 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue, while the lower X-axis time scale indicates latency referenced to the onset of the target. Selected waveforms recorded at anterior (F3, Fz, F4), central (C3, Cz, C4) and posterior (P3, Pz, P4) electrode locations are shown.

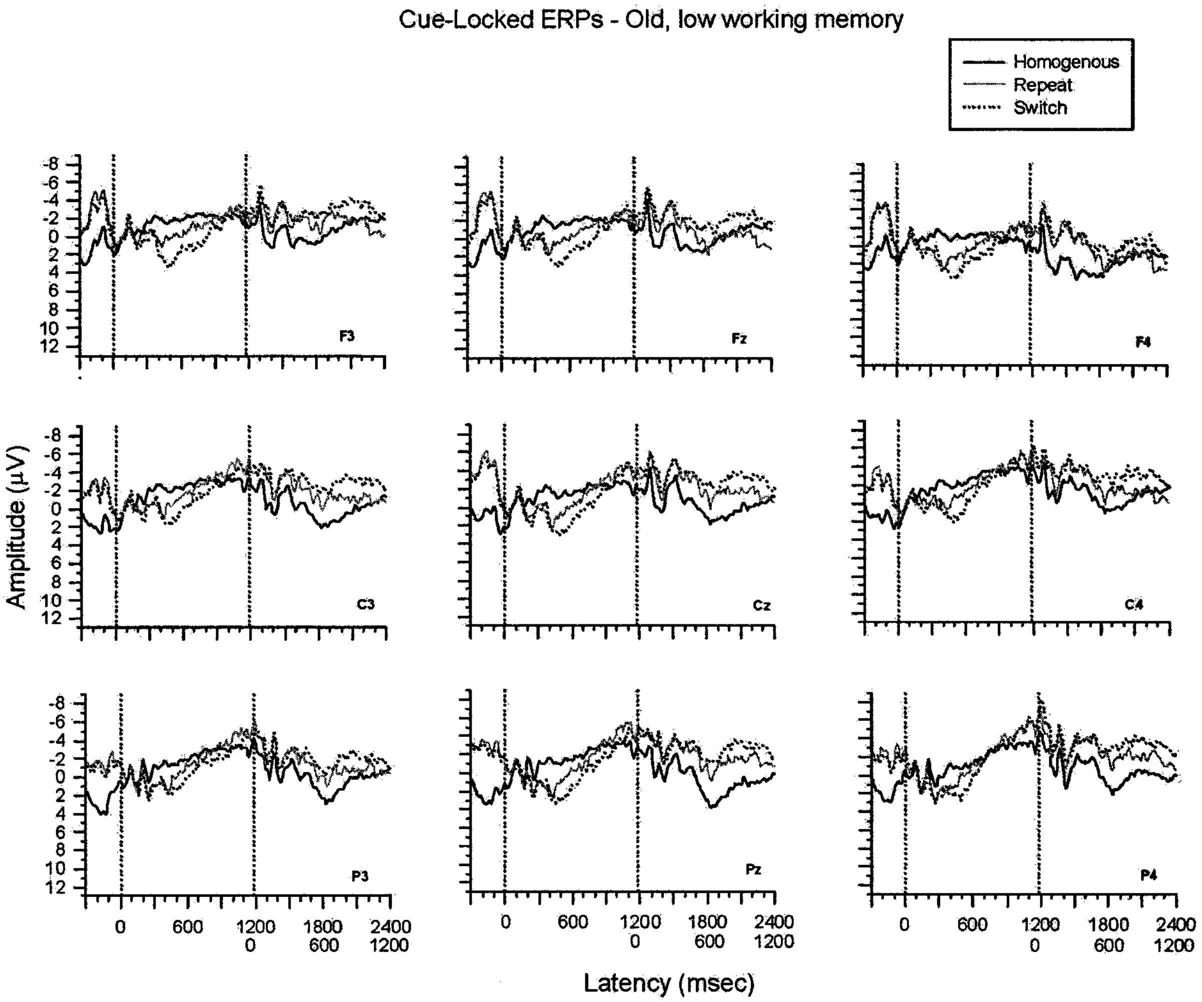

Figure 4. Low working memory older adults' cue-locked grand average waveforms for homogeneous, repeat and switch trials. ERP activity is shown over the entire cue-target interval, however, the waveform was baseline corrected from 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue, while the lower X-axis time scale indicates latency referenced to the onset of the target. Selected waveforms recorded at anterior (F3, Fz, F4), central (C3, Cz, C4) and posterior (P3, Pz, P4) electrode locations are shown.

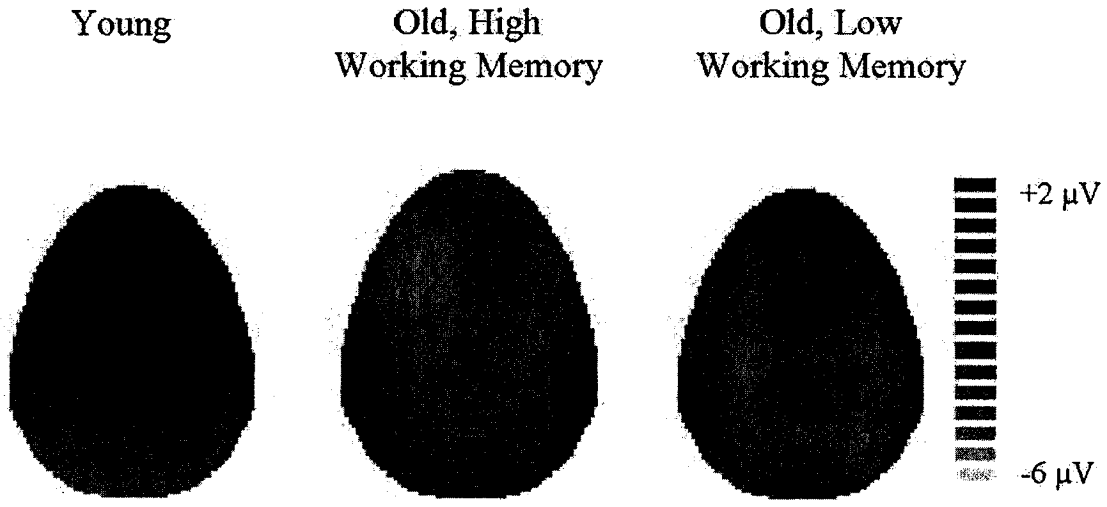

Figure 5. Topographic scalp plot of the voltage for the cue-locked negative slow wave recorded between 800 and 1180 ms. Topographic maps show repeat trial activity for younger adults, high working memory older adults and low working memory older adults. Compared to low working memory older adults and younger adults, high working memory older adults show greater negative slow wave activity (i.e., lighter shading) across fronto-lateral regions.

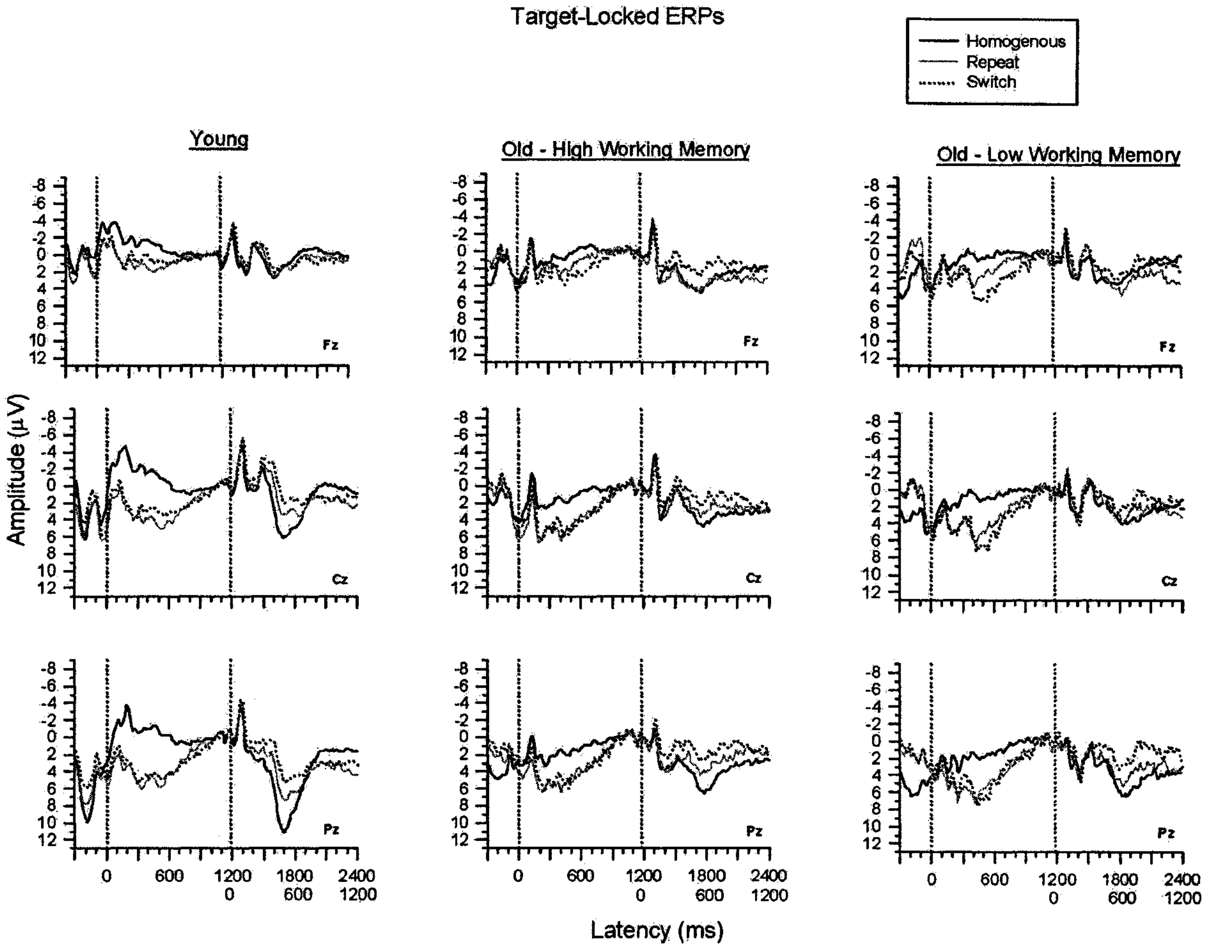

Figure 6. Target-locked grand average waveforms for homogeneous, repeat and switch trials. ERP activity is shown over the entire cue-target interval, however, the waveform was baseline corrected 0 to 100 ms into the cue interval. The first and second vertical dotted lines indicate cue and target onset, respectively. The upper X-axis time scale indicates latency referenced to the onset of the cue, while the lower X-axis time scale indicates latency referenced to the onset of the target. Waveforms recorded at midline (Fz, Cz, Pz) electrode locations are shown for younger adults, high working memory older adults and low working memory older adults.

MANUSCRIPT 3

Abstract

The current study investigated the separability of two typical markers of task switching performance, namely the mixing cost reaction time (RT) and the local switch cost RT. Performance on these two markers was regressed onto different neuropsychological measures of executive control. These included 1) the ability to execute task alternations 2) the ability to inhibit non-relevant information during the retrieval process, and 3) the ability to exercise restraint over strong response tendencies. Results indicate that the mixing cost is strongly associated with the ability to inhibit non-relevant information, whereas the local switch cost is strongly associated with the ability to execute task alternations and the ability to exercise restraint over strong response tendencies. The data was collected among a group of older adults (70-86 years of age), yet age continued to predict changes in mixing but not local switch cost RT. This indicates that advancing age continues to play a role in predicting task switching performance, even in late-life.

Selection of mental sets: Is one process enough to account for all costs?

Most models of action monitoring assume that some form of endogenous control is necessary when a change in task is required or when the task context is associated with task ambiguity (Miller & Cohen, 2001; Norman & Shallice, 1996; Rogers & Monsell, 1995). Endogenous control is usually seen as a higher order cognitive process composed of multiple abilities, such as focusing attention on relevant information, updating the contents of working memory, inhibiting the influence of task irrelevant information and exercising restraint over strong response tendencies.

Exploring the dynamics of control behaviour can be achieved by looking at decrements in performance under task alternating situations (Meiran, 1996; Rogers & Monsell, 1995). In recent years, a paradigm that has often been used to examine task alternation abilities is the task switching paradigm. In this paradigm, participants switch between different tasks in blocks of mixed-task trials (where, occasionally, tasks repeat) or they perform the same task repeatedly in single-task or homogeneous blocks. Two switch costs, can be measured using the task switching paradigm: the local switch cost and the mixing cost. The local switch cost is determined as the difference in performance between switch trials and repeat trials in mixed-task blocks and is thought to reflect the reconfiguration of task settings at trial-to-trial transitions (Kray , 2005; Rogers & Monsell, 1995). On the other hand, the mixing cost, assess the difference in performance between trials that repeat in mixed-task blocks and trials that repeat in single-task blocks. The mixing cost reflects the ability to deal with multi-task contexts in general. Results from a confirmatory factor analysis reveal that these two costs reflect distinct components of attentional control (Kray & Lindenberger, 2000). Further evidence that the local switch cost and the mixing cost reflect different components of task switching comes from a recent neuroimaging study which showed that the mixing cost and local switch cost activate different brain regions (right anterior prefrontal cortex activity and left prefrontal and parietal cortex activity, respectively; see Braver et al., 2003). Furthermore, there is evidence that advancing age is differentially sensitive to the different task switching abilities. In particular, older adults show substantially greater mixing costs than younger adults whereas their local switch costs do not differ (Kray et al., 2004; Kray & Lindenberger, 2000; Mayr, 2001).

Some studies (Kramer et al., 1999, Kray et al., 2002), however, have shown that older adults do have larger local switch costs than younger adults, but that this difference disappears with practice or is reduced when a small number of task sets are switched between. Nevertheless, it appears that the local switch cost cannot be reduced (even with practice) when subjects have to keep track of the switching sequence in order to switch every five trials, suggesting that it is working memory (WM) capacity which explains the poor performance of older adults in mixed-task situations, not task switching *per se.*

There is little doubt that WM plays a key role in a broad array of complex cognitive abilities (especially in tasks requiring divided attention) and that WM capacity declines with advancing age (see Craik & Jennings, 1992). However, WM is composed of a wide variety of different processes, some of which are particularly sensitive to the effects age. These processes include inhibition, coordination, planning, updating and switching (Miyake et al., 2000), the same processes though to be indexed by the local switch cost and the mixing cost (albeit to different degrees). Unfortunately, there is currently very little convergent evidence describing the nature of the executive control demands indexed by the local switch cost and the mixing cost specifically. One exception is a study conducted by Kray and Lindenberger (2000), which showed that both the general cost (conceptually similar to the mixing cost) and the local switch cost were highly correlated with typical marker abilities from the fluid intelligence domain (reasoning abilities and perceptual speed) whereas they were not related to measures from the crystallized domain (knowledge and vocabulary). In addition, relations of WM to general and local switch costs were more negative among older adults than among younger adults, suggesting that individual differences in working memory capacity may play a central role in predicting the size of the mixing and local switch costs among older adults. Unfortunately, besides distinguishing between fluid mechanic and crystallized abilities, the Kray and Lindenberger study did not systematically investigate specific executive processing abilities and their relationship to the mixing and local switch cost. As a result we can only speculate as to the nature of the attentional executive processes specifically captured by the mixing and local switch costs.

In the present work, we tested a group of older adults to see if specific executive control functions would predict reaction time (RT) performance on mixing and local switch costs. Three executive processes were investigated for which evidence was reported in the literature in regards to age-related decreases in performance. These processes are 1) the ability to execute task alternations 2) the ability to inhibit non-relevant information during the retrieval process, and 3) the ability to exercise restraint over strong response tendencies (see Zacks & Hasher, 1997). These processes were measured by administering the Trail Making Test (Reitan & Davison, 1974), a proactive interference measure (adapted from Moscovitch & Winocur, 1983), and the Stroop Test

(Stroop , 1935), respectively. A further rationale for selecting these three executive processes was that they have previously been described as cognitive primitives, or discrete components of executive functioning (Miyake et al., 2000) and are thought to be necessary components underlying the ability to multitask (see Allport et al., 1994; Allport & Wylie, 1999; Arbuthnott & Frank, 2000b). Performance on these three executive processes was then correlated with RT mixing and local switch cost measures obtained from a cued, randomly alternating task switching study (see Manuscript 2). It was hypothesized that when diverse executive control functions are sampled, the mixing cost and the local switch cost would load on different tasks, each measuring a different component of attentional control.

Since decline in performance is thought to accelerate in late-life, we expected that age would continue to explain part of the variance in some of the executive control measures administered, despite the fact that our analyses were restricted to a group of older adults. Tasks that correlate significantly with age, therefore, are likely to indicate cognitive control functions that continue to show late-life decline. It is important to point out that we also measured WM capacity (raw scores on the Letter Number Sequencing subtest, Wechsler, 1997). Since WM capacity may predominantly reflect differences in the amount of inhibition that is applied to keep memory traces free from the interfering effects of competing information (Engle & Kane, 2004), WM should load most heavily on the proactive interference score.

Finally, a number of authors have recommended that performance in baseline conditions be controlled for, either by looking at difference scores, or better yet, by looking at ratio or log transformed scores (Verhaeghen and De Meersman, 1998;

Arbuthnott & Frank, 2000b). Analyzing transformed scores, as opposed to raw scores, makes it possible to assess relative performance changes, thus providing information that is somewhat independent of psychomotor speed and visual scanning speed. This approach was used in the present study.

Method

Participants

Twenty-seven older adults (8 men and 19 women; mean age =75.8, SD=4.4) participated in this study. Characteristics of the sample are described in Manuscript 2.

Tasks

The study reported here consisted of five tasks, the Trail Making Test (Reitan & Davison, 1974), a proactive interference measure (adapted from Moscovitch & Winocur, 1983), the Stroop Test (Stroop , 1935), the Letter Number Sequencing subtest from the WAIS-III (Wechsler, 1997), and a task switching paradigm (see Goffaux et al., 2006). Participants first performed the task switching experiment and then, on a separate day, the remaining neuropsychological tests.

Trail Making Test

The Trail Making Test measures the time taken to link randomly arranged letters (Trail A) or randomly arranged letters and numbers (Trail B) into an alphabetic (A-B-C…) or alphanumeric (1-A-2-B...) sequence. In the alphanumeric sequence, subjects must exercise additional cognitive control because they are required to switch between sequential numbers and letters. As a result their RT increases when compared to their performance on the alphabetic sequence. The difference in time needed to complete the two forms provides a measure of executive control. The difference score can also be proportionalized by dividing the performance on form 2 by the performance on form 1. This proportional score is a better indicator of task alternation abilities than is performance on form 2 alone (Arbuthnott & Frank, 2000b). The proportional Trail Making score adequately reflects the control necessary to execute switches between well-learned sequences (Arbuthnott & Frank, 2000b).

Proactive Interference

Proactive interference involves 4 trials of immediate recall of 8-word lists, each list being drawn, without replacement from the same taxonomic category (body parts), followed by one trial (trial 5) of free recall of a list from a different category (fruits – adapted from Arbuckle & Pushkar Gold, 1993). Three performance measures can be calculated from the proactive interference test. The first is the build-up of proactive interference score which is calculated by subtracting the total number of correct words recalled on trial 1 from the total number of correct words recalled on trial 4. This difference score usually gives negative values since proactive build-up interferes with recall at trial 4 and since proactive build-up is absent on trial 1. The difference score, therefore, indexes the extent of interference from previously relevant but currently irrelevant information during the retrieval process. The second measure derived from the proactive interference test is the release from proactive interference measure. This is calculated by subtracting the total number of correct words recalled on trial 4 from the total number of correct words recalled on the release trial (trial 5). Trial 5 is known as the release trial because it involves the free recall of items selected from a new taxonomic category. Such a category switch preserves against the proactive interference that has been building up through trials 1-4. As a result, the difference score is usually positive since a larger number of items should be recalled on trial 5 than on trial 4. Release from proactive interference is really a measure of the ability to disinhibit (see Arbuckle & Pushkar Gold, 1993). Finally, it is possible to record the total number of words recalled on trial 1, a trial which is unaffected by any other word list and which can be used as a rough estimate of verbal short-term memory.

Stroop Test

For the Colour Stroop test (Lezak, 1995), subjects first have to read a list of coloured words, out loud, as fast as possible. Subjects are then asked to name the ink colour of a similar list of coloured words. Performance is typically slower on the ink naming trial than on the word reading trial because participants have to effectively inhibit the dominant word reading response during the ink naming trial. The interference measure is calculated by subtracting the time necessary to read the first list from the second list. Again, it is best to proportionalize the scores by dividing the performance on the ink naming list form the performance on the word reading list, thus controlling for baseline differences in psychomotor speed. Controlled or selective attention is thought to support performance on the Stroop task by biasing the information-processing system towards the goal-compatible dimension (West, 20004). Most of all, however, the Stroop Test is associated with conflict processing stemming from competitor priming at the target level. In other words, the Stroop test measures the restraint that must be applied when different target responses features compete with one another and where the stronger response must be inhibited.

Letter Number Sequencing

The Letter Number Sequencing subtest (Wechsler, 1997) consists of a series of randomly inter-mixed digits and letters presented orally by the examiner. Participants have to sort the alphanumeric list by first repeating the numbers in ascending order, then the letters in alphabetic order. The test is sensitive to the processing and storage functions of working memory and can be distinguished from verbal short term memory tests which index rote recall but not the ability to both hold and manipulate information. Letter Number Sequencing depends on a number of different skills including short term acquisition and retrieval, sequential processing, and planning abilities (Kaufman & Lichtenberger, 1999). It can, therefore be considered as a general working memory measure but does not describe the specific cognitive abilities that may affect its performance.

Task Switching Paradigm

The task switching paradigm used here is the same as the one described in Goffaux et al. (2006). Essentially, the task consisted of 16 concrete nouns for which the participant performed one of three semantic classification tasks: (A) an existence judgement (is it living or non-living?), (B) a size judgement (is it large or small?) or (C) a breadth judgement (is it wide or narrow?) on any given trial. Response rules and target words were multivalent. A cue was therefore provided ahead of each target word (1180 ms) in order to specify the task to be performed. The period of time between the response and the presentation of the cue for the next trial was either 200 ms when following a correct response or 800 ms when following an incorrect response. Target words were presented either in homogeneous blocks (where only one classification scheme was necessary) or in heterogeneous blocks (where all three classification schemes were presented randomly). From the trials present in these two types of blocks it was possible to calculate RT mixing costs and RT local switch costs (see Manuscript 1). Importantly, RTs were log transformed for each type of trial (homogeneous, repeat and switch), therefore minimizing the effects of individual differences in baseline performance when calculating the mixing and local switch costs.

Results

Table 1 displays the results obtained from the task switching paradigm and from each one of the neuropsychological tests. Intercorrelations (Pearson Product Moment) between the different neuropsychological measures and the two task switching costs are displayed in Table 2. A number of findings were noteworthy: First, the mixing cost and the local switch cost correlated with very different measures but not with each other. The mixing cost correlated highly with release from proactive interference and with age, whereas the local switch cost correlated highly with the Stroop task and with the Trail Making test, but not with age, and not with the proactive interference measures. Second, the Letter Number Sequencing task was mildly associated with every other measure, including age, but was not significantly correlated with any of them.

Given the significant relationship between age and the mixing cost and between release from proactive interference and the mixing cost, hierarchical regression analyses were conducted in which the order of entry of variables (i.e., release from proactive interference and age) was systematically varied. The purpose of this procedure was to determine the extent of overlap between proactive interference and age to explain the variance in mixing cost RT. This allowed us to confirm if age-related changes in mixing cost RT are mediated by changes in release from proactive interference. The contributions of the individual subsets to R^2 across the possible orders of entry are shown in Table 3. Results clearly indicate that the relative magnitude of the contribution of age to explain the mixing cost (as reported in Table 2) was reduced when entered in the second step of the regression equation (when entered after proactive interference). On the other hand, the magnitude of the relationship between proactive interference and the mixing cost remained high, even when entered after age in the regression equation.

Discussion

The major finding in the present study was that the local switch cost and the mixing cost were associated with unique predictors. This means that the ability to deal with multi-task contexts and the ability to reconfigure the cognitive system when switching from one task to another are empirically separable. In particular, the current finding adds to the Kray and Lindenberger (2000) study which originally showed a significant relation between task switching and fluid intellectual abilities. In the current study the local switch cost, but not the mixing cost, was associated with the ability to execute task alternations (Trail Making Test) and the ability to exercise restraint over strong response tendencies (Stroop Test). This means that the set switching construct is associated with attentional control processes necessary to manage rapid alternations between two or more tasks and with competitor priming effects. These results are consistent with previous findings (Arbuthnott & Frank, 2000b; Waszak, Hommel, & Allport, 2005) and also suggest that distractor suppression occurs mostly during transition trials, not repeat trials (or else performance on the Stroop would have correlated significantly with mixing cost RT).

For the mixing cost, the strongest association was found with the release from proactive interference. This means that the increase in task sets from one (single-task block) to three (mixed-task block) also increases the interference between tasks and the need to inhibit previously activated cognitive content in order to select the correct task set. Dealing with proactive interference, therefore, seems to be a critical factor in predicting individual differences in mixing cost RT. Since proactive interference scores were more strongly associated with mixing cost performance than short term memory or WM in general, active suppression is likely a key factor in determining individual differences in dual task performance, rather than passive storage (maintenance) or some other executive component of WM.

It is interesting to note that that the build-up of proactive interference was not significantly correlated with mixing cost RT or with age. This was surprising since inefficient inhibitory control should have increased the build-up of proactive interference. Our results, however, are consistent with those recently obtained by Hasher et al. (2002). Hasher et al. (2002) found no difference between younger and older adults in the build up of proactive interference and argued that age invariance in proactive build-up was attributable to the response strategy adopted by older adults. That is, older adults, who have poor control over deletion functions, may elect to set a very low response criterion, reporting all items in working memory. On the other hand, younger adults, with good deletion abilities, may opt to set a high response criterion, reporting only those items that belong to the current list. If this is true, then older adults will produce a large list containing both correct and incorrect items (i.e., those from previous trials). Such a strategy will ensure a large number of correct items recalled but will also inflate the number of intrusion errors. Therefore, analyzing intrusion rates may be a better approach and should give an index of proactive interference that is independent of the strategy adopted to complete the task. We are currently re-scoring our data in order to include intrusion errors as a predictor.

Another feature of interest was that age correlated significantly with the mixing cost but not the local switch cost. This is consistent with evidence that age-based limitations in local task switching are often small or absent whereas age-based limitations in global task switching are often large and robust (Kray & Lindenberger, 2000; Mayr, 2001; Verhaeghen & Cerella, 2002). Most importantly, however, when proactive interference was entered before age into the regression equation, the effects of age were greatly diminished. On the other hand, proactive interference remained highly correlated with mixing cost RT, even after having controlled for the effects of age. These results suggest that the age-related increases in mixing cost RT may in part reflect a decline in the ability to deal with proactive interference (especially its release) during task set selection. This age-related effect is consistent with the age and WM literature which suggests that deletion functions are less efficient for older than for younger adults and that because of this, obsolete or irrelevant items clutter WM, making it difficult to select the appropriate information at recall (see Hasher et al., 2002). This is particularly evident when the information to be recalled is highly similar to the information to be ignored (all verbal information for example). In such instances, older adults show differentially greater recall costs than younger adults supporting the idea that selection demands are affected by the efficacy of inhibitory processes (Li, 1999). As mentioned by Li (1999), if we assume that older adults have a decline in inhibition, which then impairs selectivity, older adults should experience a higher degree of interference when information must be coordinated. Evidence, in the current study, that age-related changes in mixing cost performance are mediated by the ability to deal with proactive interference during recall supports this assumption.

The view that individual differences in WM capacity depend in part on the efficacy of inhibitory control mechanisms was not fully supported in the current study. Indeed, the correlation between WM and all other neuropsychological measures was non-significant. This unexpected finding may stem from the fact that WM performance did not demonstrate sufficient variability. Insufficient variability likely occurred because all participants were, on average, well-educated, high-functioning older adults. One way to address the problem of low intra-group variability is to use an extreme groups design, where a tertile split of the sample distribution is made and where individuals near the median are discarded. Although such a procedure increases measurement precision and increases the chance that individuals are reassigned to the same group on another measurement occasion, it is a very costly procedure, since a third of the sample is rejected. Despite this limitation, the data were re-analyzed after having conducted a tertile split of the distribution. A series of Mann-Whitney tests, appropriate for small sample sizes, were then conducted to see if the higher most and lower most WM groups differed on the various measures administered[9]. Results (see Table 4) clearly indicate that the groups differed with respect to mixing cost RT. A trend showing greater release from proactive interference for the high working memory group was also observed. Importantly, the magnitude of the WM effect (i.e., the effect size measure) was largest when comparing mixing cost and release from proactive interference scores, whereas effect size was extremely small for all other measures. This indicates that WM, proactive interference and the mixing cost share a common degree of explained variance. The results also suggest that WM is not best explained by a more general factor, such as age or rote recall, or by executive functions in general. This finding is also consistent with the notion that inhibition is a cardinal feature of WM performance (Mecklinger et al., 2003).

In conclusion, our general findings revealed that age effects varied across tasks and were not observed for all executive tasks. In particular, results showed that when reliable age differences were reported, they appeared on tasks requiring the ability to maintain relevant representations in an easily retrievable state, free from the disruptive effects of past information. This finding agrees with a growing literature which shows that beyond the effects attributable to baseline slowing, age differences are apparent when tasks involve the coordination of multiple items but not when tasks involve competitor priming, negative priming or switching abilities (see Verhaeghen & Cerella, 2002).

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[9] It is important to point out that a median split procedure, similar to the one used in Manuscript 2, was not conducted here because median splits usually reduce, rather than increase, predictor variance (see Irwin & McClelland, 2003). In Manuscript 2, loosing predictor variance as a result of a median split may have reduced our ability to detect potentially interesting effects, however, sufficient variance remained to reveal significant differences between younger adults and Old-Low participants.

Finally it is important to note that the interpretation given to age effects depend on how changes are measured and on the individuals being sampled. In the current study, only the data from older adults were analyzed. This allowed us, therefore, to chart the developmental changes that occur in late-life. Since our sample did not include younger adults (typically in their 20s) our results were not confounded by cohort differences that might have overestimated age-related differences. As a result, we provide clear evidence that continued decline in mixing cost RT and proactive interference occurs even in old age.

Table 1

Means and Standard Deviations for Age, Neuropsychological Measures and Task Switching Costs

	Mean	SD
Age (Range: 70-86)	75.8	4.4
Letter Number Sequencing	11.4	2.3
Trail B/A	2.3	0.59
Stroop (Proportional score)	1.6	0.57
Proactive Interference		
Trial 1 (Short Term Memory)	6.2	0.88
Trial 4	4.8	1.1
Trial 5 (Release Trial)	5.8	1.0
Build-up of Proactive Interference	-1.5	1.4
Release from Proactive Interference	1.1	1.6
Local Switch Cost (Log Transformed)	.057	.048
Mixing Cost (Log Transformed)	.175	.087

Table 2

Intercorrelations Among the Mixing Cost, the Local Switch Cost and Predictors

	Correlations								
Variable	1	2	3	4	5	6	7	8	9
1. Age	-	.02	.37	.20	-.28	.34	-.44*	.36	.45*
2. Letter Number Sequencing		-	-.32	-.19	-.04	.11	.11	-.29	-.27
3. Trail B/A			-	.32	.23	-.23	.06	.46*	.29
4. Stroop (Proportional score)				-	.14	-.21	.09	.41*	.01
5. Proactive Interference Trial 1 (Short Term Memory)					-	-.57*	.07	-.04	-.15
6. Build-up of Proactive Interference						-	-.67*	-.06	.34
7. Release from Proactive Interference							-	.25	-.41*
8. Local Switch Cost (Log Transformed)								-	.04
9. Mixing Cost (Log Transformed)									-

* p<.05

Table 3

Predictors of Mixing Cost RT (Log Transformed)

	Mixing Cost			
Order of Entry	Increase in R^2	F increase	ß	t
I. 1. Release from Proactive Interference	.171	4.73*	-.41	-2.2*
2. Age	.130	4.20	.37	2.0
II. 1. Age	.203	5.89*	.45	2.4*
2. Release from Proactive Interference	.156	5.37*	-.40	-2.3*

* p<.05

Table 4

Mann-Whitney Tests Conducted Between High (N=9) and Low (N=9) WM Groups

Variable	Low-WM Mean (SD)	High-WM Mean (SD)	Mann-Whitney	P	η^2
1. Age	74.6 (3.5)	75.6 (3.9)	z=-.53	.59	.02
2. Trail B/A	2.3 (.65)	2.0 (.49)	z=-1.0	.31	.09
3. Stroop (Proportional score)	1.6 (.61)	1.4 (.53)	z=-.58	.56	.02
4. Proactive Interference Trial 1 (Short Term Memory)	5.9 (1.1)	6.0 (.71)	z=-.57	.57	.01
5. Build-up of Proactive Interference	-1.1 (1.5)	-1.3 (1.2)	z=-.20	.84	.01
6. Release from Proactive Interference	0.2 (1.1)	2.4 (2.5)	z=-1.6	.10	.28
7. Local Switch Cost (Log Transformed)	.06 (.04)	.03 (.04)	z=-1.2	.21	.09
8. Mixing Cost (Log Transformed)	.21 (.08)	.13 (.06)	z=-2.3*	.02*	.28

*p<.05

GENERAL DISCUSSION

The study presented in this thesis was designed to explore the effects of age and working memory on multitasking abilities. These effects were operationalized as changes in response speed, response accuracy and electrophysiological activity. Each one of the three manuscripts included in this thesis was designed to investigate specific aspects of task switching, first among younger adults (Manuscript 1) then across different groups, including younger adults, older adults with high working memory and older adults with poor working memory (Manuscript 2), and finally, in relation to other executive control functions (Manuscript 3).

In Manuscript 1, the behavioural and ERP responses of younger adults were recorded for different types of trials (homogeneous, repeat, and switch) and across different types of task blocks (mixed and single task blocks). Electrophysiological responses were further decomposed into cue- and target-locked waveforms. Results revealed that the RT switch cost and the RT mixing cost were accompanied by specific trial type differences in both cue- and target-locked waveforms. It was found that cue-locked negative slow waves develop only in response to mixed-task trials (i.e., repeat and switch trials but not homogeneous trials) and that negative slow wave amplitudes were larger for repeat trials than for switch trials. Since negative slow waves developed in response to repeat cues but not homogeneous cues, part of the mixing cost is likely attributable to the exertion of attentional and preparatory processes on repeat but not homogeneous trials. In addition, since the amplitude of negative slow waves were reduced on switch as opposed to repeat trials, part of the local switch cost must be attributable to a reduced preparation on switch as opposed to repeat trials. This preparation difference presumably reflects the consequence of task set reconfiguration on switch as opposed to repeat trials. Differences in target-locked activity were also observed. Specifically, larger P300 amplitudes were obtained following homogeneous, repeat, and switch targets respectively. These results suggest that target evaluation differs depending on the nature of the event or trial type. Condition differences in target ambiguity and/or cognitive resource availability are thought to underlie the P300 difference obtained between homogeneous, repeat and switch trials and are thought to explain part of the mixing and local switch cost. These findings will be discussed in more detail in the following sections.

In Manuscript 2, the effect of age and working memory on task switching performance was investigated. Results showed that advancing age affected only the mixing cost and that working memory capacity explained this change. Specifically, high working memory capacities in old age preserved against response slowing in mixed-task blocks. The rapid responses of older adults with high working memory were accompanied by enhanced frontal activity during the preparatory period (i.e., larger cue-locked negative slow waves across frontal leads). Evidence of additional frontal activity in response to mixed-task trials was not observed for younger adults, despite their similarly fast RTs. This suggests that high working memory older adults counteract neuronal decline through the use of additional neurocognitive networks. Such reorganization may help older adults compensate for the problems they typically encounter when updating task sets. The results reported in Manuscript 2 also revealed that older adults with poor working memory show large negative slow waves in response to homogeneous cues, which the other two groups do not show. This suggests that poor working memory drives older adults to rely on the external context in order to monitor task set selection, even during situations where conflict between task sets is absent. Manuscript 2 also revealed that even when target evaluation is slowed and generally requires greater frontal control with advancing age (i.e., delayed peak P300 onset and greater P300 amplitudes across frontal scalp regions for all older adults), condition differences in P300 amplitudes do not change with age or working memory. This means that the processes involved in target evaluation likely follow low-level processing streams which all participants have to complete in order to successfully classify target events.

Finally, results from Manuscript 3 indicate that the local switch cost was highly correlated with the ability to execute task alternations and the ability to exercise restraint over strong response tendencies, whereas the mixing cost was highly correlated with the ability to inhibit non-relevant information during the retrieval process. In addition, only the mixing cost was significantly correlated with advancing age. A series of hierarchical regression analyses confirmed that age differences in mixing cost performance were mediated by the ability inhibit non-relevant information. In addition, comparing high and low WM older adults using an extreme groups design (where subjects scoring near the median are discarded) reveals that high WM individuals have smaller mixing costs and show greater release from proactive interference than low WM individuals. Together, these results indicate that WM is a construct which is closely tied to inhibition (see also Kane & Engle, 2002) and that age-related changes in mixing cost RT are tied to age-related changes in interference control. The findings obtained in each one of the three manuscripts will now be discussed in greater detail. An attempt will be made to integrate these findings with the current task switching literature. Throughout, avenues for future research will be proposed.

It's all Under Control: the Effects of Preparation on the Local Switch Cost.

Results reported in Manuscript 1 indicate that the local switch cost was accompanied by ERP changes in both cue- and target-locked activity. These findings suggest that RT differences between repeat and switch trials are preceded by differences in target preparation and target evaluation. Unfortunately, since the electrophysiological differences observed between repeat and switch trials were also accompanied RT differences, it is difficult to appreciate the functional significance of these electrophysiological changes. For example, does the ERP difference reflect fundamental variations between repeat and switch trials or does it simply capture differences that arise when participants are prepared to answer rapidly (i.e., regardless of the type of trial)? To answer this question we equated repeat and switch trials on RT and compared their cue- and target-locked activity. Results showed that despite similar RTs, repeat trials had greater cue-locked negative slow wave activity than switch trials across posterior scalp regions while no differences were found in target-locked activity. Together, these results suggest that differences in cue-locked preparatory activity reflect fundamental differences between repeat and switch trials. As discussed in Manuscript 1, these data fits nicely with De Jong's intention activation model where task set reconfiguration can be fully completed ahead of time, given a participant's intention to do so. However caution should be exercised before assuming that the intention activation model is correct. This is because we did not explore all possible post-target changes. Post-target activity also includes response-related activity. Previous task switching studies reveal that response-locked averages are characterized by a negative going waveform peaking at about 70 ms following response onset (Falkenstein et al., 2001; Kray et al., 2005; West, 2004). This negativity is tied to response monitoring and has been called the medial frontal negativity (MFN) (Gehring & Willoughby, 2002). It is largest when responses are given in high conflict situations (West, 2004). Due to the necessity to switch task sets on switch trials, greater conflict might be expected on switch as opposed to repeat trials. Conflict monitoring should be high on switch trials since the previous task's response assignments need to be overridden. If we assume that Rogers and Monsell's two-step model is correct— namely that task set reconfiguration cannot be fully completed prior to the target — then we should expect the MFN to be largest on switch trials, even if a RT local switch cost is absent. Unfortunately, no one has ever compared the MFN of RT-equated repeat and switch trials. So before concluding that De Jong's intention activation model is correct, further analyses, conducted on the response-locked average, would be necessary.

Even if RT-equated repeat and switch trials were found to show a difference in response-locked activity, the data reported in Manuscript 1 clearly show that RT-equated repeat and switch trials differed with respect to the cue-locked activity. Therefore, even when RT is controlled for, preparatory processes differ depending on the nature of the task (i.e., whether or not it calls for a different task from the one seen on trial n-1). Such preparation effects have frequently been interpreted as evidence that task set reconfiguration must be taking place prior to a switch target. This mental "gear changing" perspective finds its origins in the initial work of Rogers and Monsell (1995) where it was shown that the size of the local switch cost was reduced when participants are given time to prepare for a new task. However, it is still a matter of debate, whether advanced preparation truly helps the mind to exercise effortful reconfiguration or whether it simply facilitate some form of general task activation process that becomes easier as task sets repeat. If the latter is true then the local switch cost may represent nothing more than an emergent property, perhaps reflecting positive priming effects on repeat trials, rather than task set reconfiguration effects *per se* (see Altmann, 2004). To investigate this issue it is useful to consider neuroimaging data since the reconfiguration model and the general activation model make different predictions regarding the nature of the activation between repeat and switch trials. For example, the task set reconfiguration model predicts that brain activation should differ between repeat and switch trials since switch trials require task set reconfiguration whereas repeat trials do not. On the other hand the general activation model predicts no difference between repeat and switch trials (or at best minimal differences) since the same preparatory or activation process is expected for both repeat and switch trials. As reported above, repeat and switch trials (equated for RT) differed in cue-locked activity, suggesting that some form of task set reconfiguration process is at play. However, this difference was found only across posterior scalp regions, not frontal regions (repeat and switch trials had equally large frontal activity). This finding was unexpected since a large number of studies have shown that the prefrontal cortex is important when establishing cognitive control and when updating task representations (Dove et al., 2000; Konishi et al., 2002; Monchi et al., 2001; Pollmann et al., 2000). Frontal activity on repeat trials (not just switch trials), suggests that repeat trials also require some degree of task set activation or configuration. If this is correct, then why should repeat and switch trials differ in parietal activity?

Recently, it has been suggested that the parietal cortex receives biasing signals from the prefrontal cortex and that this influences task-specific processing (Tomita et al., 1999). Such processing may include the activation of visuomotor transformation rules or more generally, the selection of stimulus-response mappings (Corbetta & Shulman, 2002). Given the greater parietal activity obtained on repeat trials, it is reasonable to postulate that stimulus-response mappings remain easier to activate on repeat trials (i.e., they remain in a primed state). This interpretation supposes that one of the reasons why stimulus-response mappings are more easily retrieved on repeat trials than switch trials is because they have been used recently. Curiously, this interpretation has much in common with the activation model, which argues that some form of task priming facilitates preparation on repeat trials (Altmann, 2004). Could this mean that task set reconfiguration is not a distinctive feature of the local switch cost? Despite this legitimate possibility, promising new data, published by Monsell and colleagues (2003), confirms that task set reconfiguration is unique to switch trials, but only under distinct testing conditions. First, testing should be done using predictable switching paradigms (i.e., alternate runs designs). Doing so minimizes uncertainty regarding the occurrence of a repeat trial and therefore prevents the use of conservative response strategies (i.e., switch-ready strategies). This is important because conservative response strategies interfere with complete preparation on repeat trials and forces participants to configure on repeat trials. Under such circumstances, Altman is entirely correct: repeat and switch trials would be processed in the same way. Second, and more importantly, if repeat trials occur in randomly alternating paradigms, only the third or fourth repeat trial should be analyzed, since, by then, any endogenous restraint (or bias toward switching) has been abandoned and an asymptotic level of readiness is achieved. Monsell et al. (2003) argued that if these kinds of repeat trials are used when computing the local switch cost then the local switch cost can be used as an index of reconfiguration. With respect to the current study, frontal differences between repeat and switch trials may have been missed because we used a randomly alternating design and analyzed only the first repeat trial after a switch. Given Monsell et al.'s (2003) conclusions, frontal task activation demands for repeat and switch trials should be equally large under these circumstances[10]. Interestingly, in this thesis, it would be possible to look at repeat trials that follow runs of three or more repeats, use them to calculate a local switch cost and compare this new local switch cost to the current local switch cost. Combined with the ERP data already collected, this would be an ideal way to confirm Monsell's claims and prove that the local switch cost is related to task set reconfiguration. Future studies should also investigate the role played by task difficulty, switching probability, and number of task sets before assuming that the link between task set reconfiguration and the switch cost is obsolete.

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[10] Cued task switching designs typically use the first repeat trial after a switch as the baseline value from which to compare switch trials (see Poulsen et al., 2005; Brass et al., 2005; Rushworth et al., 2002). These ERP studies all reveal significant RT local switch costs and all find switch sensitive frontal activity (occurring early in the cue-target interval). However, none of these studies used a task switching design that involved switching between as many as three different tasks within the same block of trials. As a result repeat trials may have required less active reconfiguration which explains why repeat trials showed less frontal activity than switch trials (despite the fact that a randomly alternating cued design was used).

When Repeating is Costly: Origins of the Mixing Cost

Results from Manuscript 1 also contain the first published RT and ERP data comparing homogeneous and repeat trials in a task switching paradigm. The general finding was that repeat cues were characterized by the development of a negative slow wave whereas homogeneous cues were not. In addition, homogeneous targets produced greater P300 amplitudes than repeat targets. This means that preparing for and responding to a repeat target differed depending on the type of block in which it occurred (i.e., mixed- or single-task). These findings also agree with the idea that there are multiple sources underlying the mixing cost. One of these sources clearly affects task set preparation, since repeat trials but not homogeneous trials showed a negative shift in the cue-locked waveform. In Manuscript 1 this difference was interpreted as evidence of participants' use of the external cue when preparing for repeat but not homogeneous targets. Essentially, it was argued that since mixed-task cues (especially in randomly alternating designs) might signal a task change at any moment, they must necessarily be processed. This explains why negative slow wave activity develops following repeat cues but not homogeneous cues. Interestingly, this raises the possibility that part of the mixing cost is attributable to the objective probability of switching in mixed-task blocks. In a comprehensive investigation of probability effects in task switching, Dreisbach et al. (2002) showed that when repeat cues announce repeat trials with different probabilities (100%, 75%, 50%, or 25%), repeat RT is dramatically affected. Probability effects were so powerful that an unexpected repeat trial (25%) was even slower than an expected switch trial (75%), by as much as 73 ms![11]

In our design, task cues always announced the correct type of trial (100% accuracy). However switch trials were much more frequent than repeat trials (73% as opposed to 27%). The greater frequency of switch trials might have affected advanced repeat preparation, similar to the way an ambiguous low probability repeat cue would, encouraging some degree of preparatory restraint during repeat trials. This means that our repeat RTs may have strategic origins and that part of our repeat cue-locked negativity may reflect the need for trial-to-trial preparation born out by the possibility of a more likely task switch. If this is true, then the information conveyed by an external cue should affect repeat trial preparation, not just switch preparation.

To test this assumption, Hsieh & Cheng (2006) directly compared the effects of valid (foreknowledge) versus neutral (non-foreknowledge) cueing on repeat trial performance. Hsieh & Cheng used the pair-wise paradigm devised by Sohn and colleagues (Sohn & Anderson, 2001; Sohn & Carlson, 2000) where participants were presented with a pair of tasks that were either the same (repeat condition) or different (switch condition). On half of the blocks (all randomly alternating between pairs of tasks) participants knew that the second task in a pair would repeat (foreknowledge condition: AA-BB-BB-AA…) and in the other half, participants did not know (non-foreknowledge condition). In the foreknowledge condition, therefore, the identity of the first task predicted the identity of the second task and thus task 1 acted as a valid cue for

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[11] Dreisbach did not find that the local switch cost was reducible to a probability difference between repeat and switch trials since a local switch cost persisted even when repeat and switch trials were equally expected. An activation or priming advantage on repeat trials must still account for some, impenetrable, part of the local switch cost.

task 2. In contrast the identity of task 1 failed to predict the identity of task 2 in the non-foreknowledge condition. In this condition, task 1 acted only as a neutral cue for task 2. Hsieh & Cheng reasoned that if participants exercised trial-to trial preparation when preparing for repeat trials, they should prepare differently depending on the type of cueing provided (informative versus neutral). Hsieh & Cheng's study, therefore, provided an excellent way to confirm that external task cues play an important role when preparing for repeat trials. It is important to point out that Hsieh & Cheng also recorded the negative slow wave which develops in preparation for the second task. This gave them a way to record the preparatory activity that develops ahead of task 2. Their RT results showed that valid cueing decreased repeat latencies whereas their ERP results showed that the amplitude of the posterior negative slow wave varied depending on the information conveyed by the task cue. Specifically the authors found that repeat trials were characterized by larger negative slow waves when the second task was validly cued (i.e., in the foreknowledge condition), suggesting that external cues play a key role in helping participants prepare for repeat trials.

Hsieh & Cheng's results confirm that repeat trials require trial-to trial preparation and that the negative slow wave can be used to index changes in preparation. However, Hsieh & Cheng's results do not show how the effects of probability influence repeat performance during informative cueing conditions. In other words, to fully appreciate how the possibility of a further task switch influences repeat trial performance (even if a repeat trial is validly cued ahead of time) future studies should use a cued, randomly alternating task switching design where the proportion of repeat trials is manipulated and where cue-locked waveforms are recorded. To our knowledge, such a study has never been conducted.

Up to now, we have interpreted the mixing cost as having strategic origins. That is, mixing cost effects occur because transient preparation is necessary on all mixed-task trials (including repeat trials) given the possibility of a further switch trial. Even though the logic underlying the strategic view is compelling, some authors argue that task uncertainty does not account for the presence of the mixing cost. Championed by Los (1999), this argument holds that the mixing cost has nothing to do with the strategies adopted when task uncertainty is high. To support his assumptions, Los (1999) conducted an experiment where he manipulated switch probabilities and cueing effects (informative versus neutral cues). Los argued that if the mixing cost has strategic origins, testing conditions where the probability of switching is high should force participants to use conservative response strategies (staying switch-ready, for example). In turn, this conservative strategy whould be abandoned if an informative cue is presented ahead of the mixed-task target (in Los' case, the cue occurred 1300 ms before the target). This should result in maximum preparation for repeat trials and small mixing costs compared to a situation where advanced cueing is non-informative. In short, if an informative cue is presented in a high-switch probability mixed-task block, smaller mixing cost should be seen than if a neutral cue is presented in a high-switch probability mixed-task block. Los' RT results showed that informative pre-cueing had no effect on the mixing cost (i.e., no difference between the informative and the neutral pre-cue conditions), suggesting that response strategy differences between repeat and homogeneous trials do not exist. However Los also found that an informative cue tended to reduce the error rate. This meant that switch-ready strategies drove the error rate up on repeat trials unless an informative pre-cue was presented. Los' findings regarding response accuracy are far from trivial and can be used as evidence in support of the strategic view. It is probable, therefore, that at least part of the mixing cost comes from strategic differences in the way participants prepare for repeat as opposed to homogenous trials.

Another important difference between repeat and homogeneous trials comes from the nature of the association linking target stimuli and responses. For example, in homogeneous blocks, targets are univalent, which means that a stimulus is associated with only one task. On the other hand, mixed-task targets are typically multivalent, which means that mixed-task stimuli contain a combination of attributes that are associated with all of the other tasks involved in task switching. Thus, in the homogeneous block, the target activates only task-appropriate behaviours whereas in the mixed-task block, the target activates both task-appropriate and task-irrelevant behaviours. This type of stimulus-based interference increases RT on all mixed-task trials, even if sufficient time for endogenous preparation is afforded and even if the task repeats (Koch & Allport, 2006). In addition to stimulus ambiguity, response ambiguity can also occur. This happens when the attributes of different tasks are mapped onto the same response choices. This is usually referred to as multivalent response effects. In the context of task switching, performance decreases when multivalent responses are used, but only when the currently relevant attribute of the target and the currently irrelevant attribute of the target call for opposing responses (i.e., when incompatible response mappings are present –see Rogers & Monsell, 1995; Meiran et al., 2001). These effects can only become manifest when the target appears, which explains why some aspect of task switching is immune to advanced, endogenous control.

In Manuscript 1 and 2, target-evoked conflict was proposed as a possible cause for the mixing cost. Target-evoked conflict was also thought to underlie the homogeneous versus repeat difference in P300 amplitude. It was assumed that if target events are ambiguous (because of the negative effects of associative priming), then they should be difficult to categorize and the amplitude of the P300 should decrease. Since homogeneous trials were unambiguous and repeat trials were ambiguous (or multivalent), homogeneous trials should be easy to categorize whereas repeat trials should be difficult to categorize. Such categorization differences probably explain why homogeneous trials had larger P300 amplitudes than repeat trials. This interpretation of the P300 has much in common with the template matching view of the P300 (Chao et al., 1995). According to this view, when subjects come to expect a certain task set, they develop a neural representation or template. The easier it is to match targets with templates, the larger the P3 wave. On the other hand, if targets are ambiguous (as in mixed-task blocks) then matching should be difficult and the size of the P3 wave should decrease. The observation of larger P300 waveforms on homogeneous as opposed to repeat trials in this study agrees with this interpretation. A different, but complementary view of the P300 can also be advanced to explain our target-locked mixing cost difference. This complementary interpretation of the P300 falls under the rubric of resource allocation theory, and predicts smaller P300s when the pool of cognitive resources available is small (Kramer & Spinks, 1991). In this way, the P300 amplitude observed on any given task will decrease to the extent that additional tasks tap into the same, limited pool of resources. As far as task switching is concerned, the extent to which tasks sets are difficult to prepare (and therefore decrease the amount of available resources) should affect target evaluation processes. Since task set preparation is more difficult on repeat than on homogeneous trials, fewer resources should be available when it comes time to evaluate repeat as opposed to homogenous targets. The smaller P300 amplitude observed on repeat as opposed to homogeneous trials is consistent with this interpretation.

Before leaving this section, it is important to point out that condition differences in P300 amplitude are notoriously difficult to interpret, mostly because of the large number of different factors that affect the amplitude of the P300 waveform. In this thesis we offered two explanations - the template matching view and the resource allocation view - as possible accounts for the P300. Although described in these terms, the inspiration for these two theories can be traced back to the original work of Ray Johnson Jr. (1984; 1986). Over two decades ago, Johnson proposed a triarchic model of the P300. In his model, Johnson showed that the variables which modulate the amplitude of the P300 can be located on one of three dimensions: demand characteristics, task discriminability, and event frequency. Differences in demand characteristics assume that the amplitude of the P300 decreases when processing demands are high. Its predictions are similar to the ones advanced by the resource allocation theory. On the other hand, differences in task discriminability assume that the amplitude of the P300 decreases when the complexity/discriminability of target stimuli are high. This dimension of Johnson's triacrchic model makes the same predictions as those advanced by the template matching view of the P3 – namely that the discriminability of the target affects stimulus evaluation and modulates the amplitude of the P300. Finally, Johnson's event frequency dimension assumes that the amplitude of the P300 is responsive to the processing of probability information. In this way, rare, improbable events generate larger P300 waveforms than frequent, probable events. This dimension of Johnson's triarchic model was later revisited by Donchin and Coles (1988) who proposed the context updating model of the P300. According to the context updating model, frequent events help consolidate the information held in working memory whereas infrequent events require that working memory be updated. Updating the information held in working memory is a cognitively demanding process which is reflected by increases in the amplitude of the P300. In the manuscripts, P300 differences were not interpreted using the context updating model because the context defining target classification had been correctly cued ahead of time. Targets may have been difficult to match with respect to the context (i.e. the template matching theory may be correct) but the context itself never required updating when the targets appeared. Only the cues, therefore, could have forced context updating processes. In this situation we could have expected larger P300 waveforms following repeat as opposed to homogeneous cues since a few repetitions of the same context information (repeat trials) remains relatively unexpected compared to a large number of repetitions of the same context information (homogeneous trials). This prediction finds support from the widely reported finding that progressive repetitions of the same task leads to progressively smaller P300 amplitudes (see Johnson, 1984, 1986, 1993). Of course, in the task switching paradigm, the best test of this prediction would be to compare the activity recorded following switch cues to the activity recorded following repeat cues. This is because switch cues directly call for a change in context information whereas repeat cues do not. Interestingly, a number of authors have found larger P300 waveforms following switch as opposed to repeat cues (Barceló et al., 2002; Karayanidis et al., 2003; Kieffaber & Hetrick, 2005). In our study, this effect was difficult to observe since we used a short response-cue interval (200 ms). Such a short interval probably led to an overlap of the cognitive processes occurring after response execution and early during cue processing. Under such circumstances, a change in the amplitude of the cue-locked P300 waveform would be difficult to isolate and interpret. A future study, similar to this one but using a longer response-cue interval, could help determine the importance of context updating in response to the cue.

Aging, WM and the Mixing Cost

In Manuscript 2 the data obtained for older adults were compared to the data obtained for younger adults. Results showed that aging affected only the mixing cost. Importantly our results also showed that individual differences in working memory capacity affected this age-related change. We found that the RT mixing cost of older adults with high working memory was similar to the RT mixing cost of younger adults whereas the RT mixing cost of older adults with low working memory was larger than the RT mixing cost of younger adults. In addition to RT changes, a change in cue-locked activity was also observed. At frontal regions, and for all mixed-task trials, older adults with high working memory had larger negative slow waves than the other two groups. This finding is consistent with a number of recent PET and fMRI studies (Cabeza et al., 1997; Cabeza et al., 2002; Cabeza et al., 2004; Reuter-Lorenz et al., 2000; Rypma & D'Esposito, 2000) which found that frontal control during cognitive performance tends to increase among high performing older adults. Interestingly, the greater frontal control of older adults is typically observed as a hemispheric asymmetry reduction. In other words, instead of showing specific left or right hemisphere activity, as revealed by younger adults, older adults show both left and right prefrontal cortex activity (i.e., reduced hemispheric asymmetry)[12]. Evidence that frontal control in older adults tends to be less lateralized was originally noted during episodic memory retrieval (Cabeza et al., 1997), probably because of the strong expectations concerning the lateralization of prefrontal cortex activity during memory retrieval. During memory retrieval, prefrontal cortex activity tends to be right lateralized among younger adults (Tulving et al., 1994). When older adults perform the same memory retrieval task, their prefrontal activity is bilaterally distributed (Cabeza, 2002; Cabeza et al., 1997; Dolcos et al., 2002). While there is growing evidence to support the claim that older adults show reduced hemispheric asymmetry, there is still some disagreement concerning the function of this lack of asymmetry. One hypothesis argues that age-related asymmetry reductions reflect an age-related difficulty in engaging specialized neuronal mechanisms. This account is referred to as the dedifferentiation account. As noted by Dolcos et al. (2002), the dedifferentiation account is best understood as a developmental theory. It argues that there is a gradual evolution from unspecific to specific cognitive abilities during childhood, and that in late adulthood, the opposite occurs. That is, there is once again a

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[12] Although this was not reported in Manuscript 2, negative slow waves for repeat and switch trials were reliably more negative across the right frontal part of the scalp for younger adults ($\underline{p}<.05$), whereas older adults with high working memory and older adults with low working memory failed to show reliable inter-hemispheric differences ($\underline{p}>.4$ for both groups). Repeat and switch hemispheric asymmetries (for younger adults) are difficult to appreciate when looking at Figure 2 of Manuscript 1 (compare F3-F4 and FC3-FC4), probably owing to the rather small voltage difference between the left and right hemispheres (approx. 1µV). Nevertheless, the variability of the inter-hemispheric difference was quite small (±SEM=0.35) and the effect reliable. Finally, it is important to point out that even though both groups of older adults failed to show a reliable inter-hemispheric difference, older adults with high working memory showed much larger frontal negativities (overall) than older adults with low working memory, possibly reflecting important differences in the recruitment of frontal control.

tendency to rely upon general, less distinct cognitive abilities. So, whereas children undergo a functional differentiation of their cognitive abilities, older adults undergo a functional dedifferentiation.

An alternative view of the age-related asymmetry reduction suggests that bihemispheric recruitment in old age plays a compensatory role. This account is consistent with evidence that bilateral activity in older adults is associated with enhanced cognitive performance (see Cabeza et al., 2002). It is also consistent with evidence that following unilateral brain damage, recovery of function is usually associated with the recruitment of the unaffected contralateral side (Abo et al., 2001). At this point, it is important to make a distinction between cognitive and neuronal compensation. Whereas cognitive compensation suggests that older adults may be completing the task using different cognitive strategies (Baltes & Baltes, 1990; Freund & Baltes, 1998), neuronal compensation argues that older adults recruit different (homologous) brain regions to complete the same task using the same strategies as younger adults. Recently, Logan and colleagues (2002) collected data which suggest that age-related hemispheric asymmetry reductions are associated with a change in neural architecture not cognitive strategy. Logan et al. (2002) found that during episodic memory encoding (i.e., the intentional learning of words), younger adults show greater activity in the left prefrontal cortex, whereas older adults show similar levels of activity in both the left and right prefrontal cortex. Importantly, when both younger and older adults were instructed to use the same encoding strategy (for example, having to use a concrete encoding strategy) the age-related hemispheric asymmetry reduction remained, suggesting that this activation difference is unrelated to changes in cognitive strategy. With respect to our data, this would suggest that younger and older adults adopt the same strategy when preparing for repeat trials (staying switch ready at all times for example) but that, depending on bihemispheric activity, some older adults are better equipped to implement this strategy.

This last point raises an important question: what, exactly, does our age-related compensatory activity reflect? As mentioned in Manuscript 2, some authors have argued that the greater negative slow wave activity of older adults reflects the efforts exerted in order to deal with task set maintenance difficulties (Kray et al., 2005; West, 2004). This explanation was advanced because a cueing design was used where the cue disappeared well before the target appeared. Since age-related differences in negative slow wave activity occurred once the cue disappeared, the authors surmised that the problem must have been associated with an age-related difficulty in maintaining the cued information. In this thesis, we were successful in demonstrating that the negative slow wave activity difference remains despite the presence of the cue during the preparatory interval, thus age-related difficulties in task set maintenance could not explain this finding. What seems clear is that the prefrontal activity observed among high working memory older adults must be related to the task selection process itself. Since working memory clearly modulated this age-effect, our task switching results can be understood as an age-related change in working memory functioning.

Working memory can be seen as a combination of two, mutually dependent functions: storage (including task maintenance) and selective attention (including task manipulation). Whereas storage functions serve to retain the representation of current task demands, attentional processes are responsible for the selection of task relevant representations and actions. Selective attention essentially acts to prioritize the information held within memory. Recent research on aging and working memory suggest that age-related declines in working memory capacity are related to decreases in the effectiveness of selective attention, not storage capacity (May et al., 1999). With respect to our data, this would suggest that the large frontal negativity observed for high working memory older adults reflects compensatory activity triggered to facilitate the selection or retrieval of task sets from memory. If we consider that retrieval functions are compromised with advancing age, we should not be surprised to find that older adults have a difficult time dealing with multitasking situations when multiple sources of information have to be retrieved over a short period of time.

Several researchers have proposed that selective attention worsens with advancing age because task-irrelevant information disrupts attentional processes (Hasher & Zacks, 1988; Persad et al., 2002; Sweeney et al., 2001, but see Macleod et al., 2003, Burke, 1997, and McDowd, 1997). This hypothesis has been attributed to an age-related decline in inhibitory function. For example, Hasher and Zack (1988) have argued that with advancing age, we are less able to suppress the intrusion of irrelevant information and to inhibit the selection of inappropriate behaviours. With the loss of inhibitory control, processes that guide the selection of information become burdened by the presence of irrelevant information. This, in turn, slows down the retrieval of goal-oriented information and leads to production errors. Current models of executive control suggest that inhibitory functions depend on a network of prefrontal structures, including dorsolateral, ventrolateral and medial prefrontal regions of the cortex (Konishi et al., 2005; Sakagami et al., 2006). The presence of age-related changes in frontal negative slow wave activity during the preparatory period may be a sign of the aging brain's susceptibility to disruption by irrelevant information. Unless older adults are capable of recruiting greater frontal control to offset normal age-related deficits in inhibition, greater interference will occur during the selection of cued information, leading to larger mixing costs. This is entirely consistent with the results obtained in this thesis.

Some models of working memory, such as the two-stage model of working memory proposed by Petrides and colleagues (see Owen et al., 1996a, 1996b) argue that the dorsolateral prefrontal cortex is particularly important in helping to guide the retrieval and manipulation of task representations held in working memory. These representations can be maintained across different regions of the cortex depending on the nature of the information. In our task switching study, prefrontal regions are thought to be involved in the modulation of neural activity within posterior regions of the brain, enhancing task relevant information and dampening task irrelevant information. Given the parietal distribution of our cue-locked negative shift, the information retrieved likely contains the set of S-R rules used to guide target classification (Deiber et al., 1997; Rushworth et al., 2001). The advantage of Petrides' working memory model is that it provides a neuroanatomical framework which can help explain the functional significance of our data. Using Petrides' model to interpret our data, it is possible to argue that the greater prefrontal activity of older adults with high working memory reflects the compensatory use of frontal control during the cued selection of task sets. This compensatory frontal activity may be closely linked to the efforts exerted in attempt to inhibit the further activation of irrelevant information and to facilitate the activation of currently relevant information from parietal regions.

Many authors believe that inhibition is not a unitary phenomenon, but instead can be broken down into a subset of different inhibitory processes (see Kramer et al., 1994). In the domain of task switching, one form of inhibition that might be applied to all mixed task trials is attentional inhibition. According to attentional inhibition theory, inefficient inhibition results in ineffective selective attention, which, in turn, results in the intrusion of task irrelevant information into working memory (Hasher & Zacks, 1988). Exercising this form of inhibition should improve performance on all mixed task trials, resulting in small mixing costs. Since, older adults have great difficulty exercising attentional inhibition (Connelly et al., 1991), their performance should suffer when multiple task sets are presented. The larger mixing cost of older adults is consistent with this hypothesis. In addition, the larger mixing cost of older adults with poor working memory suggests that individual differences in working memory capacity may reflect individual difference in inhibitory processing. This is consistent with the work of Hasher and colleagues (Hasher & Zacks, 1988; Hartman & Hasher, 1991) who suggest that the ability to inhibit irrelevant thoughts has important effects on working memory skills. It is important to mention that attentional inhibition should not be confused with reactive inhibition, which is thought to be recruited solely during switch transitions and which serves to clear the mind from the preceding task's action rules (see Houghton & Tipper, 1994 as well as Sinai et al., submitted). Recent research confirms that reactive inhibition must be triggered when switching between task sets (Sinai et al., submitted) and that older adults are capable of exercising this form of inhibition (Mayr, 2001). This may explain why the RT local switch cost of older adults is comparable to the RT local switch cost of younger adults. Much of the age effect in task switching, therefore, may result from a change in attentional inhibition, not reactive inhibition.

To recap, older adults with poor working memory skills have difficulty retrieving cued information in mixed-task blocks, whereas older adults with high working memory skills do not. Although individual differences in working memory capacity (and possibly inhibitory processing) are thought to account for this difference, the groups may have showed additional differences in their cognitive abilities. Since a battery of neuropsychological tests was also administered, this gave us an ad-hoc opportunity to make sure that there weren't any other major differences between the high and low working memory groups. Thus, as reported in Manuscript 3, high and low working memory older adults were compared on a variety of different cognitive measures. In addition, mixing and local switch costs were correlated with the scores obtained on the different neuropsychological tests. Results from Manuscript 3 (effect size data for example) clearly indicate that high working memory participants have smaller mixing cost scores and show greater release from proactive interference than low working memory participants. Importantly, no other difference was found. In addition, the mixing cost and the local switch cost correlated with very different measures. The mixing cost correlated with proactive inhibition and with age, whereas the local switch cost was associated with the ability to execute task alternations and the ability to exercise restraint over strong response tendencies. These results suggest that the deletion function of inhibition is more efficient for older adults with high working memory than for older adults with low working memory and that this helps high working memory older adults maintain small mixing cost RTs. Together with the neuroimaging data recorded in Manuscript 2, it is possible to argue that preserved inhibitory skills of high working memory participants occurred because of a general enhancement of bilateral prefrontal cortex activation. High working memory participants, therefore, activate prefrontal control processes to enhance the coordination of memory retrieval and the inhibition of irrelevant information during the retrieval process.

In Manuscript 2 we also showed that older adults with poor working memory had greater parietal negative slow waves than the other two groups when preparing for homogeneous targets. This was interpreted as evidence that trial-to-trial preparation was necessary for low working memory older adults, even in situations where actual or potential conflict was absent (i.e., in the homogeneous block, where only one task set was present). This finding suggests that low working memory older adults treat homogeneous trials like repeat trials. If this is correct, then why does this group have the largest RT mixing cost? One would expect smaller RT differences between repeat and homogenous trials if repeat and homogenous trials are processed in the same way and if homogeneous trials are effortful. Perhaps the answer to this lack of correspondence in the data lies in how (relatively) important homogeneous and repeat trials are to the mixing cost. For example, even if trial-to-trial preparation is necessary when preparing for homogeneous trials, this may change the mixing cost very little, simply because competition is completely absent in single task conditions, and responses, therefore, remain consistently faster than repeat trials. If correct, this also means that the larger mixing costs of low working memory older adults occur because they have a difficult time dealing with repeat trials, not homogeneous trials. In our data, this can be appreciated by looking at group differences in RT for repeat and homogeneous trials. As can be seen in Table 1 of

Manuscript 2, group differences were largest for repeat trials, not homogenous trials. This confirms that changes in the mixing cost depend largely on changes in repeat trial performance. This also means that processing differences in repeat trial preparation, not homogeneous trial preparation, must be driving group differences in the RT mixing cost. The small mixing cost and large prefrontal repeat activity of older adults with high working memory confirms this assumption. It is possible to suggest, then, that the extent to which older adults recruit frontal control during repeat but not homogeneous preparation determines the extent to which the mixing cost is affected (or unaffected).

Senescence and the Myth of the Preserved Local Switch Cost

The cue-locked electrophysiological results reported in Manuscript 1 and 2 suggest that all mixed-task trials, even repeat trials, require some degree of task set activation. As mentioned earlier, the comparison between repeat and switch trials in randomly alternating task blocks may not be an ideal way to isolate task set activation differences since both types of trials require some degree of trial-to-trial activation (see Monsell et al., 2003). This means that any age-related change in the ability to retrieve task sets is underestimated when calculating the local switch cost in randomly alternating task bocks. To remedy this, task switching paradigms should rely on designs which estimate the "true" cost of switching. Using testing parameters which encourage full preparation after the first repeat trial is an ideal way to achieve this. According to Monsell et al. (2003), predictable-switching paradigms (e.g., alternating-runs designs) present this advantage. Historically, however, predictable-switching paradigms have failed to reveal an age-related increase in the size of the RT local switch cost (Kray &

Lindenberger, 2001). This may occur because advancing age is truly immune to changes in task set reconfiguration or because some additional burden, unique to predictable task switching, equally affects repeat and switch trials. As described next, the latter hypothesis is favoured. An important component of cognitive control that might affect all types of trials in predictable task switching is the increased attention monitoring demand associated with having to keep track of the switching sequence. Increasing attention monitoring demands to keep track of the switching sequence should impair advanced preparation for repeat and switch trials and lead, here again, to an underestimation of the local switch cost. In predictable-switching paradigms, therefore, the local switch cost is underestimated because there are high attention monitoring demands, resulting from weak environmental support (i.e., explicit retrieval cues are not presented ahead of the target). Given the underestimation of the local switch cost that occurs for both predictable and unpredictable task switching designs (albeit for different reasons), it is currently very difficult to isolate the true cost of switching and test whether or not older adults have an impaired local switch cost. This concern was best described by Kray (2005) when she noted that, on the one hand, external task cues facilitate the retrieval of the next task set but on the other, strategic processes slow down the speed of responding on task-repetition trials because of the expectancy of a further task change. All of this suggests that if we want to capture the true cost of switching we have to use an alternate-runs paradigm where external task cues are also provided or, we have to use a cued, randomly alternating paradigm where only the third or fourth repeat trial is used to calculate the local switch cost. In both cases, the switching sequence does not need to be monitored, endogenous preparation is facilitated and conservative response strategies are either absent or abandoned. Using either one of these two testing strategies to investigate age-related changes in the size of the local switch cost has never been attempted. In the current research, the second option – namely using the third or fourth repeat trial to compute the local switch cost – could be tried since repeat trials that follow runs of three or more repeats have been included in our design[13].

Even though the true cost of switching may have been underestimated in recent task switching studies, some authors still found that the size of the local switch cost increases with advancing age. For example, Kray, Li & Lindenberger (2002) found that older adults have larger RT local switch costs than younger adults, but only when a large number of task sets are used (i.e., 4 as opposed to 2). The authors surmised that switching between a large number of task sets magnifies selection demands, thus increasing the size of the local switch cost. Their reasoning is consistent with the idea that response mappings are hard to select when they overlap completely across tasks (i.e., when multivalent responses are used). Kray, Li, and Lindenberger's (2002) findings are also consistent with those of Mayr (2001) and Meiran et al. (2001) who found that age-differences in task switching are larger when there is an overlap between response attributes (or stimulus attributes). In the current thesis, we found that much of the age effect in task switching occurs because older adults have a hard time retrieving the relevant task set, not because they have a hard time dealing with ambiguous targets. In other words, our ERP differences were found only during the preparatory interval not

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[13] Preliminary analyses, conducted only on behavioural data, reveal that repeat trials that follow runs of 3 or more repeats were not responded to more quickly than repeat trials that immediately follow a switch. This result may have occurred because most of the new repeat trials followed, at best, a run of 5 repeats. This may have been insufficient to allow repeat trials to reach an optimal degree of gain. Future studies are necessary to investigate this issue.

during the response-locked period. At first glance, this finding seems to contradict those obtained by Kray, et al., (2002); Mayr (2001) and Meiran et al. (2001). However, a recent study conducted by Koch & Allport (2006) may help elucidate this apparent discrepancy. Koch & Allport (2006) used a cued, randomly alternating task switching design where both targets and responses were ambiguous (i.e., multivalent targets and responses). The authors found that ambiguous targets interfered much less with performance when long cue-target intervals were used. Their data, therefore, supports the idea that ambiguous targets lose some of their interfering properties when competition between task sets decrease (because a cue is provided ahead of time). In this thesis, a relatively long cue-target interval was used (1,180 ms, even longer than Koch & Allport's 900 ms interval) which may explain why age-differences in task switching were seen only in response to the cue, not the target. Unfortunately, we did not manipulate the cue-target interval, therefore, future studies should be conducted to find out how much of the age-related change in task switching can be attributed to cue-based preparation or target ambiguity.

Obligatory Processing During Target Evaluation

As discussed in Manuscript 2, the ERP results obtained for older adults clearly show that target stimuli are processed more slowly, as manifested by the delay in the peak P300 latency of all trials. The data reported in Manuscript 2 also show that the P300 waveform of older adults is more frontally distributed, suggesting that they rely on a different set of cortical generators when evaluating target stimuli (see Fabiani et al., 1998, Friedman, 2003, and Kok, 2000 for similar findings). These age-related differences appear to correspond to global age effects since they do not interact with trial type. It is not surprising to find, therefore, that for all three groups (younger adults, older adults with high working memory and older adults with low working memory) the P300 mixing and local switch costs were the same. This finding suggests that condition differences in target evaluation are relatively stable and immune to the deleterious effects of declining working memory capacity. With respect to task switching, this suggests that target evaluation is an obligatory process that follows low level processing streams. If correct, then condition differences in target classification (i.e., the mixing cost and the local switch cost contrasts) should remain stable despite changes in cognitive control. In addition, obligatory processes suppose that the only way differences in cognitive control can come to affect target evaluation is in an all-or-none fashion. That is, if an individual has too few cognitive resources to meet the obligatory processing requirements necessary to evaluate targets, then a correct response cannot be given. In this manner, the best measure of cognitive control is response accuracy. During target-evaluation, then, differences in age and working memory might influence performance by affecting the probability of success on a given number of trials. Interestingly, we found that, unlike younger adults, older adults had a significant accuracy mixing and local switch cost. In fact the mixing cost accuracy rate of Low-Old participants was larger (9.23%) than that of High-Old participants (6.00%) and younger adults (0.58%)[14] (Remember that the mixing cost accuracy score represents the difference in accuracy between repeat and homogeneous trials. A large accuracy mixing cost means repeat and switch trials have very different accuracy rates.).

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[14] The difference between Low-Old and young was significant whereas the difference between Low-Old and High-Old showed a trend ($\underline{p}_{1\text{-tailed}}$=.07).

Final Thoughts

The results of this thesis have provided encouraging new findings, which have helped to better understand how differences in working memory capacity affect age-related differences in task switching. In particular, the results suggest that a high working memory capacity may preserve against age-related changes in advanced endogenous preparation. As a whole, the discussion section also points to the importance of paying attention to design and methodological issues when interpreting RT and ERP results. The task switching paradigm, as a research tool, is only now starting to show its full potential. However, important limitations concerning the significance of the local switch cost and the mixing cost still need to be resolved before age and ERP differences can be clearly understood. As pointed out in this thesis, it is becoming increasingly clear that the interplay between target ambiguity, advanced preparation, and the probability of a further task switch can all affect performance. Unless controlled for, or manipulated individually, interpreting results can be a challenge.

Throughout this Chapter, avenues for future research have been proposed, which, if carried out could help validate some of the theories currently discussed in the literature. These proposed research avenues are tied to the limitations of the current research project. For example, retrieval requirements present on repeat trials are thought to arise because cued, randomly alternating designs prevent participants form engaging fully in task set reconfiguration following a switch trial. To test this assumption, it would have been important to manipulate the run length of repeat trials following a switch. This would have given us a chance to see if conservative response regimes were indeed adopted. It would have also confirmed whether or not older adults adopt extremely conservative response strategies. In addition, manipulating the frequency of switch trials could have changed the adoption of conservative response strategies. As a result it would have been possible to see if older adults are differentially sensitive to the effects of probability.

An additional limitation of the current research includes the use of a fixed cue-target interval. A fixed cue-target interval prevented us from drawing strong conclusions regarding the functional significance of the cue-locked activity. To avoid this limitation, it would have been important to manipulate the preparatory interval in two distinct testing conditions, one where the cue is always visible (as in the current design) and one where the cue remains visible for a brief period[15]. By looking at the cue-locked waveforms under these different conditions, stronger conclusions can be drawn regarding the nature of the preparatory activity (i.e., whether it relates to task set retrieval or task set maintenance). In addition to manipulating the cue-target interval, it would have been interesting to manipulate the response-cue interval. Manipulating the response-cue interval can help to address whether or not older adults are sensitive to the effects of task set dissipation. As mentioned in Manuscript 2, recent research indicates that task sets dissipate more slowly for older adults, which may cause greater interference when switching between trials. As a result, studies that are interested in testing age-related changes in the local switch cost should include a condition where the response-cue interval is manipulated. Finally, results reported in Manuscript 2 reveal that condition differences in target evaluation are relatively stable and unaffected by changes in working

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[15] A within groups design is advisable here.

memory capacity. This means that the difference in target evaluation between repeat and switch trials is the same for all groups. However, before assuming that this is an invariable truth, future studies should manipulate the degree of stimulus and/or response ambiguity.

Despite these limitations, the present study presents several innovations. For example, this is the first project to compare the cue and target locked activity of repeat, switch and homogeneous trials within the same study and among the same subjects. In addition, this is the first project to have looked at the preparatory activity of RT equated repeat and switch trials. This is particularly interesting because it helped to show that repeat and switch trials present fundamental differences in endogenous preparation. Finally, results from Manuscript 2 showed that individual differences in working memory capacity of older adults affected endogenous preparation in mixed-task situations. This helped to explain why some older adults showed large RT mixing costs whereas others did not.

Given the cross-sectional design used in the present research, future studies may want to explore age and working memory differences using a longitudinal approach. As a result, hierarchical linear modeling of the different multitasking skills (nested within groups of high and low working memory older adults) could be used to obtain a clearer picture of the developmental trajectory adopted by high and low working memory subjects. In fact, this could be done using a cross-sectional longitudinal design to see if the developmental trajectories of younger and older adults differ. Another research avenue could be to further investigate the validity of the inhibition account. One way to achieve this might be to conduct a *directed forgetting* study among high and low working memory older adults. Directed forgetting is usually studied by having participants remember some items while forgetting others, typically in a list-learning procedure (Bjork, 1970). Subsequent attempts to retrieve the to-be-remembered and to-be-forgotten items consistently reveal an advantage for "remember" as opposed to "forget" items. The most frequently cited explanation for this difference is that forget items are inhibited, therefore diminishing retrieval success at recall. Age differences in directed forgetting typically show that older adults have more difficulty than younger adults intentionally forgetting verbally presented items (Zacks et al., 1996). Thus, for older adults, to-be-forgotten information may enter into working memory, even though it is irrelevant and hinders the retrieval of to-be-remembered items. Using both the directed forgetting paradigm and the task switching paradigm among high and low working memory seniors could help validate the idea that inhibitory deficits are a key factor in predicting the larger mixing costs of low working memory seniors. Regardless of the research approach taken, the ultimate goals are to better understand task switching and to better understand how advancing age affects the ability to multitask.

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APPENDIX A

Sample of Experimental Instructions

Task-Set Switching Instructions

Response Set-up

General Introduction:

In this experiment, you will be shown different words; for example the word "BABY". You will be asked classify the different words that you see according to three different dimensions. These dimensions are: **Existence**, **Breadth** and **Size**.

- For the **Existence** category, you will have to press
  the left button on your response pad if the word is a living word and
  the right button if the word is a non-living word.
- For the **Breadth** category, you will have to press
  the left button on your response pad if the word is a narrow word and
  the right button if the word is a wide word.
- Finally, for the **Size** category, you will have to press
  the left button on your response pad if the word is a large word and
  the right button if the word is a small word.

Homogeneous Block # 1:

1. Let's practice classifying these words into their correct categories.

In this first part, you will be asked to classify each word only according to the dimension **Existence**. Remember that you will have to press

the left button on your response pad if the word is a living word and
the right button if the word is a non-living word.

Before the presentation of each word, a cue telling you that the word must be classified according to the **Existence** dimension will be presented in the centre of the screen. **I will also ask you to hold your head as still as possible during this experiment. This will help us gather more precise data. Also please try not to blink or blink only if necessary.** Do you have any questions?

2. Now that you have practiced, let's do it again, but this time it will no longer be a practice run. Remember that you will have to press

the left button on your response pad if the word is a living word and

the right button if the word is a non-living word.

Homogeneous Block # 2:

1. Now, let's practice classifying the words only according to the dimension **Breadth**. Remember that you will have to press

the left button on your response pad if the word is a narrow word and

the right button if the word is a wide word.

Again, before the presentation of each word, a cue telling you that the word must be classified according to the **Breadth** dimension will be presented in the centre of the screen. **Remember to hold your head as still as possible during this experiment and to try and blink as little as possible.**

2. Now that you have practiced, let's do it again, but this time it will no longer be a practice run. Remember that you will have to press

the left button on your response pad if the word is a narrow word and

the right button if the word is a wide word.

Homogeneous Block # 3:

1. Now, let's practice classifying the words only according to the dimension **Size**. Remember that you will have to press

the left button on your response pad if the word is a large word and

the right button if the word is a small word.

Again, before the presentation of each word, a cue telling you that the word must be classified according to the **Size** dimension will be presented in the centre of the screen. **Remember to hold your head as still as possible during this experiment and to try and blink as little as possible.**

2. Now that you have practiced, let's do it again, but this time it will no longer be a practice run. Remember that you will have to press

the left button on your response pad if the word is a large word and
the right button if the word is a small word.

Heterogeneous Block #1:

You have now practiced classifying all the different words according to large/small, wide/narrow and living/non-living dimensions. You have also learned the corresponding button press associated with each of these dimensions. Let me repeat them to you once again:

- For the **Existence** category, you will have to press
  the left button on your response pad if the word is a living word and
  the right button if the word is a non-living word.
- For the **Breadth** category, you will have to press
  the left button on your response pad if the word is a narrow word and
  the right button if the word is a wide word.
- Finally, for the **Size** category, you will have to press
  the left button on your response pad if the word is a large word and
  the right button if the word is a small word.

So, for this next exercise, you will have to continue classifying the words based on what the cue tells you, just as you did previously, except this time the categories (**Existence**, **Breadth** & **Size**) will be presented to you in a random fashion.

Do you have any questions?

Heterogeneous Block #2:

Let's repeat the same task you just did.
Do you have any questions?

APPENDIX B

Consent Form

Code no._________

CONSENT FORM

Study of Electrical Brain Responses during Attention Switching

Purpose of the Study:

I have been informed that the purpose of this research is to study the effects of age on electrical brain responses during certain cognitive functions (such as the ability to plan). Planning will be measured by a switching task in which I will have to pay attention to different cues and targets in order to "plan" a correct response. The recorded electrical brain waves measured during this switching task will then be compared across participants of different ages to determine the effects of age on switching activity. The study will consist of two phases. In one phase, I will be administered paper and pencil tasks designed to measure various cognitive skills. The other phase involves the recording of my electroencephalogram (EEG) while I am performing a switching task.

With respect to the study itself, I understand the following:

This EEG study will be conducted at the Loyola Campus of Concordia University. The electroencephalogram (EEG) is a recording of electrical brain activity measured at the scalp (similar to an EKG recording of heart activity). To record EEG, a nylon cap containing small sensors (electrodes) will be placed on my head. To obtain proper recordings, the scalp area underneath each sensor will be lightly rubbed with electrolytic gel using a blunted needle. The gel resembles a facial scrub and is used to clean and prepare the skin surface.

The study will be conducted in a small testing room. Before and after doing the “task-switching / planning" exercise, I understand that I will be given a few other tests to complete. Some of these tests will be audiotaped so that responses may be reliably scored. One such test (administered only to older subjects) will require the completion of a brief interview describing my current life situation.

With respect to my participation in the study, I understand the following:

This study will require two sessions of approximately 2½ hours each. If I am not among the older participants, my participation will require only one 2½ hour session. I have been informed that certain demographic information (age, sex, education, health status) will be recorded. I understand that this study is not a medical test. It is for research purposes only and it is not diagnostic, meaning that it will not yield any results about my health. I understand that my individual results will not be provided to me but that I will be informed of the general findings of the study. However, in the unlikely event that any potentially significant irregularity in my EEG is observed, this information will be forwarded to my family physician provided I give my permission to do so.

1. Advantages to Participating in the Study: The researchers hope to learn more about the brain processes involved when one is switching between tasks and how these are affected by age. Although this will not benefit me directly, this research could add to our scientific understanding of age related differences in thought processing. In addition, I will gain knowledge about how psychological research is conducted. I also understand that I will be given a small sum of money to acknowledge my participation in the study.

2. Disadvantages and Risks of Participating in the Study: EEG testing is a painless and non-invasive (using no foreign substances like medications, tubes, or needle injections) procedure. Nevertheless, while the scalp is being prepared for recording, some people may experience a mild and temporary discomfort where the skin is being rubbed. It is also possible that I will find it boring or frustrating to look at the information on the computer screen. However, I will be given frequent breaks whenever required to avoid this. I understand that, in the *unlikely* event that any finding of possible clinical significance is made and communicated to my physician, it may be recommended that I have additional testing which would not have taken place if I had not participated in this study.

3. Confidentiality: I understand that my participation in this study is *confidential*, that is, the researcher will know but will not disclose my identity in any published report or scientific communication. My records will not be identified by name; instead a subject code will be used. If the present study is published, only group results will be mentioned, insuring my confidentiality as a participant in this experiment.

4. Withdrawal from the Study: I understand that my participation in this study is voluntary and, if I agree to participate, I may withdraw my consent and discontinue participation *at any time* without negative effects.

5. Participant's Rights: I have fully discussed and understood the purpose and procedure of this study and have had the opportunity to ask any questions.

The following are the names, addresses, and telephone numbers of the research supervisors to whom I may address my concerns or questions about the research or any injuries or adverse reactions that might occur:

Dr. Natalie Phillips (Ph.D), **Dept. of Psychology,** **Concordia University,** **7141 Sherbrooke Street West,** **West,** **Montreal, Quebec,** **H4B 1R6** **Tel: 848-2218**	**Dr. Dolores Pushkar (Ph.D.)** **Dept. of Psychology,** **Concordia University,** **7141 Sherbrooke Street** **Montreal, Quebec,** **H4B 1R6** **Tel: 848-7540**

I have understood the contents of this consent form and have had the opportunity to ask questions. I agree to participate in this study.

Date	Signature of Subject	Print Name
	Signature of Investigator	Print Name
	Signature of person explaining informed consent	Print Name

2001/2002 All participants will receive a copy of this consent form.

APPENDIX C

Health Questionnaire

Interviewer: ____________ Date: ______________
Availability: _________

Health Questionnaire

In this research, we need to know whether there are factors, in addition to the ones we are studying, that may be affecting the results. Your answers to a few short questions will aid us in this effort. All answers will be kept strictly confidential. Thank you for your help.

Demographics

- Name: ___________________________
- Phone Number: _____________________
- Date of Birth: __________________ Age: _______
- Gender: M __ F __
- Handedness: R __ L __ Ambidextrous __
- Type of Residence: Single family home __ Apartment/Condo __ Seniors' Residence __

Language

- Place of Birth: ______________________
- Languages Spoken: __________________
- Primary Language/Language of Choice: __________________
- Language at home: ___________________ At Work: _________________
- Language of Education: ____________________
- When did you first learn English? _______________
- When did you become fluent in it? __________________
- *Interviewer's subjective rating of subject's fluency (1-5, where 1 is least fluent) and comments:*

- Education - how many years including kindergarten? (finished -- primary school, highschool, college, university?) _____________
- Have you ever skipped or repeated a grade? Why? _________________

- Occupation - Present: ________________________
  - Past: __________________________
  (What would you consider to be/to have been your primary occupation?)

Medical History

- Do you have now, or have you had in the past -

- Visual problems: Nearsighted / Farsighted
Glasses / Contact lenses
Cataract: Left / Right
Colour blind: NO / YES

- Trouble hearing: NO / YES
Hearing Aid: Left / Right

- How would you rate your overall health at the present time?

Very good ( ) Fair ( ) Poor ( )

- Compared to 5 years ago, is your health?

Better ( ) About the same ( ) Worse( )

- How much do your health problems stand in the way of your doing the things you want to do?

Not at all ( ) A little ( ) A great deal ( )

The following questions deal with specific illnesses or conditions that people may have. Please check those symptoms or diseases you have experienced in the past 5 years.

1. Headache .... _____
2. Dizziness................................ _____
3. Varicose veins......................... _____
4. Hemorrhoids........................... _____
5. Low blood pressure .... _____
6. Drug allergy............................ _____
7. Bronchitis................................ ____
8. Hyperventilation..................... _____
9. Bursitis.................................... _____

23. Slipped disk.................... _____
* 24. Hepatitis........................ _____
25. Kidney stones.................. _____
26. Peptic ulcer..................... _____
27. Pancreatitis..................... _____
28. Ovarian cyst .... _____
29. Deafness........................ _____
30. Collapsed lung................ _____
31. Vaginal infection.............. _____

10. Lumbago................................ _____

* 11. Migraine............................. _____

12. Hernia .... _____

13. Irregular heart beats .... _____

14. Overweight .... _____

15. Anemia................................. _____

16. Anxiety reaction .... _____

17. Gout .... _____

18. Pneumonia .... _____

* 19. Depression .... _____

20. Kidney infection .... _____

21. Inability for sexual
intercourse .... _____

22. Hyperthyroid......................... _____

* 32. Chest pain...................... _____

33. Nervous breakdown........... _____

34. Pelvic inflammatory disease.. _____

35. Blood clot in blood vessels... _____

36. Hardening of the arteries...... _____

37. Emphysema...................... _____

38. Tuberculosis.................... _____

39. Alcoholism...................... _____

40. Drug addiction.................. _____

41. Cirrhosis of the liver........... _____

42. **Parkinson's disease**.......... _____

43. Blindness........................ _____

44. Breast inflammation............_____

45. Asthma................................. _____

46. Glaucoma.............................. _____

47. Gallstones .... _____

48. Arthritis................................ _____

49. Leukemia .... _____

50. **Multiple sclerosis** .... _____

51. Cataracts .... _____

52. Uremia .... _____

53. Muscular dystrophy............ _____

54. **Cerebral palsy**................ _____

55. **Heart failure**.................. _____

56. Uterine fibroids.................._____

57. Rheumatism....................._____

58. Cancer .... _____

59. Difficulty in focussing
vision .... _____

60. Other (specify: e.g. colour
blindness) .... _____

** Inquire further re: nature and/or treatment with participant*

*Footnote: Items in **bold** are exclusion criteria*

- Have you ever been unconscious, had a head injury or had blackouts? NO / YES
  Cause:
  Duration:
  Treatment:
  Outcome:

- Have you been seriously ill or hospitalized in the past 6 months? NO / YES
  Duration:
  Cause:

If Yes - <u>Treatment</u>: With what? Since when? Current status?

Do you have now, or have you had in the past -

• Stroke	NO / YES	When?	Transient ischemic attack?
• Heart disease	NO / YES	Nature (MI, angina, narrowing of arteries):	
• High blood pressure	NO / YES	Controlled?	
1. Surgery	NO / YES	Nature:	
• Seizures	NO / YES	Age Onset: Cause:	Freq: Treatment:
• Diabetes	NO / YES	Type I / Type II	Age Onset:
Insulin dependent?	NO / YES	Treatment:	

Medication

Type	Reason for consumption	Age/Duration of consumption/Dose

Hormone replacement? / Steroids?

Alcohol, Tobacco, Drug Consumption (1 drink = 1 beer, 1 glass of wine, 1 oz of liquor) - **Current/Past**

	Amount (per day/week/month/year)		
	Present	Past	Age of Consumption
Alcohol			
Tobacco			if Yes: packs/day (exclude if 20 pack-years)
Drug use			

Present Problems - Are you currently troubled by any of the following?

- Concentration / Attention problems NO / YES Nature:
- Memory problems NO / YES Nature:
- Difficulties finding words NO / YES Nature:

Address for correspondance: