

# Neurophysiological Measures of Task-Set Switching: Effects of Working Memory and Aging

Philippe Goffaux,<sup>1,2</sup> Natalie A. Phillips,<sup>1,2,3</sup> Marco Sinai,<sup>1,2</sup> and Dolores Pushkar<sup>1,2</sup>

<sup>1</sup>Department of Psychology, Concordia University, Montreal, Québec, Canada.

<sup>2</sup>Centre for Research in Human Development, Concordia University, Montreal, Québec, Canada.

<sup>3</sup>Lady Davis Institute for Medical Research/Jewish General Hospital, Montreal, Québec, Canada.

**We investigated age-related differences in task-switching performance by using behavioral measures and event-related brain potentials. We tested younger and older adults, and we separated older adults into groups with high and low working memory (WM); that is, we separated them into old-high-WM and old-low-WM groups. On average, all participants responded more slowly in mixed-task than in single-task blocks (i.e., reaction time or RT mixing cost). Younger adults and old-high-WM participants had equivalent RT mixing costs and showed larger posterior negative slow-wave activity when preparing for mixed trials than for single-task trials, suggesting that mixed-task trials required trial-to-trial preparation. Old-high-WM participants also showed frontally distributed activity on mixed-task trials, suggesting their use of executive control to offset age-related differences in mixed-task preparation. In contrast, old-low-WM participants had large RT mixing costs and large posterior event-related brain potential negativities during single-task trials, suggesting that they prepare during single- and mixed-task blocks. High WM, therefore, may help older adults offset the age-related difficulties often observed when they are task switching.**

**Key Words:** Task switching—Mixing cost—Working memory—Event-related brain potentials—Negative slow wave.

**R**EPORTS of associations between increasing age and decreasing executive functions are not uncommon (e.g., West, 1996; also see Raz, 2000). However, executive control processes are not a homogeneous construct and identifying the various subcomponents 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 this study, we used a task-switching paradigm to explore age-related differences in executive function. Specifically, using behavioral measures and electrophysiological responses (i.e., event-related brain potentials or ERPs), we examined whether older adults with high capacities of working memory (WM) would show task-switching performances comparable with those of younger adults. We review the relevant task-switching literature (behavioral and electrophysiological studies) and examine how advancing age affects the ability to multitask.

Use of the task-switching paradigm allows cognitive researchers to decompose performance into specific between-trial effects. Studies that have focused on trial-specific processes reveal that the cognitive control processes triggered when having to task switch are affected by a large number of factors, including time for preparation (Meiran, 1996; Rogers & Monsell, 1995), priming effects (Waszak, Hommel, & Allport, 2005), stimulus and response ambiguity (Meiran, Chorev, & Sapir, 2000), and the number of task sets in WM (Kray, Li, & Lindenberger, 2002). The vast majority of studies also reveal that, ultimately, switching to a different task cannot be completed in advance, no matter how much preparation time is given (Koch & Philipp, 2005; Rogers & Monsell; but see De Jong, 2000 for a different interpretation). Thus, comparing performance on repeat and switch trials when these alternate within the same block of trials (known as a heterogeneous or

mixed-task block) isolates such between-trial effects. This so-called local switch cost (i.e., greater switch RT/errors than repeat RT/errors) is thought to index processes triggered to reconfigure the mind for a new set of task goals and response rules (see Rogers & Monsell). In contrast, comparing performance on repeat trials in mixed-task blocks to repeat trials that occur within a single-task block (i.e., a homogeneous block) isolates sustained cognitive control processes. This so-called mixing cost (i.e., greater repeat RT/errors than homogeneous RT/errors) is thought to index the engagement of extra WM processes needed to coordinate and retrieve the instructions for all relevant task settings in a mixed-task block (Meiran et al.).

For fast and accurate performance, task switching requires that attention, preparation, and WM resources be mobilized. Because these processes represent components of executive control, it is not surprising to find age differences in task-switching performance (De Jong, 2001; Kray & Lindenberger, 2000; Kray, Eber, & Lindenberger, 2004; Mayr, 2001; Meiran, Gotler, & Perlman, 2001). In particular, the literature on aging and task switching points to a very specific age-related deficit. Results to date show that elderly adults have larger RT mixing costs than do younger adults but equal RT local switch costs (Kray & Lindenberger; Mayr; Meiran et al.), which suggests that aging hinders performance when one has to coordinate multiple task sets in WM, but not when one is actively switching between task sets (but see Hahn, Andersen, & Kramer, 2004 and Kramer, Hahn, & Gopher, 1999 for evidence of age-related increases in RT local switch cost under particular testing situations). This is consistent with a large body of literature showing that WM declines with advancing age and that performance, therefore, is most affected in mixed-task situations (see Reuter-Lorenz & Sylvester, 2005 for a review).

In addition, it seems that aging is more detrimental to the processing component of WM than it is to the efficient

maintenance of material-specific buffers (Dobbs & Rule, 1989). This means that the maintenance abilities, and their underlying neural substrates, are relatively spared with normal aging, whereas processing components of WM and their neural substrates are largely affected (Reuter-Lorenz & Sylvester, 2005; Rypma & D'Esposito, 2000). We can expect, therefore, that individual differences in WM capacity in older adults will affect the processing component engaged when they are task switching. Individual differences in WM are known to influence higher-order cognitive functions (see Kane & Engle, 2002). For example, WM differences predict variations in reasoning, language comprehension, and even general fluid intelligence (Barrett, Tugade, & Engle, 2004). In one important finding, Unsworth and Engle (2007) recently showed that individual differences in WM capacity occur only when memory scans are required (i.e., when cue-dependent searches are required to actively retrieve stored information). Interestingly, this is one of the key features that distinguishes single- from mixed-task blocks in the task-switching paradigm.

In the current study, we measured the electrical neural activity generated when a person was performing an externally cued task-switching experiment. We achieved this by recording the ERPs triggered by the presentation of either 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. ERP studies show that task switching can be fractionated into distinct waveforms associated with either pretarget processes, target-locked processes, or both (Goffaux, Phillips, Sinai, & Pushkar, 2006; Karayanidis, Coltheart, Michie, & Murphy, 2003; Kieffaber & Hetrick, 2005; Lorist et al., 2000; Poulsen, Luu, Davey, & Tucker, 2005; Rushworth, Passingham, & Nobre, 2002). The results of these studies indicate that, when one is switching, pretarget processes elicit a large negative slow wave, distributed over posterior scalp regions. Negative slow waves are characterized by slow negative-going potentials sustained over a relatively long epoch (e.g., a few hundred milliseconds or more) and 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). Larger negative slow waves are usually observed prior to repeat trials than prior to switch trials, which suggests that it is easier to anticipate and prepare for an impending repeat target than it is for an impending switch target (Goffaux; Karayanidis et al.; Lorist et al.).

In addition to the local switch cost, we recently showed that the mixing-cost contrast was associated with a difference in the cue-locked activity of homogeneous and repeat trials distributed across the entire scalp (Goffaux et al., 2006). Whereas repeat trials showed a negative-going deflection in the cue-locked interval, homogeneous trials exhibited an absence of the waveform. In mixed-task but not single-task contexts, environmental cues might signal a task change at any moment, and so these cues must necessarily be processed (Braver, Reynolds, & Donaldson, 2003). This likely explains why repeat cues were characterized by negative slow-wave activity whereas homogeneous cues were not.

Studies that have examined ERPs and task switching among older adults have been rare, although Kray, Eppinger, and Mecklinger (2005) and West (2004) recently found that older

adults have an enhanced negativity when they prepare for mixed-task as opposed to single-task blocks (most evident at frontal electrode sites). Both studies interpreted the larger negativity of older adults as evidence of an age-related difficulty in the ability to maintain a currently relevant task set over time under mixed-task conditions. This interpretation was supported by the fact that, in both studies, the cue disappeared before the target appeared. However, it is unknown whether older adults would still show larger negativities if the cue was present during most of the preparation interval. If older adults continue to show this pattern when the cue is present, then this would suggest an age-related change in task-set activation or retrieval, rather than task-set maintenance.<sup>1</sup> The importance of WM capacity in explaining this age-related change also remains to be explored. Thus, we examined these possibilities in the present study.

In support of the retrieval hypothesis, it is interesting to note that Karayanidis and colleagues (Karayanidis et al., 2003; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005) report data that show that negative slow waves develop under both cue-based and memory-based (i.e., alternating runs) conditions. On one hand, their cue-based condition included visual cues that were present throughout the preparatory interval, therefore reducing maintenance demands. On the other hand, their memory-based condition placed heavy maintenance demands because participants had to remember the switching sequence and the appropriate task representation. Despite the difference in maintenance demand between conditions, the buildup of a slow negativity appeared under both testing conditions. These results strongly argue against interpreting slow negative shifts exclusively in terms of task-set maintenance. Instead, negative shifts likely reflect the task-retrieval process that has to be exercised under both cue-based and memory-based conditions.

In the current study we examined age differences in task-switching performance by using behavioral (RT and accuracy) and electrophysiological responses during the cue-target interval. Because it was difficult to know from past studies whether age differences were due to problems in maintaining tasks in WM or whether they were 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 maximize their preparation and minimize maintenance demands. Thus, our study was designed to isolate age differences in task-set preparation. We also examined whether differences in WM 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 WM task (the WAIS-III Letter-Number Sequencing task, or LNS).<sup>2</sup> If WM affects target preparation, then we should find group differences in cue electrophysiological activity and in behavioral measures.

## METHODS

### *Participants*

There were 20 younger adults (6 men and 14 women; age,  $M = 24.5$ ,  $SD = 3.4$ ) and 27 older adults (8 men and 19 women;

age,  $M = 75.8$ ,  $SD = 4.4$ ) who participated in this study. Data for the young have previously appeared in the literature (see Goffaux et al., 2006); however, it is important to note that both younger adults and older adults were recruited and tested contemporaneously (data for younger adults were published separately because they focused on additional comparisons not germane to age differences). Older adults consisted of community-dwelling volunteers. All participants reported being free of neurological or cardiovascular diseases. All participants were remunerated \$20 for their participation and provided informed consent. Younger adults had more years of formal education (young,  $M = 18.7$ ,  $SD = 2.3$ ; old,  $M = 15.6$ ,  $SD = 2.9$ ;  $F = 15.10$ ,  $MSE = 7.35$ ,  $p = .0001$ ,  $\eta^2 = .251$ ). However, according to the WAIS-III Vocabulary subtest (Wechsler, 1997), they did not differ from older adults on vocabulary (young,  $M = 53.7$ ,  $SD = 9.8$ ; old,  $M = 56.4$ ,  $SD = 9.4$ ;  $F = 0.88$ ,  $MSE = 92.23$ ,  $p = .35$ ,  $\eta^2 = .019$ ), suggesting comparable intellectual abilities across groups.

We used performance on a measure of WM (raw score on the LNS; Wechsler, 1997) to separate older adults into high- and low-WM participants, by dividing older adults according to the median of their group performance on the LNS subtest. As a result, we included 13 older adults in the Old-low-WM group (10 women and 3 men; age,  $M = 75.1$ ,  $SD = 3.7$ ) and 14 older adults in the old-high-WM group (9 women and 5 men; age,  $M = 76.4$ ,  $SD = 5.0$ ). It is important that old-high-WM participants and younger adults had similar LNS scores (old-high-WM adults,  $M = 13.1$ , range = 11–16,  $SD = 1.7$ ; young adults,  $M = 14.1$ , range = 10–20,  $SD = 2.9$ ;  $F = 1.31$ ,  $p = .26$ ,  $\eta^2 = .039$ ), and that both were significantly higher than those of low-WM older adults (old-low-WM adults,  $M = 9.5$ , range = 8–10,  $SD = 0.7$ ; both  $F$ s  $> 31.25$ , both  $p$ s  $< .001$ , both  $\eta^2$ s  $> .502$ ).

To make sure that our old-high-WM and old-low-WM groups did not differ with respect to executive abilities in general, we compared our older adults on typical clinical measures of frontal lobe functioning, namely the Color Stroop Test (Stroop, 1935) and the Trail Making Test (Reitan & Davison, 1974). Results revealed no difference between the groups on either test (both  $F$ s  $< 2.76$ , both  $p$ s  $> .11$ , both  $\eta^2$ s  $< .099$ ). In addition, high- and low-WM older adults obtained similar vocabulary scores ( $F < 1.00$ ,  $MSE = 92.17$ ,  $p = .96$ ,  $\eta^2 = .001$ ) and had comparable years of formal education ( $F < 1.00$ ,  $MSE = 9.30$ ,  $p = .97$ ,  $\eta^2 = .001$ ).

### Materials and Apparatus

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

Each experimental trial consisted of a cue–target sequence (see Figure 1). We mapped the responses to the same two buttons for all tasks; thus, response competition was high. We counterbalanced these task–response mappings across participants. We presented the 16 nouns and the three cue words

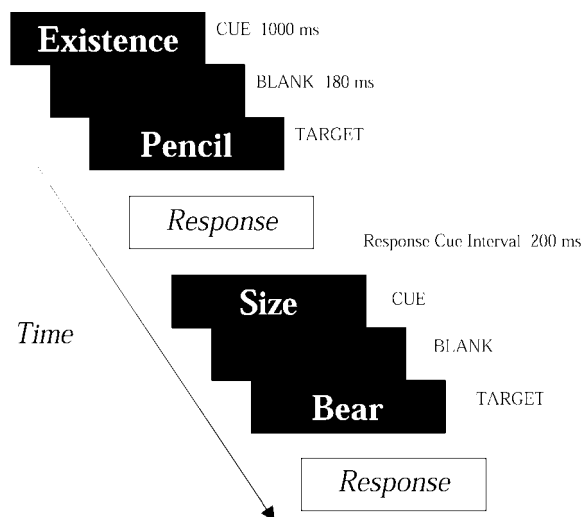


Figure 1. Example of the cue–target sequencing and timing used in our design.

(*existence, size, or breadth*) in white, 24-point font; they appeared on a black-background computer screen.

### Procedure

Participants first completed the computer-based task-switching experiment and then the LNS and Vocabulary subtests. For the task-switching experiment, cues were presented for 1 s and were followed by a target stimulus 180 ms afterward for a total cue–target interval of 1,180 ms. The period of time between the response and the next cue was either 200 ms following a correct response or 800 ms following an error. Participants were instructed to respond as accurately and as quickly as possible. Target words were kept on screen for a maximum of 5 s or until a response was given.

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. The first 80 trials of each block were practice trials. We randomized the ordering of the three homogeneous blocks across participants. Participants then completed two heterogeneous 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. On average, participants switched much more often than they repeated (73.5% as opposed to 23.5% of the time). 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 from interfering with the task–response associations.

### Electroencephalogram Recordings

We obtained the electroencephalogram (EEG) signal from the following electrodes: FPz, Fz, FCz, Cz, CPz, Pz, FP1, FP2, F3, F7, F4, F8, FC3, FC4, FT7, FT8, C3, C4, CP3, CP4, T5,

Table 1. Mean and Standard Deviation of Untransformed and Transformed RT, and Accuracy

Participants	Trial Type			Cost	
	Homogeneous	Repeat	Switch	Mixing	Local Switch
Young participants					
Raw RT	550.0 (59.7)	748.2 (113.5)	836.6 (180.1)	198.2 (82.7)	88.4 (80.8)
Transformed RT	2.74 (0.05)	2.87 (0.07)	2.91 (0.09)	0.13 (0.05)	0.04 (0.04)
Accuracy	96.2 (3.2)	95.6 (3.3)	94.2 (3.9)	-0.58 (3.2)	-1.4 (4.5)
Old-high-WM participants					
Raw RT	723.5 (67.8)	1051.7 (174.5)	1202.5 (269.8)	328.2 (209.0)	150.8 (141.9)
Transformed RT	2.86 (0.04)	3.02 (0.07)	3.07 (0.10)	0.16 (0.09)	0.05 (0.05)
Accuracy	98.0 (2.6)	92.0 (7.6)	86.9 (12.9)	-6.0 (5.8)	-5.1 (7.1)
Old-low-WM participants					
Raw RT	776.6 (129.4)	1212.0 (199.2)	1398.9 (222.2)	435.4 (196.4)	186.9 (133.8)
Transformed RT	2.89 (0.07)	3.08 (0.08)	3.14 (0.08)	0.19 (0.08)	0.06 (0.04)
Accuracy	97.8 (2.2)	88.6 (5.1)	83.3 (5.8)	-9.2 (5.2)	-5.3 (5.8)

Note: RT = reaction time; WM = working memory. Untransformed RT is given in milliseconds; transformed RT is given in log milliseconds; accuracy is given as a percentage.

T6, TP7, TP8, P3, P4, O1, and O2. We used a forehead electrode as ground. We referenced all EEG electrodes to the left ear during acquisition and rereferenced them offline to a linked ear reference. We recorded the electro-oculogram (EOG) bipolarly, and we corrected EOG artefacts offline for all participants by using a regression algorithm (Gratton, Coles, & Donchin, 1983). We sampled EEG activity continuously at 100 Hz and amplified it by using Neuroscan Synamps in a DC-30-Hz bandwidth.

## RESULTS

### Behavioral Data Reduction

We eliminated those RTs greater than 2.5 *SD* of the individual's block mean or less than 200 ms. We analyzed RT data only for correct trials that followed at least two correct responses. We first conducted a Task (existence, size, breadth)  $\times$  Block (heterogeneous Blocks 1 and 2)  $\times$  Cost Type (local switch cost, mixing cost) analysis of variance (ANOVA) on RT and accuracy scores to test whether cost types differed as a function of block or semantic task. We conducted this analysis independently for younger adults, old-low-WM participants, and old-high-WM participants. For all of our behavioral analyses, we describe higher-order interactions and decompose them by using simple effects with Bonferroni-corrected pairwise comparisons. The RT and accuracy analyses failed to show any significant interaction involving cost type for younger adults (all  $F$ s < 1.05, all  $p$ s > .05, all  $\eta^2$ s < .050), old-high-WM participants (all  $F$ s < 2.74, all  $p$ s > .05, all  $\eta^2$ s < .164), and old-low-WM participants (all  $F$ s < 1.20, all  $p$ s > .05, all  $\eta^2$ s < .121). This indicates 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 in the following paragraphs.

### Behavioral Results

Comparisons made using raw RT data (Table 1) revealed a significant mixing cost,  $F(1, 44) = 176.78$ ,  $MSE = 13188.69$ ,  $p = .001$ ,  $\eta^2 = .801$ , such that participants were faster on

homogeneous than on repeat trials. We also obtained a significant local switch cost,  $F(1, 44) = 67.06$ ,  $MSE = 6826.08$ ,  $p = .001$ ,  $\eta^2 = .604$ , revealing faster responses on repeat than on switch trials.

To see if the size of the mixing and local switch cost differed between groups, we compared logarithmically transformed cost scores to control for general slowing in baseline performance among older adults. ANOVA results (Group  $\times$  Cost) revealed that the groups differed on the mixing cost,  $F(2, 44) = 2.84$ ,  $MSE = 0.006$ ,  $p = .05$ ,  $\eta^2 = .120$ , such that old-low-WM participants had larger RT mixing costs than did younger adults ( $p < .02$ ), whereas old-high-WM participants and younger adults had similar RT mixing costs ( $p = .31$ ). Old-high-WM and old-low-WM participants had similar RT mixing costs ( $p = .32$ ). All participants had similar RT local switch costs:  $F(2, 44) = 0.72$ ,  $MSE = 0.002$ ,  $p = .492$ ,  $\eta^2 = .032$ .

Results for performance accuracy (Table 1) revealed group differences,  $F(4, 88) = 10.02$ ,  $MSE = 36.39$ ,  $p = .001$ ,  $\varepsilon = .777$ ,  $\eta^2 = .313$ . Whereas younger adults did not show an accuracy mixing or local switch cost (both  $p$ s > .81), old-high-WM and old-low-WM participants did (all  $p$ s < .01). Moreover, the high- and low-WM older adults also had bigger accuracy mixing costs than did the younger adults (all  $p$ s < .001). All three groups had comparable-accuracy local switch costs (all  $p$ s > .05).

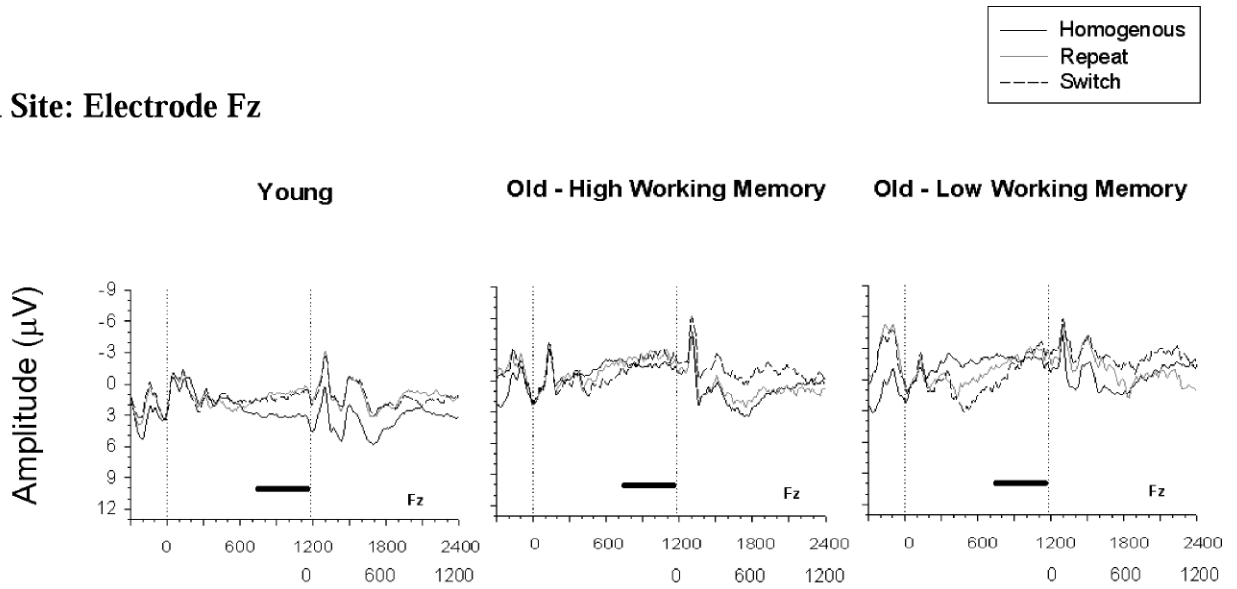
### ERP Data Reduction

We had the cue-locked waveforms time locked to the presentation of the cue and baseline corrected between 0 and 100 ms after cue onset (see Figure 2). This postcue 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 (see Goffaux et al., 2006).

We analyzed the ERP waveforms as a function of scalp region. We computed the mean waveform amplitudes as a function of anteriority and laterality (left anterior, F3, FC3; midanterior, Fz, FCz; right anterior, F4, FC4; left central, C3; midcentral, Cz; right central, C4; left posterior, CP3, P3; midposterior, CPz, Pz; right posterior, CP4, P4). To capture the time course of negative slow-wave activity, we calculated cue-locked mean amplitude across the 800- to 1180-ms postcue



## Frontal Site: Electrode Fz



## Parietal Site: Electrode Pz

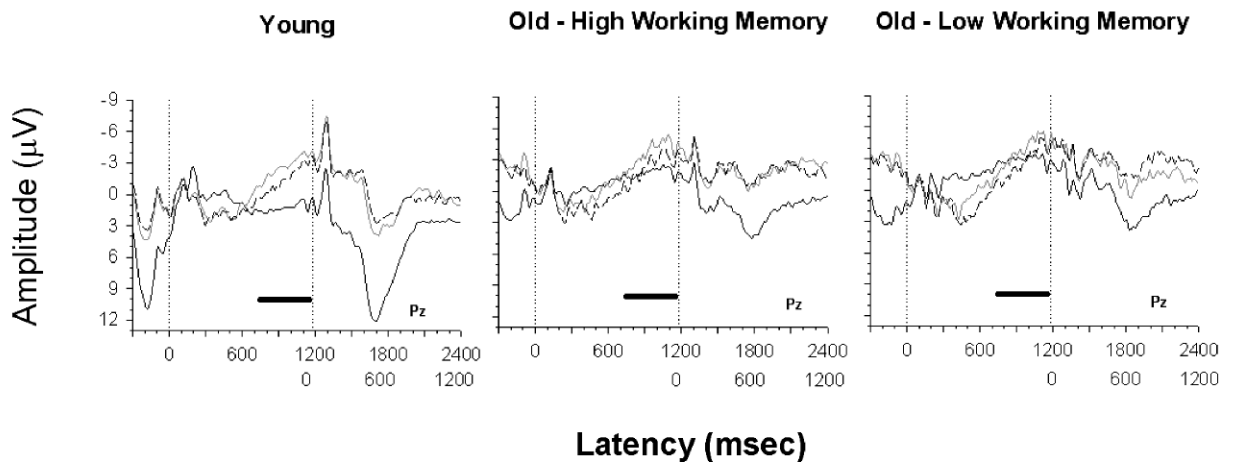


Figure 2. Selected cue-locked grand average waveforms. The vertical dotted lines indicate cue and target onset, respectively; upper and lower x-axis time scales indicate latency referenced to cue and target onset, respectively. Black bars across the x axis indicate the period of analysis. See text for additional details.

epoch. In our ERP figures (see Figure 2), this epoch is highlighted by a large black bar across the x axis.

We also examined the target-locked P300 amplitude and latency by peak scoring the most positive point in the 300- to 800-ms posttarget interval. Results from the target-locked analyses did not reveal any Group  $\times$  Trial Type interaction (all  $F_s < 1.6$ , all  $p_s > .12$ ), and we obtained trial type effects similar to those reported in Goffaux and colleagues (2006) across all participants; thus, in this study we focus on only cue-locked effects.

## ERP Results

We analyzed group and trial type differences in the cue-locked data as a function of scalp region by using a series of

mixed-design ANOVAs. We analyzed data from midline and lateral electrode sites in separate ANOVAs, with midline analyses employing a Group  $\times$  Trial Type  $\times$  Electrode Site (anterior to posterior) factorial design and analyses from lateral electrode sites employing a Group  $\times$  Trial Type  $\times$  Anteriority  $\times$  Laterality (left to right) factorial design. Significant main effects of trial type and group are reported, followed by significant higher-order interactions when present. We describe and decompose higher-order interactions by using simple effects with Bonferroni-corrected pairwise comparisons. ERP data are depicted in one of two forms. Figure 2 shows the ERP waveforms plotted as a function of time (in milliseconds) and amplitude (in microvolts) at individual electrode sites for each of the three conditions. In contrast, Figures 3 and 4 depict

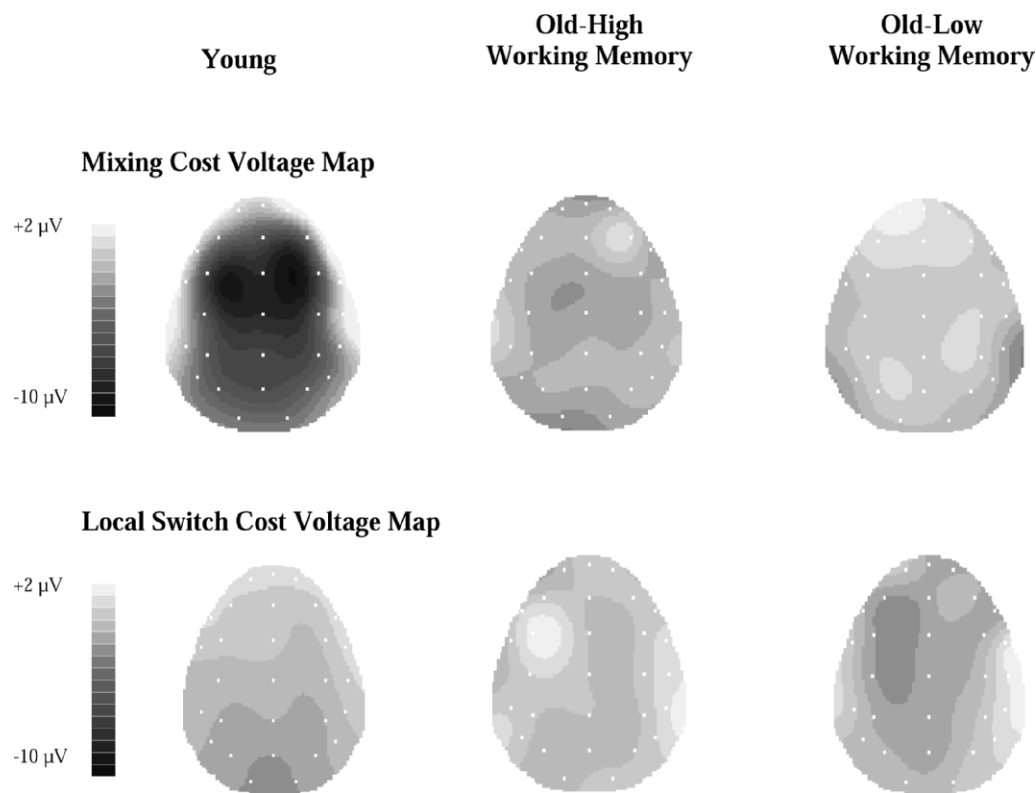


Figure 3. Topographic maps of the microvolt difference between the cue-locked negative slow waves (800-1,180 ms; dots = electrode locations). Larger mixing or local switch cost effects are depicted by darker shading. Younger adults and high-WM older adults show a mixing-cost effect across the entire scalp; low-WM older adults do not. All groups show a local switch cost effect, evident at posterior regions.

variations in ERP amplitude distributed across the scalp (i.e., a surface potential map).

#### Cue-Locked Mixing Cost

As illustrated in Figure 2, for heterogeneous conditions, younger adults showed a negative slow-wave potential that became progressively larger by the time the target appeared and that was absent from the homogeneous condition. Both older adult groups, however, showed negative slow-wave activity for homogeneous, repeat, and switch trials (compare the ERP waveforms for each group across the cue-locked epoch highlighted by the large black bars on the figures' *x* axis). Negative slow-wave activity on homogeneous trials was most striking in the old-low-WM group.

The ANOVA results obtained at midline sites revealed a significant main effect of trial type,  $F(1, 44) = 22.48$ ,  $MSE = 17.50$ ,  $p = .0001$ ,  $\eta^2 = .338$ , indicating that repeat trials were more negative than homogeneous trials. We also found a significant main effect of group,  $F(2, 44) = 7.82$ ,  $MSE = 59.87$ ,  $p = .001$ ,  $\eta^2 = .262$ . Our post hoc analyses showed that younger adults had smaller negative amplitudes overall than did either high- or low-WM older adults (all  $ps < .005$ ), whereas the latter two groups did not differ ( $p = 1.0$ ).

ANOVA results for lateral site data revealed a significant main effect of trial type,  $F(1, 44) = 19.59$ ,  $MSE = 26.64$ ,  $p = .0001$ ,  $\eta^2 = .308$ , and of group,  $F(2, 44) = 7.43$ ,  $MSE = 82.90$ ,  $p = .002$ ,  $\eta^2 = .252$ , as well as a significant Group  $\times$  Trial Type  $\times$  Anteriority interaction,  $F(4, 88) = 2.54$ ,  $MSE = 1.75$ ,  $p = .04$ ,

$\eta^2 = .103$ . Simple effects conducted on the interaction indicated that younger adults had larger negative amplitudes for repeat trials than for homogeneous trials across frontal, central, and posterior scalp regions (all  $ps < .01$ ). Old-high-WM participants also showed larger negative amplitudes for repeat than for homogeneous trials, but this was limited to central and posterior scalp regions (all  $ps < .02$ ). Low-WM seniors, however, did not show a mixing cost difference at all (all  $ps > .12$ ; see the mixing-cost voltage maps depicted in Figure 3 where low-WM older adults show little difference between repeat and homogeneous trials, i.e., nearly a 0- $\mu$ V difference). To understand the locus of this mixing-cost pattern difference observed for old-low-WM participants, we conducted simple effects to test for group differences on repeat and homogeneous trials separately.

Results revealed that old-low-WM participants failed to show a mixing cost because their homogeneous waveforms over central and posterior regions were more negative than that of the young and old-high-WM groups ( $ps < .05$ ; see electrode Pz in Figure 2, comparing the solid black line between groups), not because their repeat waveforms were smaller (repeat negativities at central and posterior regions were comparable across groups;  $ps > .05$ ). However, repeat waveforms did differ between groups at frontolateral sites (e.g., electrodes F3 and F4). Figure 4 shows this effect, which is most obvious for old-high-WM participants, by plotting the surface potential voltage map of the repeat waveform across the scalp. Repeat slow waves were reliably more negative for old-high-WM

## Repeat Trial Voltage Map

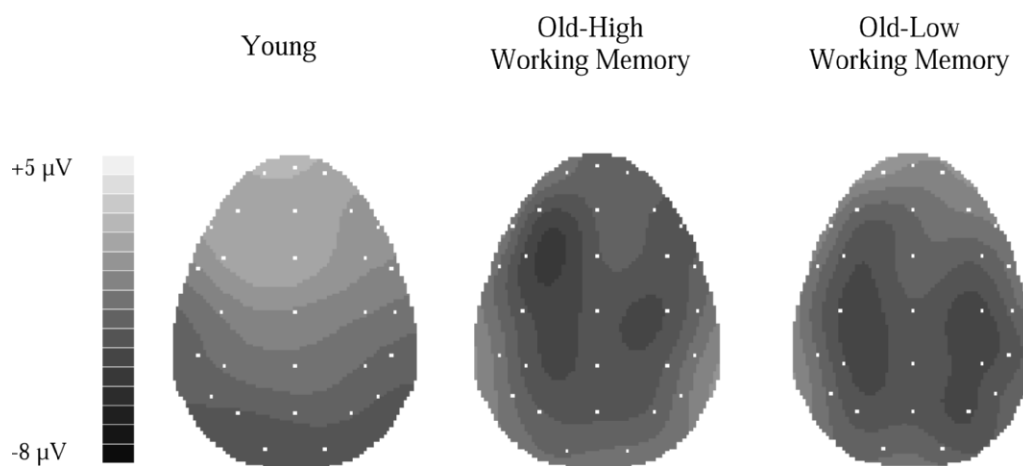


Figure 4. Topographic scalp plot of the voltage for the cue-locked negative slow wave recorded between 800 and 1,180 ms. Compared with low-WM older adults and younger adults, high-WM older adults show greater negative slow-wave activity (i.e., darker shading) across frontolateral regions.

participants than for younger adults ( $p < .02$ ), whereas old-low-WM participants and younger adults did not differ (all  $p$ s  $> .05$ ). In fact, as can be appreciated in Figure 4, frontolateral negative slow-wave activity was less pronounced in old-low-WM participants and almost absent in younger adults.

#### Local Switch Cost

Cue-locked ERP waveforms presented in Figure 2 show that switch trials were also characterized by posterior negative slow-wave activity (for all groups, see the dotted-line waveform at electrode Pz), although it appeared to be less pronounced than that of repeat trials (see light gray waveform at electrode Pz). The ANOVA results for midline sites revealed a significant main effect of trial type,  $F(1, 44) = 5.55$ ,  $MSE = 5.79$ ,  $p = .02$ ,  $\eta^2 = .112$ , indicating that repeat trials were more negative than switch trials. We also found a significant Trial Type  $\times$  Anteriority interaction,  $F(2, 88) = 13.84$ ,  $MSE = 0.380$ ,  $p = .0001$ ,  $\epsilon = .686$ ,  $\eta^2 = .239$ . Simple effects to test for trial type differences revealed that repeat trials were more negative than switch trials at central ( $p = .03$ ) and posterior ( $p = .01$ ) sites for all three groups (see the local switch cost voltage map for all three groups in Figure 3).

The ANOVA results for lateral sites revealed a significant Trial Type  $\times$  Anteriority interaction,  $F(2, 88) = 10.36$ ,  $MSE = 1.26$ ,  $p = .001$ ,  $\epsilon = .611$ ,  $\eta^2 = .191$ . Simple effects conducted to test for trial type differences indicated that repeat trials were more negative than switch trials at posterior sites ( $p = .002$ ). We also found a significant Anteriority  $\times$  Group interaction,  $F(4, 88) = 3.86$ ,  $MSE = 23.82$ ,  $p = .02$ ,  $\epsilon = .573$ ,  $\eta^2 = .150$ . Simple effects conducted to test for group differences indicated that old-high-WM participants obtained larger repeat and switch negativities than did younger adults at frontolateral sites ( $p =$

.02). Old-low-WM participants and younger adults did not differ ( $p = .16$ ).

#### DISCUSSION

Older adults with high WM performed as well as younger adults, whereas older adults with poor WM had larger RT mixing costs than did younger adults. Old-high-WM and old-low-WM participants did not differ reliably, although the difference in their mixing costs was large (over 100 ms, favoring old-high-WM participants). Nevertheless, the brain activation revealed marked and reliable differences between the two groups, suggesting that old-high-WM and old-low-WM participants are doing something quite different when they multitask. The ERP results reviewed here show how differences in WM capacity affect a person's aging brain when she or he is preparing for a target stimulus.

#### Cue-Locked ERP Effects

For homogeneous cues, younger adults did not show any negative slow-wave activity, whereas older adults did. In fact, the negativity for homogeneous cues was larger for old-low-WM participants than for the old-high-WM or young participants. Posterior negativities develop when a cue is used to prepare and are likely associated with context monitoring and the retrieval of task-relevant attributes (Johansson & Mecklinger, 2003; Goffaux et al., 2006). Given our results, this would suggest that old-low-WM participants have to rely on the external context even to prepare for homogeneous targets. 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 a functional magnetic resonance imaging activation difference when they were performing in mixed- as opposed

to single-task contexts. Importantly, this effect resulted from greater activation during single-task performance, not from diminished activation during mixed-task performance. The authors concluded that advancing age obligates the use of similar neural control when one is performing in both single- and mixed-task contexts. That study, however, did not take into account the effects of WM. As shown in the present study, when WM capacity is taken into consideration, it is clear that only low-WM seniors needed to exert trial-to-trial preparation during single-task contexts.

We also found that, at frontal sites, old-high-WM participants had larger negative slow waves than did younger adults for both repeat and switch trials, which was most obvious at frontolateral sites. Although we cannot assume a direct relationship between ERP topography and brain localization, larger frontal negativities are thought to reflect the activity of executive processes (Falkenstein, Hoormann, Hohnsbein, & Kleinsorg, 2003; Lorist et al., 2000). Large negativities for old-high-WM participants suggest that these individuals are capable of exercising executive control, especially because their RT costs were similar to those of younger participants. Age-related increases in bilateral frontal activity have previously been observed (Grady, Bernstein, Beig, & Siegenthaler, 2002; Nielson, Langenecker, & Garavan, 2002; Reuter-Lorenz et al., 2000) and are usually attributed to a general mechanism of compensatory processing (Cabeza et al., 2004). Evidence of compensatory neuronal activity has recently been provided in a positron emission tomographic study, where the brain activity of younger and older adults was recorded as they performed a difficult source memory task (Cabeza, Anderson, Locantore, & McIntosh, 2002). High-performing older adults performed as well as younger adults but showed greater bilateral prefrontal activity than younger adults. Such findings support the idea that, for older adults, greater frontolateral activation is related to compensatory processing. Given the results of our old-high-WM participants, 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.

In contrast to Kray and colleagues (2005) and West (2004), who surmised that there was a problem with task-set maintenance in advancing age because the cue disappeared well before the target appeared (at least 1,000 ms earlier), we suggest that age-related differences in task-set preparation reflect differences in task-set retrieval. Specifically, because the cue was available through the cue-target interval, the age differences we see in the cue-locked negativity on heterogeneous trials (i.e., greater negativity for repeat and switch trials in the high-WM older adults than in the young adults) over frontal regions probably reflect task-set retrieval processes. That is, we suggest that the high-WM older adults are still retrieving the task set even during the late portion of the cue-target interval, despite the continued availability of the task cue.

It can be argued that a more direct way to distinguish between task activation and task maintenance would be to directly compare conditions where the cue is always available versus conditions where the cue is only briefly available in the early cue-target interval. Nevertheless, our interpretation is congruent with recent findings that showed that older adults continue to improve their RTs, even when the preparation interval is increased from 750 to 2,300 ms (Kray, 2006),

particularly when WM demands are high. These results suggest that, for older adults, preparation will continue to be evident late in the cue-target interval, which is consistent with our observations.

One potential limitation of our study is worth noting. To reduce testing time, we were compelled to use a short response-cue interval (i.e., 200 ms). Such a short response-cue interval may allow persisting task activation from a preceding trial to interfere with preparation for the subsequent trial (Meiran et al., 2000). Meiran and associates (2001) and Cepeda, Kramer, and Gonzalez de Santher (2001) found that such proactive interference dissipates more slowly for older adults than for younger ones. This means that, when a short response-cue interval is used, age differences in RT may be inflated. However, this problem only holds for the local switch cost because proactive interference occurs only when the preceding trial is different from the current one. If tasks repeat, the previous trial should generate proactive facilitation. Thus, in the current study, if proactive effects dissipate more slowly for older adults than for younger ones, then they should have larger local switch costs and smaller mixing costs. Because 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.

Although our local switch cost results are consistent with the majority of task-switching studies (i.e., no effect of age on the behavioral or ERP local switch cost), Kray and Eppinger (2006) recently found that advancing age enhances the local switch cost when task representations are hard to disambiguate. That is, when task representations overlap a lot (i.e., when a large number of task sets and a small number of stimuli are used), negative and competitor priming effects increase and performance decreases, especially for older adults. The current study was not designed to address this issue; however, future aging projects will have to consider the importance of target ambiguity.

Another potential limit of the present study is that all of our younger adults obtained relatively high WM scores.<sup>2</sup> As a result, we were unable to separate our younger adults into meaningful high- and low-WM subgroups. It is difficult to know, therefore, whether the same effects of WM would be evident in a group of low-WM younger adults as we see in low-WM older adults. Nevertheless, our results clearly demonstrate that WM capacity moderated the typical age effect seen in task switching and influenced the cortical activation pattern associated with target preparation in older adults. In this way, our results are compatible with neuroimaging studies that have also compared high-performing younger adults, high-performing older adults, and low-performing older adults (Cabeza et al., 2002; Daselaar et al., 2003; Rosen et al., 2002). Future studies will be needed to determine whether WM capacity affects target preparation in younger adults.

Finally, it is important to point out that, in heterogeneous blocks, our participants switched between task sets more frequently than they repeated them. This means that our participants may have adopted conservative response strategies, effectively helping them to stay in a "switch-ready" state. Such conservative strategies are known to affect the performance of younger adults, especially in cued, randomly alternating task-switching designs (see Monsell, Sumner, & Waters, 2003). Older adults also adopt conservative response strategies in mixed-task situations (see DeJong, 2001); however, it is not



clear whether age-differences in task switching also have strategic origins. Future studies comparing younger and older adults will have to address this issue.

### Summary

Studying ERPs in a cued task-switching paradigm has allowed us to chart the time course and topography of cognitive control functions as they lead up to specific target events. In combination with behavioral results, we were able to show that older adults with low WM have large posterior negativities when preparing for homogeneous targets, suggesting that they need to rely on external cues even when they are preparing for single-task targets. In contrast, old-high-WM participants showed large frontal negativities when preparing for mixed-task trials and obtained small RT mixing costs, equivalent to younger participants. This suggests that relatively good WM in old age facilitates the mobilization of executive control, which helps to offset declining performance during mixed-task contexts. Overall, these results indicate that age differences in task-switching performance are mediated by individual differences in WM capacity and may, in older adults with good WM, be offset by compensatory brain activity. Interestingly, the high temporal resolution of ERPs reveals that this compensatory activity occurs quite quickly and can be activated in anticipation of a target event (i.e., during the cue interval). Thus, preparatory control appears to be variably preserved in old age, depending on other important cognitive factors such as WM.

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### CORRESPONDENCE

Address correspondence to Natalie A. Phillips, PhD, Department of Psychology, Concordia University, Centre for Research in Human Development, 7141 Sherbrooke Street West, Montréal, Québec, Canada, H4B 1R6. E-mail: Natalie.Phillips@concordia.ca

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## END NOTES

<sup>1</sup>In the current context, the term *maintenance* refers to the ability to keep a newly loaded, cue-evoked task set in preparation for a specific trial. In other words, it describes the cognitive efforts that have to be exercised in order to uphold new task representations across the period of time corresponding to the cue-target interval.

<sup>2</sup>As might be expected, the younger adults did not vary greatly in their WM performance. Preliminary analyses conducted on two subgroups of the young adults split at the median of their WM scores did not reveal any differences with respect to their mixing and local switch costs (RT and accuracy). Therefore, we do not discuss this contrast in the present study. Because we were interested in how WM affected task-switching performance in older adults and whether age differences remained when WM ability was controlled, we necessarily had to match a subgroup of high-WM older adults with a homogeneous group of young adults with comparable WM scores. Thus, we separated only the older adults into high- and low-WM groups in this report.