Task switching and bilingualism in young and older adults: a behavioral and electrophysiological investigation

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Abstract

The current study investigated behavioral and electrophysiological (event-related potential; ERP) differences associated with task switching in a sample of young and older monolingual and bilingual adults. ERPs associated with task preparation (switch and mixing positivity) and task execution processes (N2 and P3b) were investigated. Participants performed a cued letter-number task switching paradigm that included single task and mixed task blocks, while their electroencephalography was recorded. Behavioral results revealed smaller switch and mixing costs in bilinguals relative to monolinguals, in both young and older participants. There were no ERP differences in the effect size of the cue-locked mixing and switch positivities, nor the target-locked mixing and switch N2 and P3b components. However, overall larger target-locked N2 amplitudes were observed in bilinguals relative to monolinguals. In addition, bilingual older adults exhibited smaller P3b amplitudes than monolingual older adults. The smaller behavioral mixing and switch costs observed in bilinguals suggest that bilinguals exhibit superior sustained attention and faster task-set reconfiguration processes compared to monolinguals. The ERP measures provide evidence for differences in brain processes between monolinguals and bilinguals and a reliance on different processing strategies in bilingual compared to monolingual older adults.

Keywords: bilingualism, aging, event-related potentials (ERPs), task switching, switch positivity, mixing positivity, P3b, N2

Introduction

In the past decade or so, research has demonstrated that bilingualism may be associated with cognitive advantages in executive function tasks requiring attentional or inhibitory control, and in task switching abilities. However, several studies have failed to replicate these findings. This lack of replicability has generated substantial debate questioning the existence of language group differences in cognitive control processes and/or the specific conditions under which such differences might emerge (Paap, Johnson, & Sawi, 2016). Given these discrepancies, researchers have advocated for studies to be conducted under different conditions and using a combination of methodological tools in order to accurately identify the circumstances under which group differences appear (e.g., Kousaie & Taler, 2015; Treccani & Mulatti, 2015; van Heuven & Coderre, 2015).

One circumstance under which the bilingual advantage may arise is in aging populations. Bialystok, Craik, & Luk (2012) suggested that the bilingual advantage is less reliable in bilingual young adults because they are at the peak of their cognitive performance, leaving no room for bilingualism to exert its influence, whereas in older adults who are experiencing age-related cognitive changes, the effect may be more robust. Another challenge is to search for *concurrent* findings from both behavioral and neurocognitive measures (see Paap et al., 2016). Thus, we aimed to investigate the effect of bilingualism and age on task switching by comparing four groups of participants: young and older monolinguals and bilinguals. We collected behavioral and electrophysiological (event-related potential, ERP) measures. A task switching paradigm was used because the ability to shift attention from one task to another is considered an aspect of executive function (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Sylvester et al., 2003), which is thought to be bolstered in bilinguals, and it has been less extensively studied than other executive function tasks in terms of the neural consequences of aging and bilingualism.

Task switching is typically investigated using paradigms that require participants to switch between tasks requiring different decisions (Monsell, 2003). One way to test task switching is with a single task that requires participants to make a binary decision on every trial (e.g., decide if a geometric figure is red or blue), and a mixed-task condition that requires participants to shift their attention to different task requirements (e.g., in some trials, make a binary decision about the color, while in others make a binary decision about the shape, e.g., circle or square). In the mixed task, trials are classified as either a repeat trial, (e.g., a color trial preceded by another color trial), or as a switch trial (e.g., a color trial preceded by a shape trial).

Two types of costs associated with switching can be derived from task switching paradigms: 1) mixing cost, which is the difference in performance between the single task condition and repeat trials in the mixed task condition, and 2) switch cost (also known as local switch cost), which is the difference in performance between the repeat and switch trials in the mixed task condition. The mixing cost is associated with processes related to sustained attention and working memory when two or more task sets are active (Braver, Reynolds, & Donaldson, 2003), whereas the switch cost is associated with the ability to switch from one task set to another (referred to as task-set reconfiguration) (Meiran, 1996; Rogers & Monsell, 1995) and inhibition of interference from the previous trial (Wylie & Allport, 2000).

Given that bilinguals are constantly managing their two competing languages, one might expect to see differences between bilinguals and monolinguals in terms of non-linguistic task switching. Two previous studies have reported smaller switch costs in bilinguals than monolinguals (Prior & Gollan, 2011; Prior & MacWhinney, 2010), and one experiment found smaller mixing costs in bilingual than monolingual young adults (Wiseheart, Viswanathan, & Bialystok, 2016). Moreover, Soveri, Rodriguez-Fornells, & Laine (2011) found that in young bilinguals, the frequency of switching between languages predicted smaller mixing cost in terms of accuracy. However, several studies have found no evidence of superior task switching in bilinguals compared to monolinguals (Branzi, Calabria, Gade, Fuentes, & Costa, 2017; Hernández, Martin, Barceló, & Costa, 2013; Jylkkä et al., 2017; Mor, Yitzhaki-Amsalem, & Prior, 2014; Moradzadeh, Blumenthal, & Wiseheart, 2014; Paap & Greenberg, 2013; Paap & Sawi, 2014; Shulley & Shake, 2016).

With regard to aging, task switching studies have generally found larger mixing costs in older than younger adults (Kray & Lindenberger, 2000; Reimers & Maylor, 2005), but no effect of age on switch costs (for a meta-analysis see Wasylyshyn, Verhaeghen, & Sliwinski, 2011) (although see Kray, Li, & Lindenberger, 2002, who found age differences in switch cost as well; Meiran, Gotler, & Perlman, 2001).

The evidence regarding a bilingual advantage in task switching in older adults is mixed. In one study, Gold, Kim, Johnson, Kryscio, & Smith (2013) found smaller global switch costs (defined as the difference in performance between single-task and mixed-task collapsed across repeat and switch trials) in bilingual than monolingual older adults in a color-shape paradigm. A second experiment with a different participant sample found only a marginal effect (*p*=.056). Another study found smaller switch costs in older bilinguals relative to monolinguals, but no differences in mixing costs (Houtzager, Lowie, Sprenger, & de Bot, 2017). In addition, de Bruin, Bak, & Della Sala (2015) found a switch cost advantage in older active bilinguals (defined as bilinguals who use both languages in their daily life) relative to older inactive bilinguals (defined as bilinguals who mainly used one language in their daily life) and monolinguals; however, when looking at proportional cost to correct for baseline differences, the effect was no longer significant. Finally, a study by Ramos, Fernández García, Antón, Casaponsa, & Duñabeitia, (2016), found no effect of second language training on task switching in monolingual older adults.

Neural differences between monolinguals and bilinguals during task switching have also been previously investigated. Garbin et al., (2010) found that, while monolinguals activated regions typically associated with switch cost (right inferior frontal gyrus, anterior cingulate and left inferior parietal lobe), bilinguals activated the left inferior frontal gyrus and putamen. Gold et al., (2013) found that bilingual young and older adults showed lower neural switch costs in the left dorsolateral prefrontal cortex, the bilateral ventrolateral prefrontal cortex and the anterior cingulate cortex relative to monolinguals.

The shift in brain activation from anterior to subcortical/posterior regions observed by Garbin et al. (2010) and the decreased activation in regions typically associated with executive control in bilinguals relative to monolinguals (Gold et al., 2013) could be explained by the Bilingual Anterior to Posterior and Subcortical Shift model (BAPSS) (Grundy, Anderson, & Bialystok, 2017). This model posits that compared to monolinguals, bilinguals recruit subcortical brain areas more than anterior regions and activate regions associated with executive control less than monolinguals. This difference in brain activation occurs because bilinguals shift from a more demanding top-down processing strategy to a less demanding automatic strategy in nonverbal executive control tasks. That is, bilingualism is associated with more efficient brain recruitment.

In the present study we investigated task switching in a sample of young and older monolinguals and bilinguals using event-related potentials (ERPs). ERPs are waveforms that are extracted from the ongoing electroencephalogram (EEG) by time-locking the EEG to sensory or cognitive events. The amplitude and timing of the ERPs are thought to reflect the strength and timing of the underlying cognitive processes (Rugg & Coles, 1995), and the excellent temporal resolution of EEG allows for the study of cognitive processes as they unfold over time. In this study, we used a cued task switching paradigm, where a cue indicating which task to perform appears prior to the target stimulus. Thus, the ERP technique was particularly suitable for our study as it allowed us to examine brain processes associated with task preparation (cue-locked events) and task execution (target-locked events).

In cue-locked events, both switch and mixing costs are indexed by a posterior-parietal positivity starting at around 400 ms that is larger for switch compared to repeat trials. This deflection is referred to as the “switch positivity” or the “mixing positivity”, depending on how it is elicited (Capizzi, Feher, Penolazzi, & Vallesi, 2015; Jamadar, Thienel, & Karayanidis, 2015; Jost, Mayr, & Rösler, 2008; Karayanidis, Provost, Brown, Paton, & Heathcote, 2011) (for a review see Jamadar et al., 2015). The switch positivity is thought to reflect task-set reconfiguration processes such as inhibiting the irrelevant task set and activating the task set associated with the cue (Karayanidis et al., 2011; Nicholson, Karayanidis, Poboka, Heathcote, & Michie, 2005). There is evidence that the amplitude of the switch positivity is negatively correlated with reaction time on switch trials and switch cost (e.g., Karayanidis et al., 2011). The role of the mixing positivity has not been adequately characterized, although some argue that it may reflect decoding of the cue, rule retrieval and goal activation processes (Jost et al., 2008).

Target-locked events have been associated with a fronto-central negativity peaking approximately 200-350 ms post-target, resembling the N2, that is larger for switch than repeat trials (Kieffaber & Hetrick, 2005; Nicholson et al., 2005; Periáñez & Barceló, 2009). The N2 has been mostly studied in conflict resolution paradigms (e.g., Simon task, Eriksen Flanker task), where higher conflict trials elicit larger N2 amplitudes (e.g., van Veen & Carter, 2002a, 2002b). In task switching paradigms, larger N2 amplitudes indicate that increased executive control is required to process the more difficult switch condition relative to the less-demanding repeat condition (Jamadar et al., 2015).

Another component observed in target-locked events is a larger centro-parietal P3b for repeat relative to switch trials in the mixed-task condition (Kieffaber & Hetrick, 2005; Nicholson et al., 2005; Periáñez & Barceló, 2009). This component is also larger for trials in the single-task condition compared to repeat trials in the mixed-task condition (mixing cost) (Barceló, Muñoz-Cespedes, Pozo, & Rubia, 2000; Gajewski & Falkenstein, 2011; Goffaux, Phillips, Sinai, & Pushkar, 2006). The P3b is a positive deflection peaking at about 300 to 400 ms post-stimulus onset that is associated with stimulus evaluation. A reduction in its amplitude in more difficult experimental conditions is believed to reflect fewer available resources in working memory to process the target (Kok, 2001; Polich, 2007).

With respect to bilingualism, a study by Timmers, Grundy and Bialystok (2017) investigated processing differences between monolinguals and bilinguals during language and nonverbal task switching. They found that target-locked N2s were larger for repeat than switch trials in bilinguals, while monolinguals did not show a difference in N2 amplitude across conditions. These results were interpreted as evidence for earlier attention to cue processes associated with switching in bilinguals compared to monolinguals. Moreover, Timmers et al.

also found that bilinguals had a more distributed network for the ERPs (i.e., N1, N2 and P3) associated with nonverbal mixing cost than monolinguals, consistent with the view that bilingualism efficiently modifies brain networks (BAPSS framework) (Grundy et al., 2017).

The present study extends Timmer et al.'s (2017) results by investigating behavioral and electrophysiological differences between young and older monolinguals and bilinguals during a binary-choice letter-number cued task switching paradigm. We examined switch and mixing cost in terms of reaction time, accuracy, and both cue- and target-locked ERP components. We hypothesized that, if there is a robust language group difference, this difference would be reflected in both behavioral and ERP measures. In terms of behavioral measures, we hypothesized that bilinguals would exhibit smaller switch and/or mixing cost in terms of reaction time and/or accuracy relative to monolinguals.

One of the advantages of using an ERP paradigm is that it will permit an examination of where in the processing pipeline language group differences might emerge. That is, given the temporal sensitivity of ERPs, we can examine whether any observed differences between monolinguals and bilinguals emerge during task preparation, task execution or both. Furthermore, recall that there is evidence that the switch positivity is negatively correlated with behavioral switch costs (Karayanidis, 2011). Thus, if bilinguals show a smaller switch cost compared to monolinguals, then we would expect a larger switch positivity in bilinguals relative to monolinguals.

The BAPSS model proposes that bilinguals rely on early processes (associated with automatic processing) more than monolinguals, who rely more on later, more controlled processes (Grundy et al., 2017). Thus, bilinguals should exhibit larger target-locked N2 than monolinguals, while monolinguals should exhibit larger P3bs than bilinguals, indicating that monolinguals and bilinguals rely on different processing strategies. Specifically, bilinguals rely on an automatic processing strategy while monolinguals rely on controlled processing strategies. It is further expected that larger language group differences will emerge in older adults, who are experiencing age-related cognitive decline; young adults are at the peak of their cognitive functioning and therefore may not benefit from a bilingual advantage to the same extent as older adults (Kousaie & Phillips, 2012, 2017).

Methods

Participants

The study included 92 right-handed participants in total. However, due to poor EEG data quality, the data from two monolinguals and three bilingual young adults, and from five monolingual and three bilingual older adults were excluded from all analyses. Thus, the final sample comprised 43 young adults (23 monolinguals and 20 bilinguals) and 36 older adults (18 monolinguals and 18 bilinguals). Bilingual participants were highly proficient in French and English and had no functional knowledge of any other languages. Groups did not significantly differ in age or education. The young adults were recruited from the University of Ottawa, and the older adults by advertisements or word of mouth. Prior to beginning the study, all participants completed a health questionnaire to verify that they were in good health, were not taking medications known to affect cognitive function, and had no history of neurological or psychological disorders. Participants self-rated their proficiency on a scale of 1-5 in listening, reading, speaking, and writing, where 1 indicated "*no ability at all"* and *5* indicated *"native-like ability"*. Participants were remunerated $10 an hour for their participation. Ethical approval was received from the University of Ottawa and the Bruyère Research Institute. Demographic information is reported in Table 1.

Materials and apparatus

Neuropsychological battery. All participants completed a brief neuropsychological battery comprised of the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), the Forward and Backward Digit Span and Letter Number Sequencing subtests from the Wechsler Adult Intelligence Scale Version III (WAIS-III; Wechsler, 1997), and the Wisconsin Card Sorting Task (Grant & Berg, 1948). Results are reported in Table 1.

Table 1. Young and older adult mean (SD) for demographic, self-reported language proficiency, and neuropsychological measures. Monolinguals and bilinguals did not differ on any demographic or neuropsychological variables.

Variables	Young Monolingual[d]	Young Bilingual	p-value[a]	Older Monolingual	Old Bilingual	p-value[a]
Sample size (females)	23 (17)	20 (13)	NA	18 (11)	18 (10)	NA
Auditory comprehension	NA	L1[b]=4.95(0.22) L2[c]=4.70(0.47)	NA	NA	L1=4.89(0.32) L2=4.83(0.38)	NA
Reading	NA	L1=5(0) L2=4.65(0.49)	NA	NA	L1=4.89(0.32) L2=4.72(0.46)	NA
Speaking	NA	L1=4.95(0.22) L2=4.50(0.61)	NA	NA	L1=4.92(0.26) L2=4.72(0.46)	NA
Writing	NA	L1=4.95(0.22) L2=4.45(0.76)	NA	NA	L1=4.75(0.43) L2=4.39(0.61)	NA
Age (years)	22.83(3.31)	22.70(2.83)	.90	71.72(3.54)	71.39(4.03)	.80
Education (years)	16.00(1.73)	15.85(2.39)	.81	15.61(2.66)	16.00(2.59)	.66
MoCA (/30)	27.65(1.37)	27.15(1.60)	.27	27.83(1.25)	27.56(1.58)	.56
Digit Span Forward (/16)	10.22(1.88)	10.00(2.00)	.72	10.06(2.01)	10.39(2.09)	.63
Digit Span Backward (/14)	6.35(1.64)	7.15(2.58)	.22	6.72(2.42)	7.06(2.04)	.66
Letter number Sequencing (/21)	11.17(2.08)	10.80(2.89)	.63	10.75(2.74)	10.19(1.64)	.49
WCST (/6)	4.70(0.47)	4.50(0.71)	.29	3.78(1.17)	3.78(0.94)	1

[a] p-value from independent sample t-tests comparing the two language groups

[b] Dominant language; language proficiency ranking followed a 5 point Likert scale (1=no ability; 5=native-like ability)

[c] Non-dominant language

[d] Young and older adults did not significantly differ in the neuropsychological tests except for the WCST

Experimental Tasks

Participants completed a single-task and a mixed-task experiment. In both experiments, each trial started with a fixation cross (+), followed by a cue ("NUMBER" or "LETTER"). After 1000 ms, a letter-number pair appeared below the cue. The cue and the letter-number pair remained on the screen until the participant made a response or for a maximum of 5000 ms, after which there was a blank screen for 250 ms. The cue "NUMBER" prompted the participant to decide whether the number in the pair was even or odd, while the cue "LETTER" prompted the participant to decide whether the letter was a vowel or a consonant. The single-task experiment comprised a letter block and a number block of 56 trials each, while the mixed-task experiment comprised four 56-trial blocks of mixed letter/number cues. Participants always performed the single-task before the mixed task.

Mixing cost was calculated as the difference between single-task trials and repeat trials from the mixed-task experiment. Switch cost was calculated as the difference between mixed-task repeat trials (those preceded by the same trial type, i.e., number-number or letter-letter) and switch trials (those preceded by a different trial type, i.e., number-letter or letter-number). There was a total of 112 single-task trials, 111 repeat trials, and 113 switch trials. Stimuli were presented using E-Prime 2.0 presentation software (Psychology Software Tools, Pittsburg, PA, USA) on a Dell OptiPlex 780 desktop computer with Windows XP Professional operating system, an Intel Core 2 Duo processor and a 20" monitor. Participants responded using the "a", "s", "k", and "l" keys on the keyboard, and the side used to identify letters and numbers was counterbalanced across participants. Tasks and experimental conditions are illustrated in Figure 1.

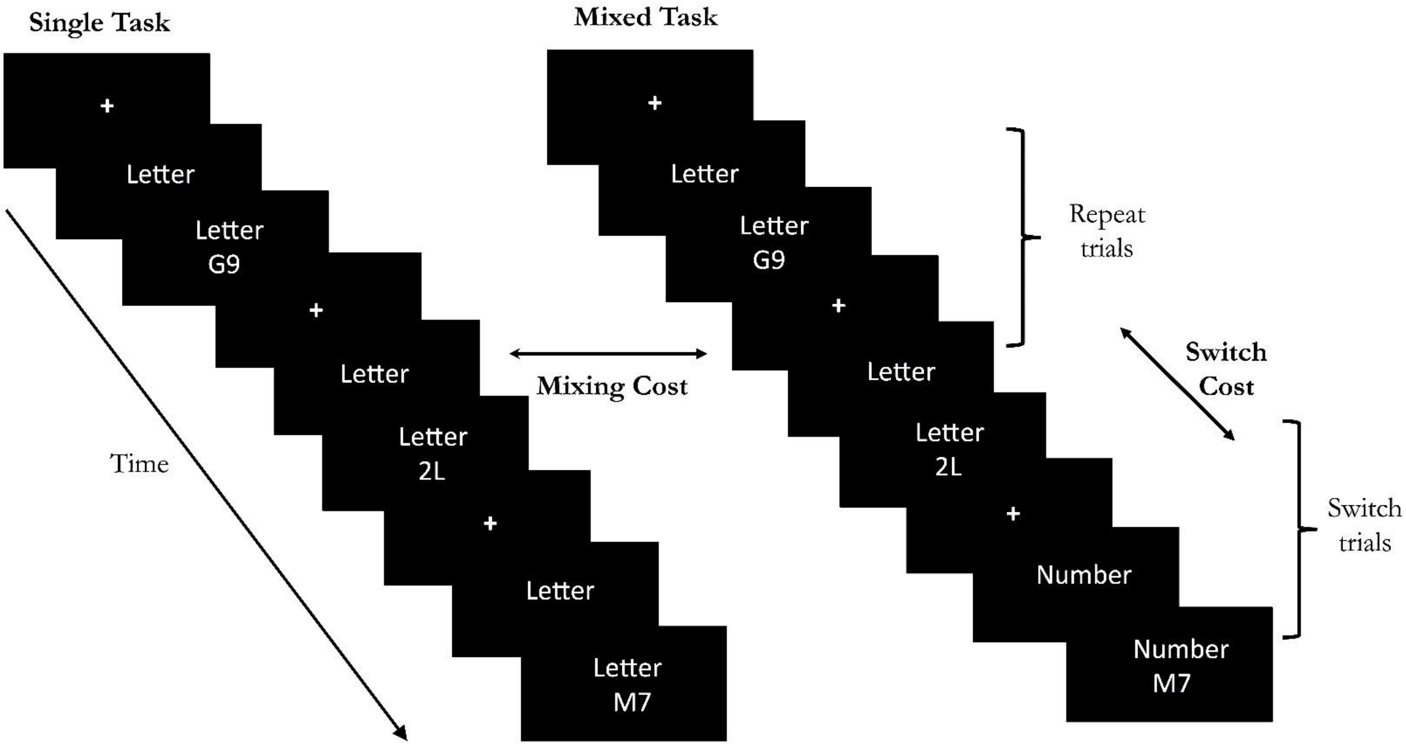

Figure 1. Task Switching Paradigm

EEG Recording and Processing

Participants were fitted with a commercially available nylon cap with 32 tin electrodes (Electro-Cap International, INC. Eaton, OH, USA). A cephalic site was used as the ground and all active sites were referenced online to linked ear electrodes. Four additional electrodes were used to record electro-occulogram (EOG) activity. These electrodes were placed above and below the left eye to monitor vertical eye activity (VEOG) and on the right and left temple to monitor horizontal eye activity (HEOG). The EEG was amplified using NeuroScan NuAmps (NeuroScan, El Paso, TX, USA) and was sampled in a DC to 500Hz bandwidth. Impedances were kept below 5 kΩ.

Data were processed offline with Brain Vision Analyzer 2.1 (Brain Products, GmBh, Gilching, Germany). A high pass .01 Hz/12 dB filter and a low pass 30 Hz/12 dB filter was applied and independent component analysis (Makeig, Bell, Jung, & Sejnowski, 1996) was used to identify eye movements and blinks that were statistically independent of the EEG activity. The continuous EEG was then segmented into discrete 1200 ms epochs starting 200 ms before the onset of the cue stimulus or of the target stimulus. The 200 ms pre-stimulus period served as a zero-voltage baseline and epochs were baseline-corrected. Epochs containing EEG activity exceeding ±100 µV were rejected from averaging. Epochs were sorted and averaged based on the following stimulus conditions: cue-locked single-task, cue-locked repeat, cue-locked switch, target-lock single-task, target-lock repeat, and target-lock switch. Only correct responses were included.

Testing Protocol

Participants took part in one testing session, lasting approximately 1.5 hours. First participants completed written informed consent, followed by the neuropsychological battery, which took approximately 30 minutes. They were then fitted with the EEG cap and seated comfortably approximately two feet in front of a computer monitor. Their EEG was recorded while they performed the experimental tasks, which lasted around 40 minutes.

Statistical Analysis

All analyses were performed with SPSS statistical software v. 20 (IBM Corporation, Armonk, NY, USA). Reported effects were significant at an alpha level of .05. Significant interactions were decomposed with Bonferroni-corrected simple effects analyses.

Behavior

Reaction time and accuracy analyses were performed on the mixing costs[1] (single-task minus repeat condition in the mixed task) and switch costs (repeat minus switch conditions in the mixed task). These data were analyzed using 2x2 ANOVAs with the factors Language Group (monolingual, bilingual) and Age (young, older). Reported effects were significant at an alpha level of .05.

ERPs

ERPs were time-locked to both the onset of the cue (cue-locked) and the target (target-locked). Mixing and switch costs were examined for each ERP component of interest, and separate ANOVAs were conducted for each component. The Greenhouse-Geisser correction for non-sphericity was used for all ERP analyses with more than one degree of freedom in the numerator (Greenhouse & Geisser, 1959). Significant interactions were decomposed with Bonferroni-corrected simple effects analyses. Given the goals of our study, the effects of interest are Language X Condition X Age, and Language X Condition interactions. Thus, interactions are reported first in all sub-sections. For the sake of clarity, only significant results involving Condition, Age, and Language Group are reported, as opposed to results involving only electrode sites.

For each ERP component, electrode sites and time windows were chosen based on the existing literature and grouped into regions of interest (ROIs) to include 9 electrodes over midline and lateral areas. Cue-locked mixing and switch positivities exhibit a centro-parietal distribution (Capizzi et al., 2015; Karayanidis et al., 2011; West, Langley, & Bailey, 2011). Thus, the ROIs (see Figure 2) created for the Anteriority factor had three levels that included

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[1] Analyses were also performed with the factor Condition (single task vs repeat from mixed task, and repeat vs switch from the mixed task). As they did not yield any additional information, we only report the analyses on the mixing and switch costs.

centro-parietal sites CP3, CPz, CP4, parietal sites P3, Pz, P4, and occipital sites O1, Oz, and O2 while the ROIs created for the Laterality factor (three levels) were left sites CP3, P3 and O1, midline sites CPz, Pz and Oz, and right lateral sites CP4, P4 and O2.

Thus, we performed a mixed ANOVA on mean amplitudes from 300 to 600 ms for the mixing positivity and on mean amplitudes from 400 to 800 ms for the switch positivity with the between-subject factors Language Group (monolingual, bilingual) and Age (young, old), the within-subject factors Condition (single-task, repeat for mixing positivity; repeat, switch for switch positivity), Anteriority and Laterality.

It is well documented that the N2 exhibits a fronto-central distribution (Folstein & Van Petten, 2008; Patel & Azzam, 2005) while the distribution of the P3b is centro-parietal (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Polich, 2007; Squires, Squires, & Hillyard, 1975). Thus, the N2 ROIs (see Figure 2) chosen for the Anteriority factor were: frontal sites F3, Fz, F4, fronto-central sites FC3, FCz, FC4, and central sites C3, Cz, C4 while the ROIs chosen for the Laterality factor were left lateral sites F3, FC3, C3, midline sites Fz, FCz, Cz, and right lateral sites F4, FC4 and C4.

Mixed ANOVAs were performed on mean amplitudes from 200-400 ms for mixing and switch N2s with the between-subject factors Language Group (monolingual, bilingual) and Age (young, old), the within-subject factors Condition (single-task, repeat for mixing N2; repeat, switch for switch N2), Anteriority and Laterality.

Lastly, given the centro-parietal distribution of the target-locked P3b, the ROIs were similar to those described in the mixing and switch positivity analyses. The mixing and switch P3b analyses were performed on mean amplitudes from 300 to 600 ms post-stimulus onset.

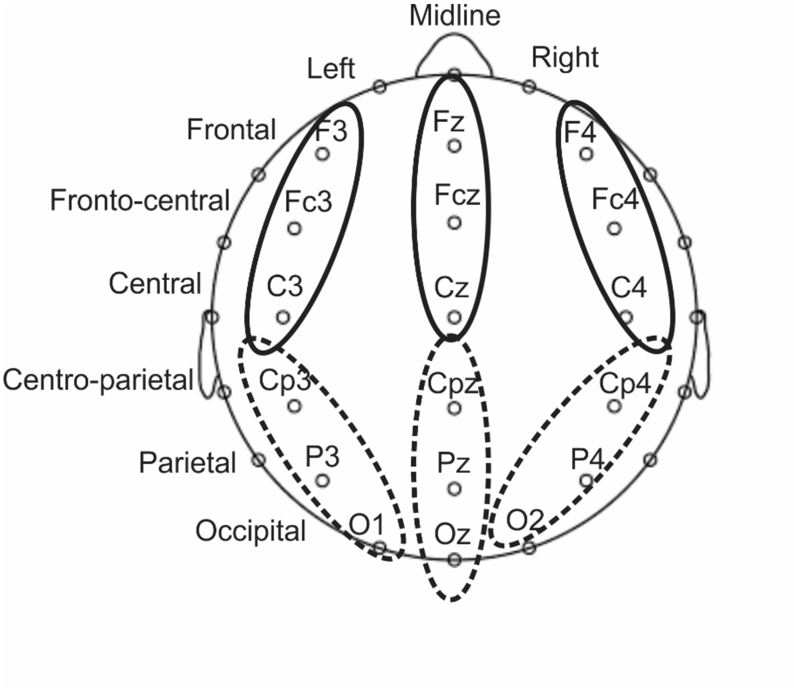

Figure 2. Regions of Interest (ROIs). The solid ellipses highlight the sites chosen for target-locked N2 analyses. The dashed ellipses highlight the sites chosen for cue-locked mixing and switch positivities and target-locked P3b analyses.

Results

Behavior

Mixing Cost: Results revealed that bilinguals had smaller mixing cost than monolinguals (main effect of Language, $F(1,75)=3.83$, $p<.05$, $\eta_p^2=.50$), and that young and older adults did not significantly differ in mixing cost ($F(1,75)=1.63$, $p=.21$, $\eta_p^2=.02$). The interaction between age and language was not significant ($F<1$).

Monolinguals and bilinguals did not differ in accuracy ($F(1,75)=1.12$, $p=.30$, $\eta_p^2=.01$), nor did young and older adults ($F(1,75)=2.45$, $p=.12$, $\eta_p^2=.03$). The interaction between age and language was not significant ($F<1$).

Mean reaction times for each task condition are displayed in Table 2. Mixing and switch costs for each group are displayed in Figure 3.

Table 2. Mean reaction time in milliseconds (SD) for each condition in the task switching paradigm

Condition	Age Group	Language Group	
		Monolingual	Bilingual
Single-task	Young	740.17(98.36)	694.84(90.11)
	Older	911.09(116.93)	833.67(91.17)
Repeat	Young	965.89(207.16)	842.21(201.81)
	Older	1193.00(281.59)	1031.08(250.86)
Switch	Young	1213.50(310.35)	984.27(264.49)
	Older	1329.48(311.67)	1109.63(244.18)

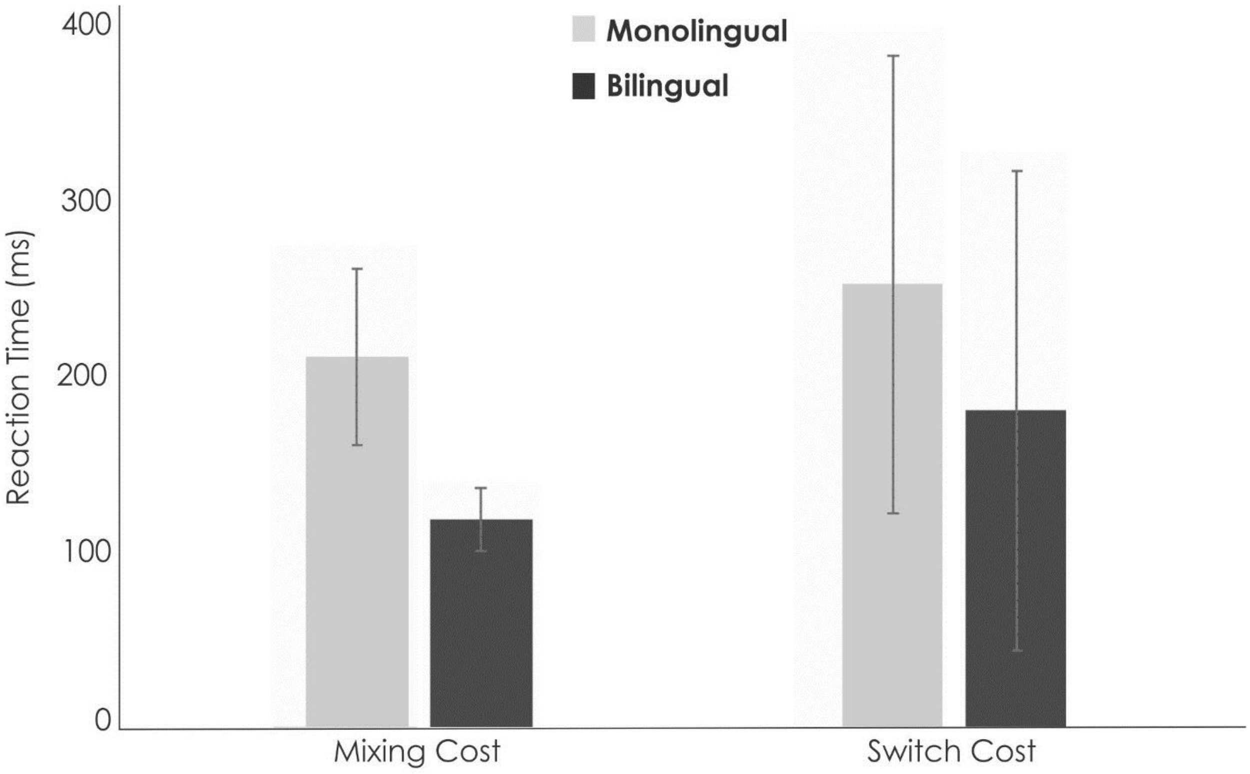

Figure 3. Mixing cost was calculated as the difference between single-task trials and repeat trials from the mixed-task experiment. Switch cost was calculated as the difference between mixed-task repeat trials (those preceded by the same trial type, i.e., number-number or letter-letter) and switch trials (those preceded by a different trial type, i.e., number-letter or letter-number). Error bars represent SE.

Switch Cost: Bilinguals had smaller switch cost than monolinguals (main effect of Language Group, $F(1,75)=9.66$, $p=.003$, $\eta_p^2=.11$) and young adults exhibit smaller switch cost than older adults (main effect of Age, $F(1,75)=11.03$, $p=.001$, $\eta_p^2=.13$). The interaction between age and language was not significant ($F<1$).

Monolinguals and bilinguals did not differ in accuracy ($F(1,75)=1.03$, $p=.31$, $\eta_p^2=.01$); nor did young and older adults ($F(1,75)=1.67$, $p=.20$, $\eta_p^2=.02$). The interaction between age and language was not significant ($F<1$).

Event-Related Potentials

Table 3. Summary of ERP results

ERP component	Description	Predictions[a]	Results
Cue-locked			
switch/mixing positivity	Large posterior parietal positivity occurring approximately 400 ms post-cue; larger for switch vs repeat trials and for repeat than single-task trials	**Mixing Positivity:** Language X Condition: bilinguals > monolinguals **Switch positivity:** Language X Condition: bilinguals > monolinguals	**Mixing positivity:** repeat > single task; young > older; Language X Condition: no significant differences **Switch positivity:** switch > repeat; Language X Condition: no significant differences
Target-locked			
N2	Fronto-centrally distributed negative-going waveform that peaks between 200-400 ms post-target and is related to conflict processing. Larger amplitude for switch compared to repeat trials reflect higher executive control demands on switch trials.	**Mixing costs:** Language X Condition: bilinguals > monolinguals **Switching costs:** Language X Condition: bilinguals > monolinguals	**Mixing costs:** Language X Condition: no significant differences; overall N2 amplitudes: bilinguals > monolinguals and older > younger **Switching costs:** switch > repeat; Language X Condition: no significant interaction; overall N2 amplitudes: bilingual > monolingual; older > young

P3b	Centro-parietally distributed positive-going waveform that peaks approximately 300 ms post-target. Amplitude is related to stimulus evaluation, with smaller amplitudes elicited in conditions that are more effortful (i.e., repeat > switch; single-task > repeat).	**Mixing costs:** Language X Condition: monolinguals> bilinguals	**Mixing costs:** single-task > repeat. Language X Condition: no significant differences; overall P3b amplitudes: young > older; monolingual older > bilingual older
		Switching costs: Language X Condition: monolinguals > bilinguals	**Switching costs:** repeat > switch. Language X Condition: no significant differences; overall P3b amplitudes: young > older monolingual older > bilingual older

[a] A larger language group effect is expected in older compared to younger adults.

Cue-locked ERPs

Mixing Cost

Mixing Positivity: There was a trend towards a larger mixing positivity effect in monolinguals than bilinguals, although this did not reach significance (Language X Condition interaction, $F(1,75)=3.10$, $p=.08$ $\eta p^2=.04$; see Figure 4 panel A). The Language X Condition X Age interaction was not significant (F<1).

Mixing positivity amplitudes were larger in repeat trials in the mixed-task condition than in the single-task condition (main effect of Condition, $F(1,75)=67.75$, $p<.001$, $\eta p^2=.48$). The effect size was larger in young adults than in older adults (Age X Condition interaction, $F(1,75)=4.50$, $p=.04$, $\eta p^2=.06$).

Switch Cost

Switch Positivity: The magnitude of the switch positivity effect did not differ between monolinguals and bilinguals (Language X Condition interaction, $F(1,75)=0.50$, $p=.48$, $\eta p^2=.007$; Language X Condition X Age interaction, $F(1,75)=1.21$, $p=.30$, $\eta p^2=.016$).

Switch positivity amplitudes were larger for switch than repeat trials (main effect of Condition, $F(1,75)=21.85$, $p<.001$, $\eta p^2=.23$); inspection of Figure 4 panel B suggests that this is due to a more sustained positivity for switch than repeat trials in both groups.

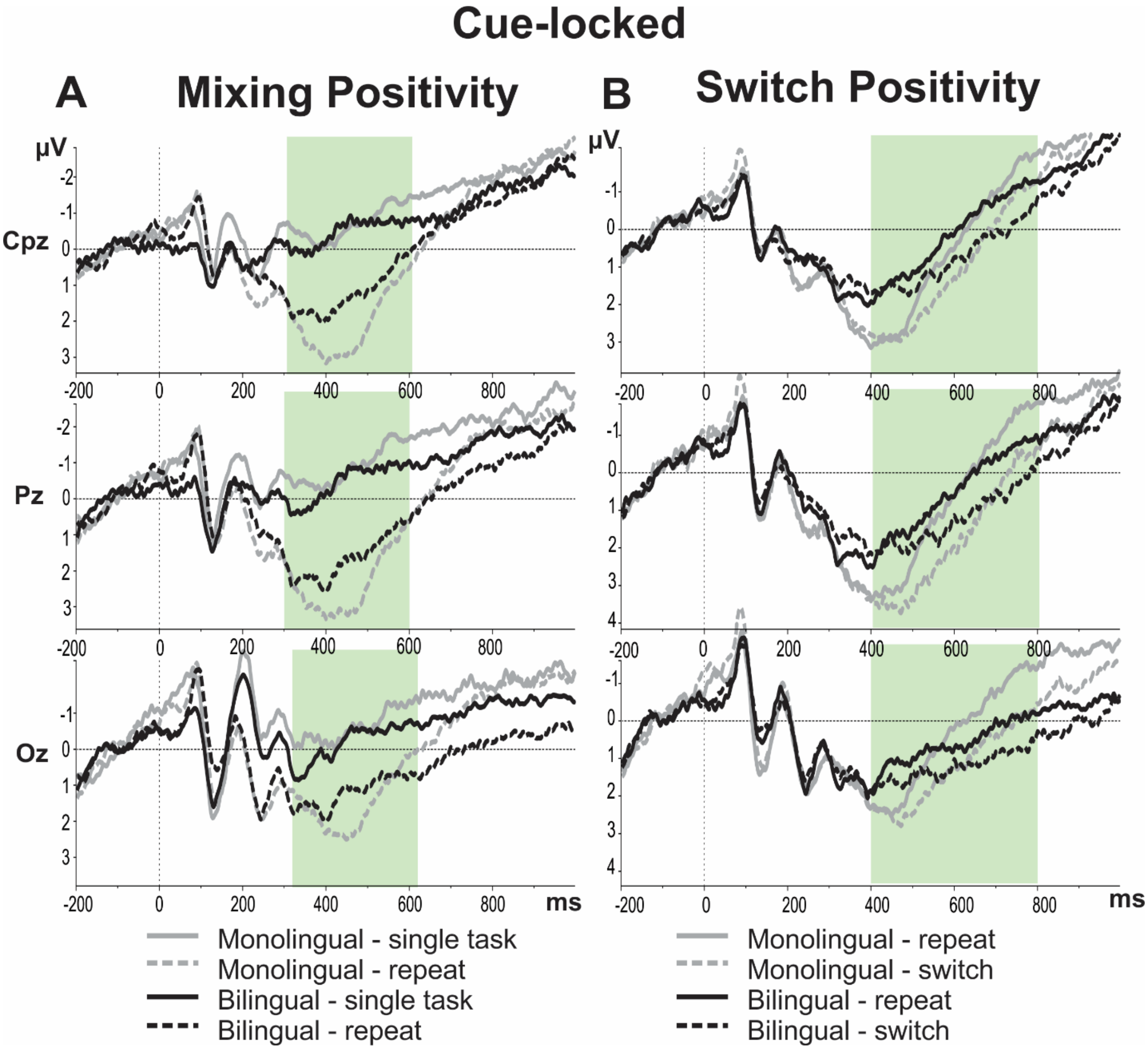

Figure 4. Cue-locked ERPs. Panel A shows the mixing positivity effect for monolinguals and bilinguals. A slightly larger mixing positivity effect is observed in monolinguals than bilinguals, particularly at CPz and Pz. Panel B shows the switch positivity effect for monolinguals and bilinguals. No significant difference is observed between monolinguals and bilinguals in the switch positivity effect. The shaded area highlights the time windows analyzed in the mixing and switch positivity effects. Negative is plotted upwards.

Target-locked ERPs

Mixing Cost

N2: The magnitude of the N2 mixing cost did not differ between monolinguals and bilinguals (Language X Condition interaction, $F(1,75)=2.02$, $p=.16$, $\eta p^2=.03$; Language X Condition X Age interaction, F<1). In addition, bilinguals exhibited larger N2 amplitudes than monolinguals (main effect of Language Group, $F(1,75)=6.40$, $p=.01$, $\eta p^2=.08$), and older adults exhibited larger N2 amplitudes than young adults (main effect of Age, $F(1,75)=5.07$, $p=.02$, $\eta p^2=.07$), particularly at central sites (Age X Anteriority Interaction, $F(1, 150)=20.57$, $p<.001$, $\eta p^2=.22$). No other interactions that included language or age were significant. Figure 5 panel A displays N2 mixing cost ERPs for all participant groups and shows the main effect of Language with bilinguals demonstrating larger mixing costs than monolinguals.

P3b: The magnitude of the P3b mixing cost did not differ between monolinguals and bilinguals (Language X Condition interaction, F<1; Language X Condition X Age interaction, F<1). Amplitudes were larger in the single-task than in repeat trials in the mixed-task (main effect of Condition, $F(1,75)=30.28$, $p<.001$, $\eta p^2=.28$). Young adults exhibited larger P3b amplitudes than older adults (main effect of Age, $F(1,75)=20.87$, $p<.001$, $\eta p^2=.22$), and monolingual older adults exhibited larger P3b amplitudes than bilingual older adults (Language X Age interaction, $F(1,75)=7.74$, $p=.007$, $\eta p^2=.10$). Figure 6 panel A displays the difference in P3b amplitudes between monolingual and bilingual older adults.

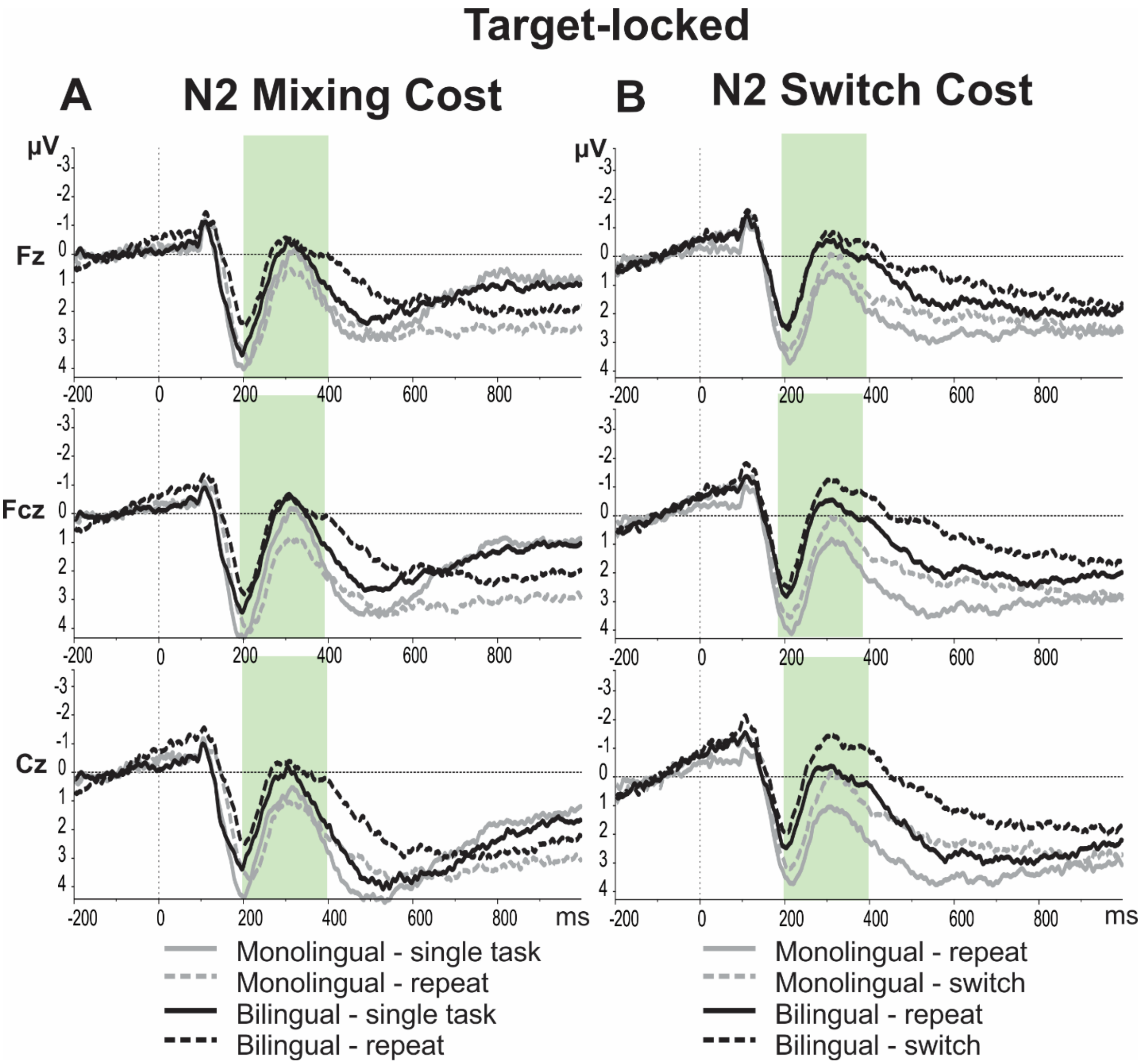

Figure 5. Target-locked N2 component. Panel A shows the mixing cost effect for all monolinguals and bilinguals. Panel B shows the switch cost effect for all monolinguals and bilinguals. The shaded area highlights the time windows analyzed. Overall N2 amplitudes are larger in bilinguals than monolinguals. Negative is plotted upwards.

Switch Cost

N2: The magnitude of the N2 switch cost effect did not differ between monolinguals and bilinguals (Language X Condition interaction, F<1; Language X Condition X Age interaction, F<1). Amplitudes were larger in the switch than in the repeat trials (main effect of Condition, F(1,75)=19.24, *p*=.001, ηp^{2}=.20). Bilinguals exhibited larger N2 amplitudes than monolinguals (main effect of Language Group, F(1,75)=10.57, *p*=.002, ηp^{2}=.12), and older adults exhibited larger N2 amplitude than young adults (main effect of Age, F(1,75)=5.65, *p*=.02, ηp^{2}=.07). Figure 5 panel B displays N2 switch cost ERPs for all participant groups and shows the main effect of Language where bilinguals show larger N2 switch costs than monolinguals.

P3b: The magnitude of the P3b switch cost effect did not differ between monolinguals and bilinguals (Language X Condition interaction, F<1; Language X Condition X Age interaction, F<1). Amplitudes were larger in repeat than in switch trials (main effect of Condition, *F*(1,75)=69.51, *p*<.001, ηp^{2}=.48). Young adults exhibited larger P3b amplitudes than older adults (main effect of Age, *F*(1,75)=17.58, *p*<.001, ηp^{2}=.19), and monolingual older adults exhibited larger P3b amplitudes than bilingual older adults (Language Group X Age interaction, *F*(1,75)=7.92, *p*=.006, ηp^{2}=.10). Figure 6 panel B shows the P3b amplitude difference between monolingual and bilingual older adults.

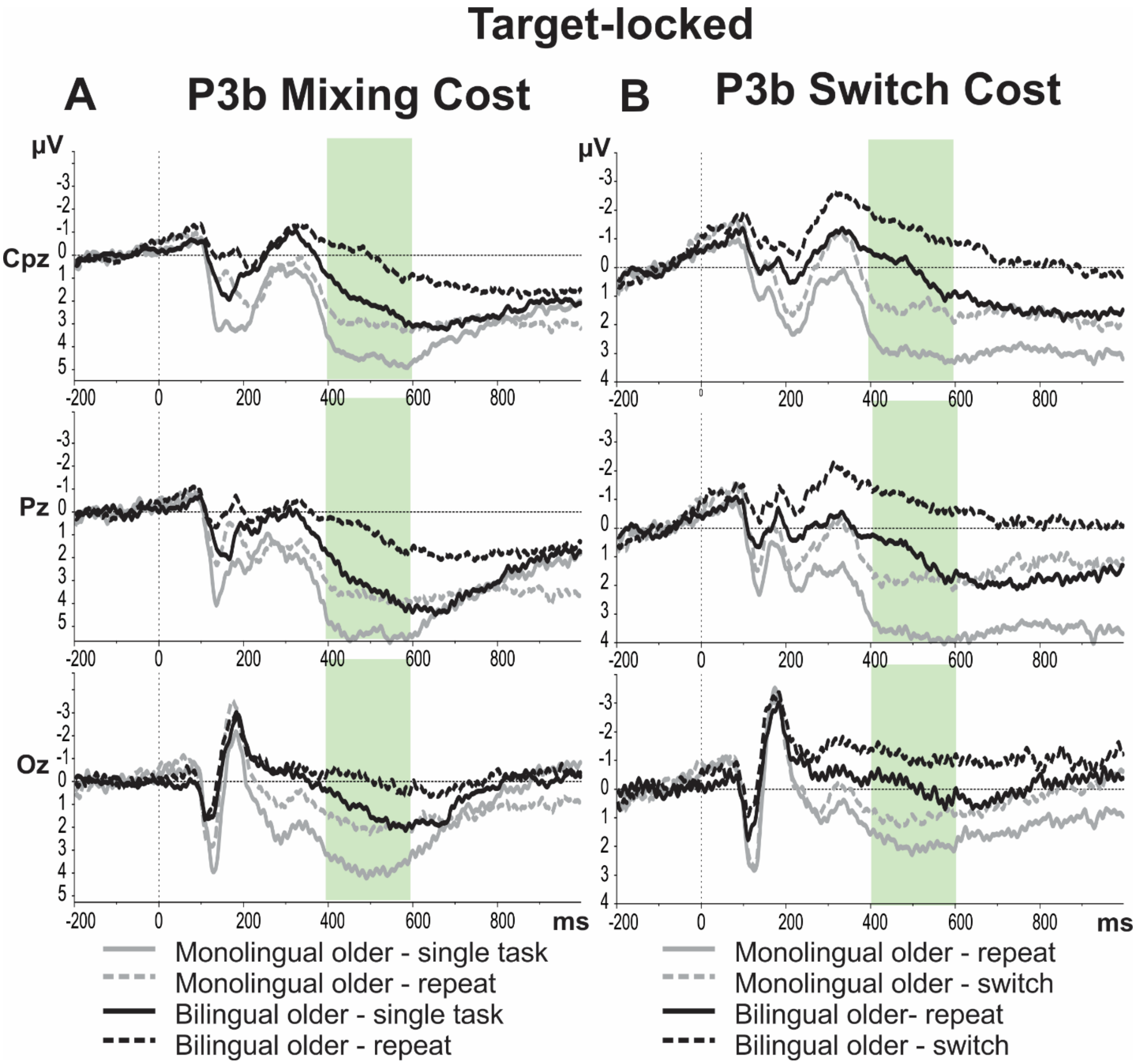

Figure 6. Target-locked P3b component for the older adult monolinguals and bilinguals. Panel A shows the mixing cost effect for older adult monolinguals and bilinguals. Panel B shows the switch cost effect for older adult monolinguals and bilinguals. The shaded area highlights the time windows analyzed. Overall P3 amplitudes are larger in monolinguals than bilinguals. Negative is plotted upwards.

Relationship between cue-locked switch positivity and reaction times

We were also interested in exploring the relationship between the ERP switch positivity component and both reaction time and switch cost. Thus, for each language group, we performed Pearson correlations between the difference wave switch positivity at sites CPz and Pz and switch cost reaction time. The behavioral switch cost was not correlated with the difference in ERP amplitudes between conditions (i.e., switch positivity) at CPz (r=.05, *p*=.78) or Pz (r=26, *p*=.12).

Discussion

This study used behavioral and electrophysiological methods to investigate the effect of bilingualism on task switching in young and older adults. Although bilinguals and monolinguals showed similar accuracy, we found that in terms of reaction time, bilinguals had smaller mixing and switch cost than monolinguals. In addition, the electrophysiological data indicate language and age group differences during task switching. However, these differences reflect differences in general cognitive processes rather than differences in specific processes related to the most difficult switch conditions. Overall, the present results provide evidence for a behavioural advantage as well as brain processing differences in bilinguals relative to monolinguals: 1) bilinguals exhibited smaller reaction time costs than monolinguals in the task switching paradigm, suggesting that bilinguals may prepare to shift from one task to another with less effort than monolinguals; 2) bilinguals exhibited larger N2 amplitudes in all conditions (single-task, repeat and switch), relative to monolinguals. Given that the larger N2 amplitudes were not restricted to the switch condition, it is not possible to conclude that bilinguals exhibit better cognitive control than monolinguals. This finding is discussed further below. 3) Bilingual older adults exhibited larger N2 and smaller P3b amplitudes than monolingual older adults, suggesting that as bilinguals age, they rely more on earlier and more automatic processing strategies and less on controlled strategies compared to monolinguals.

Behaviorally, we observed a bilingual advantage. As previously mentioned, mixing cost is associated with sustained attention (Braver et al., 2003) while switch cost is associated with task-set reconfiguration processes that can involve shifting between stimulus attributes (e.g., letter vs number), task rule (e.g., even vs odd) and action rule (e.g., respond with left hand vs. right hand) (Monsell, 2003), as well as inhibitory processes involving suppression of the prior task set and activation of the required task set (Wylie & Allport, 2000). Therefore, smaller mixing and switch costs in bilinguals compared to monolinguals indicate enhanced processing in the former group.

Enhanced executive processing is contrary to results reported in some previous studies (for a review, see Paap et al., 2016). However, most task switching studies have used the color-shape paradigm. One important distinction between our paradigm and the color-shape paradigm is that our stimuli were bivalent; that is, they involved features relevant to multiple decisions. Participants saw letter-number pairs, and depending on the cue they were presented with, they were required first to attend to either the number or the letter, ignoring the other stimulus, and then to make a decision (odd or even; consonant or vowel). Studies have shown that this type of paradigm elicits an additional *bivalency cost* (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995; Woodward, Meier, Tipper, & Graf, 2003). Thus, it is possible that we found language group differences because of our more demanding task context. This interpretation is consistent with previous studies showing that bilinguals outperformed monolinguals in more demanding versions of the Simon task (Bialystok, Craik, Klein, & Viswanathan, 2004), and the flanker task (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009).

Cue- locked ERPs

Monolinguals and bilinguals did not differ in mixing or switch positivity components, indicating that the groups do not differ in the cognitive processes associated with task preparation. Previous evidence has shown that the switch positivity is associated with task-set reconfiguration processes and the amplitude of the switch positivity has been correlated with reaction time switch cost (e.g., Karayanidis et al., 2011). In order to examine the effect of Language and Age on the relation between the switch positivity and behavioral switch costs, we performed correlations between switch positivity difference waves and reaction time switch costs. There were no significant correlations, further supporting our interpretation that monolinguals and bilinguals do not differ in task preparation processes.

Target-locked ERPs

Contrary to our hypotheses, we did not find differences in N2 or P3b mixing and switch costs between monolinguals and bilinguals. More specifically, monolinguals and bilinguals did not differ in the magnitude of the ERP effects associated with mixing and switch cost (i.e., there was no significant interaction between Language and Condition). Thus, it appears that monolinguals monitor conflict and allocate resources in a similar manner as bilinguals. However, we did find overall N2 amplitude differences (main effect of Language), with bilinguals displaying larger N2 amplitudes than monolinguals. Bilinguals exhibited larger N2 amplitudes than monolinguals not just in the switch condition, but also in the repeat and single-task conditions. Thus, although bilinguals may not necessarily be better at conflict monitoring than monolinguals in the most difficult task condition, they showed heightened conflict monitoring across all conditions of the task. This is interpretation is in line with the finding that bilinguals were faster than monolinguals in all task conditions (see Table 2). However, it is important to note that older adults also showed overall larger N2 amplitudes than young adults, contrary to what would be expected. Thus, the N2 amplitude differences must be interpreted with caution.

Finally, we also found that bilingual older adults exhibited larger N2 amplitudes but smaller P3b amplitudes in all task switching conditions compared to monolingual older adults. This finding is consistent with the BAPSS framework (Grundy et al., 2017), which proposes that, relative to monolinguals, bilinguals devote more resources to earlier than later processes. That is, bilinguals adopt a strategy that relies more on attentional demands during conflict resolution (indexed by the N2) than stimulus evaluation (P3b). Thus, we propose that during task switching, older bilinguals rely on an automatic strategy while older monolinguals rely on a controlled processing strategy. Over time, bilingualism seems to result in bilinguals adopting different processing strategies during the performance of non-verbal executive control tasks.

Conclusion

The present results provide behavioral and electrophysiological evidence for superior task switching in young and older bilinguals relative to monolinguals. Specifically, bilinguals exhibited smaller mixing and switch costs than monolinguals, and this effect was observed across young and older bilinguals. Neurophysiologically, we did not observe differences in the magnitude of the ERPs associated with cue-locked or target-locked. However, we observed overall larger target-locked N2 amplitudes in bilinguals relative to monolinguals, perhaps indicative of heightened conflict monitoring during all conditions of the task. Lastly, larger N2 amplitudes accompanied by smaller P3b amplitudes in older bilinguals relative to older monolinguals suggest that as bilinguals age, they come to rely on a different processing strategy than monolinguals. Taken together, these findings support the theory that bilingualism influences the cognitive processes involved in non-verbal task switching.

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