Earlier and more distributed neural networks for bilinguals than monolinguals during switching

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ABSTRACT

The present study investigated processing differences between young adults who were English monolinguals or English-French bilinguals on a task- and language-switching paradigm. The mechanisms responsible for task switching and language switching were investigated using electrophysiological (EEG) measures. In nonverbal task switching, monolinguals and bilinguals demonstrated equivalent behavioral mixing (pure vs. repeat) and switching (repeat vs. switch) costs, but bilinguals were more accurate in the mixed blocks. Bilinguals used a more distributed neural network than monolinguals that captured the nonverbal mixing effect and showed earlier discrimination for the switching effect in the ERPs. In language switching, more distributed networks for bilinguals than monolinguals were found for the switching effect. The scalp distributions revealed more overlap between task switching and language switching for bilinguals than monolinguals. For switch costs, both groups showed P3/LPC modulations in both tasks, but bilinguals showed extended activation to central regions for both switching tasks. For mixing costs, both groups revealed modulations of the N2 but only bilinguals showed extended activation to the occipital region. Overall bilinguals revealed more overlapping processing between task- and language-switching than monolinguals, consistent with the interpretation of integration of verbal and nonverbal control networks during early visual processing for bilinguals and later executive processing for monolinguals.

1. Introduction

Language selection is arguably at the core of bilingual language use and is a key part of the linguistic processing that is unique to bilinguals. As such, processes involved in language selection may be ultimately responsible for the domain-general processing differences found between monolinguals and bilinguals on a range of executive function tasks (for review, see Bialystok, 2017; for meta-analysis on working-memory span, see Grundy and Timmer, 2016). Bilinguals activate the lexical representations of both languages, even in environments in which only one is relevant (Colomé, 2001; Costa et al., 1999; Finkbeiner et al., 2006; Hermans et al., 1998; Martin et al., 2009; Spivey and Marian, 1999; Thierry and Wu, 2007; Timmer et al., 2014a, 2014b; Timmer and Schiller, 2014; Wu and Thierry, 2012), yet they rarely speak in the unintended language (Gollan et al., 2011; Poulišs, 1999). Therefore, bilinguals are able to selectively attend to the target language in the context of the jointly-activated and competing alternatives (Bialystok et al., 2012). To achieve this, a control system is necessary to select the target language without intrusion from the non-target language (Green, 1998), a process that over time leads to enhanced attentional processing for bilinguals (Bialystok, 2015). These attentional and control processes required for language selection are potentially the basis of executive function performance advantages in bilinguals (Bialystok, 2017). Thus, understanding the relation between language control and nonverbal executive control is essential for identifying the mechanisms by which bilingualism is associated with improved outcomes on executive function tasks.

A switching paradigm is ideal for comparing language and non-verbal control processes because the paradigm can be set up in the same manner for both domains with the only difference being the stimulus and response outputs. The current study examined bilinguals and functional monolinguals who had only rudimentary knowledge of a second language, performing both nonverbal and language switching while EEG was recorded. The inclusion of a functional monolingual group offers the opportunity to investigate monolingual-bilingual processing differences in these tasks, and ERPs provide time-sensitive data to identify potential processing differences between language groups and tasks. Evidence from fMRI research with bilinguals indicates that
Table 1

<table>
<thead>
<tr>
<th>Task</th>
<th>Condition</th>
<th>Component</th>
<th>Literature</th>
<th>Present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonverbal task switching</td>
<td>Switch cost</td>
<td>N1</td>
<td>Greater N2 for pure than repeat trials through central to occipital regions for bilinguals only (Fig. 4).</td>
<td>No significant effects for monolinguals (Fig. 4).</td>
</tr>
<tr>
<td></td>
<td>Mixing cost</td>
<td>N2</td>
<td>Greater N2 for pure than repeat trials through frontal region for both groups. Greater N2 for repeat trials through central to occipital regions for bilinguals.</td>
<td>Greater N2 for pure than repeat trials through central to occipital regions for bilinguals only (Fig. 7).</td>
</tr>
<tr>
<td>Language switching</td>
<td>Switch cost</td>
<td>N1</td>
<td>Not discussed in previous literature.</td>
<td>No significant effects for monolinguals (Fig. 9).</td>
</tr>
<tr>
<td></td>
<td>Mixing cost</td>
<td>N2</td>
<td>Not discussed in previous literature.</td>
<td>Greater P3/LPC for pure than repeat trials throughout parietal-occipital regions for bilinguals. No significant effects for monolinguals (Fig. 12).</td>
</tr>
</tbody>
</table>

For language switch costs, several explanations have been proposed. One influential explanation is the inhibitory control model (Green, 1998). This view suggests that every time a concept is named its lexical representation receives a language tag. Lexical representations from the opposite language are then inhibited, increasing the threshold for accessing those representations. On a switch trial, the inhibited language needs to be reactivated, creating a delay in naming. Other explanations do not assign a role to inhibition (Costa et al., 1999; Finkbeiner et al., 2006; La Heij, 2005; Roelofs, 1998; Verheoef et al., 2009). For example, La Heij (2005) suggested that the target language receives additional activation without inhibition of the other language. However, none of these explanations is able to account for all reported results (for review see Declerck and Philipp, 2015). Hence, it is likely that switch costs do not reflect a single process, such as inhibition, but rather indicate several processes that may be different for variants of a switching task (such as language switching and nonverbal switching) and for individuals with different language backgrounds (such as monolinguals and bilinguals). Therefore, to obtain a more complete description of performance on these tasks, we examined the ERP components involved in switching.

ERP studies for switch costs in task switching reveal an N2 component (Moulden et al., 1998; Periáñez and Barceló, 2009; Rushworth et al., 2002) and P3 component (Periáñez and Barceló, 2009). The N2 shows greater negativity for repeat than switch trials, consistent with studies showing greater negativity for less effortful trials as in the repetition of a cue. Cue repetition is a form of sensory priming which can lead to an enduring memory trace for the repeated stimulus (Moulden et al., 1998; Periáñez and Barceló, 2009; Rushworth et al., 2002). In contrast, the P3 shows greater positivity for switch trials than repeat trials and reflects greater working memory required for switch trials as in the distinction between switch costs and mixing costs. Switch costs are the slower responses for switch trials than repeat trials in a block in which two types of decisions are intermixed (e.g., color and shape decisions for task switching or English and French naming for language switching). Mixing costs are the slower responses for repeat trials during a mixed block that includes two decision types than for the same trials in a single task block (for review see Meiran, 2010). Research focusing on differences between monolinguals and bilinguals on nonverbal switching tasks has mainly revealed a smaller switch cost for bilinguals than monolinguals (Garbin et al., 2010; Houtzager et al., 2017; Prior and Gollan, 2011; Prior and Macwhinney, 2010), although some studies have reported reduced mixing costs for bilinguals (Hillman et al., 2006; Wiseheart et al., 2016). Moreover, some studies have shown a relation between frequency of language switching in daily life and accuracy on pure and repeat trials (Soveri et al., 2011). Not all studies have found differences between monolinguals and bilinguals during nonverbal task switching (e.g., Paap et al., 2017; Paap and Greenberg, 2013), but more sensitive measures than reaction time are often needed in populations of young adults who are at ceiling performance (Grundy et al., 2017b). Because of its high temporal resolution, electroencephalography (EEG) is an ideal method to capture processing differences between groups.

The task switching literature explains switch costs in terms of reactivation of decision rules and reconfiguration of the appropriate stimulus-response (S-R) mappings for the new decision rule (Periáñez and Barceló, 2009). Thus, switch costs reflect attending to the cue and remembering the associated rule. If a new rule is activated, the S-R mappings need to be reconfigured to execute the appropriate response (Hernández et al., 2013; Jost et al., 2008; Meiran, 2010; Prior and Macwhinney, 2010).

For language switch costs, several explanations have been proposed. One influential explanation is the inhibitory control model (Green, 1998). This view suggests that every time a concept is named its lexical representation receives a language tag. Lexical representations from the opposite language are then inhibited, increasing the threshold for accessing those representations. On a switch trial, the inhibited language needs to be reactivated, creating a delay in naming. Other explanations do not assign a role to inhibition (Costa et al., 1999; Finkbeiner et al., 2006; La Heij, 2005; Roelofs, 1998; Verheoef et al., 2009). For example, La Heij (2005) suggested that the target language receives additional activation without inhibition of the other language. However, none of these explanations is able to account for all reported results (for review see Declerck and Philipp, 2015). Hence, it is likely that switch costs do not reflect a single process, such as inhibition, but rather indicate several processes that may be different for variants of a switching task (such as language switching and nonverbal switching) and for individuals with different language backgrounds (such as monolinguals and bilinguals). Therefore, to obtain a more complete description of performance on these tasks, we examined the ERP components involved in switching.
when reconfiguring S-R mappings (Periáñez and Barceló, 2009).

For language switching, an N2 (Christoffels et al., 2007; Jackson et al., 2001; but see Verhoef et al., 2009) and a late positive component (LPC: Jackson et al., 2001; Liu et al., 2016; Liu et al., 2014; Martin et al., 2013) have been reported. However, evidence for the N2 is inconsistent and there is no agreement on its interpretation. The LPC in language switching is similar to the P3 in task switching in that there is greater positivity for switch than repeat trials (Jackson et al., 2001). This positivity again indexes working memory load for switch trials during language production (Jackson et al., 2001; Liu et al., 2016, 2014; Martin et al., 2013). The LPC and the P3 are related and may even be extensions of the same component (Davidson and Pitts, 2004; Finnigan et al., 2002). Given that we report results from both language and task switching, to avoid confusion we refer to these components as the P3/LPC. The predictions for the ERP components in the present study and relevant findings from previous literature are presented in Table 1.

Mixing costs in task switching reflect task-set interference in mixed-task blocks relative to single-task blocks. In a mixed presentation, both tasks must be kept in mind and cues indicating the task to be performed need to be constantly monitored; in a single task presentation, there is only one cue and therefore no task-set interference (Braver et al., 2003; Koch et al., 2005; Rubin and Meiran, 2005). The P3/LPC component in mixing costs reflects task difficulty and indicates the attentional resources available for stimulus processing and memory updating. Smaller P3/LPC amplitudes have been reported for more difficult tasks that result in reduced attentional resources (McCarthy and Donchin, 1981; Polich, 1987). Therefore, smaller P3/LPC amplitudes have been found for repeat than pure trials (Gomer et al., 1976; Kok, 2001; Wijers et al., 1989). This pattern may seem contradictory to that in the switch cost where repeat trials have demonstrated smaller amplitudes than switch trials. However, this is due to two cognitive processes having opposite effects on P3 amplitudes: attentional resources and task difficulty. When more attentional resources are available the P3 increases (mixing cost), but the P3 also increases with task difficulty (switch cost) (Kok, 2001).

In language switching, behavioral evidence has shown that trials in single language blocks are named faster than repeat trials in mixed blocks. However, to the best of our knowledge, only one study has investigated the ERP correlates of language mixing costs, and this study found a modification of the N2 component, with greater negative amplitudes for repeat than pure trials (Christoffels et al., 2007). The authors suggest that this pattern could reflect reduced access to L1 lexical representations in the mixed language context than pure language blocks as a means of facilitating naming in the L2. This N2 modulation during language mixing contrasts with the task switching literature where the mixing cost is associated with the P3/LPC component (McCarthy and Donchin, 1981; Polich, 1987).

The current study examined the processes engaged by monolinguals and bilinguals during nonverbal task switching and language switching to identify the effect of bilingualism on executive functions. The intention is to determine the processing differences between monolinguals and bilinguals performing these tasks as a means of explaining performance differences previously reported between language groups on a range of executive function tasks and understand how bilingual experience modifies the processes involved in selection and attention across domains.

Although several studies have compared performance of monolinguals and bilinguals engaged in nonverbal task switching (e.g., Prior and Macwhinney, 2010), it is difficult to compare groups on language switching because the experience is unique to bilinguals. A study by Abutalebi et al. (2008) addressed this challenge by asking monolinguals to switch between generating nouns and verbs to a pictorial cue. However, the processes involved in switching between form classes are not necessarily the same as those involved in switching between languages, so a more direct approach is needed. In the present study, participants switched between languages by naming numbers in French and English. English monolinguals in Canada have a rudimentary understanding of counting in French because of school requirements.

There were three main predictions. First, we expected that bilinguals would show earlier attentional processing than monolinguals, indexed by ERP components for switching and mixing effects. This prediction follows from infant studies that have demonstrated earlier attentional processing for bilinguals (Sebastian-Galles et al., 2012; Weikum et al., 2007), a difference that may extend to attending to switching cues in adulthood. Second, we expected a more distributed activation of networks for bilinguals than monolinguals during nonverbal task switching. This prediction follows from fMRI studies indicating integrated pathways for bilinguals for verbal and non-verbal domains (Abutalebi et al., 2013). Third, we explored whether the ERP components for language switching and nonverbal task switching would show more overlap for bilinguals than monolinguals. If bilinguals extend the processes trained during language switching to perform task switching, then there would be a convergence of networks for the two tasks. Evidence for these hypotheses would point to processing differences between monolinguals and bilinguals that could be part of the mechanisms explaining group differences in executive function based on earlier attention, better monitoring, and more integrated networks.

2. Method

2.1. Participants

Twenty-eight monolingual English speakers with minimal knowledge of French and thirty balanced bilingual English-French speakers participated in the experiment. They all reported having normal or corrected-to-normal vision. None of them was color-blind or had a history of neurological impairments or language disorders. All participants completed the Language and Social Background Questionnaire (LSBQ; Anderson et al., 2017) to assess their language experience. Based on the participants included in the final analyses, the groups were statistically equivalent on age: t < 1, socioeconomic status: t < 1, overall English proficiency: t < 1, and verbal and nonverbal intelligence: t(41) = 1.63, ns (Shipley; Zachary and Shipley, 1986). For English proficiency bilinguals did not differ on any of the components, Reading: t(41) = 1.61, ns, Speaking, Comprehension, and Writing t < 1. Further, bilinguals had higher proficiency in English than French for all components, Speaking: t(19) = 2.83, p < .05, Comprehension: t(19) = 3.06, p < .01, Reading: t(18) = 1.97, p = .064, and Writing: t(18) = 3.02, p < .01.

Data from fifteen participants were eliminated due to technical problems in EEG recording (monolingual: n = 3; bilingual n = 8); high error rates (30% incorrect on the mixed blocks of the nonverbal task; each group n = 1), or not finishing the experiment (each group n = 1), leaving a total of 23 monolingual (7 males) and 20 bilingual (8 males) participants who were included in the analyses. Table 2 presents an overview of background measures.

2.2. Design and procedure

Participants signed an informed consent form, filled out the LSBQ and completed the verbal and nonverbal components of the Shipley. Participants were then tested individually in a quiet and dimmed EEG room seated approximately 90 cm from the computer screen. Each participant first performed the nonverbal switching tasks followed by the language switching tasks. For nonverbal switching, the stimuli were colored shapes and participants switched between tasks to decide if the stimulus was colored or greyscale (color task) and if it had corners or was rounded (shape task) by pressing the ‘z’ or ‘m’ key. For language switching, the stimuli were digits and participants switched between naming them in English and French. The onset of the speech response
there were 24 repeat trials and 23 switch trials as the order of nonverbal and language switching. Within each mixed block, there were 6 blocks of 48 trials each, for a total of 288 mixed trials for each participant. Therefore, the task was counterbalanced across participants, as was the assignment of cue to task was counterbalanced across participants, as was the assignment of the “z” or “m” keys to a response in the nonverbal task. Each pure block consisted of 48 trials. The mixed condition consisted of 6 blocks of 48 trials each, for a total of 288 mixed trials for each of nonverbal and language switching. Within each mixed block, there were 24 repeat trials and 23 switch trials as the first trial could not be coded as either a switch or repeat. Therefore, the first trial for each block in both the pure and mixed conditions was removed from the analyses. Participants could take short breaks after every block. The pure blocks were preceded by 8 practice trials and the mixed block by 16 practice trials. Participants were given the opportunity to repeat the practice trials until they felt comfortable enough to move on to the experimental blocks; participants practiced between 1 and 3 times.

Each trial consisted of a jittered fixation cross (400–600 ms) followed by the stimulus and cue presentation that remained on the screen until the participant gave a response (button press or verbal response) or after a time-out of 2000 ms. A blank screen was presented for 750 ms between each trial. The fixation-cross and cues were centered on the screen and presented in white on a black background; number stimuli were presented in white for the language task and the shape stimuli were presented in color or grayscale for the nonverbal task. During the practice phases feedback (“correct” or “incorrect”) was presented visually for 1000 ms after each trial.

### Table 2
Mean responses (and standard deviations) to the LSBQ and background measures by language group.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Monolinguals</th>
<th>Bilinguals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>22.2 (4.6)</td>
<td>23.5 (5.6)</td>
</tr>
<tr>
<td>Mother's Education</td>
<td>3.5 (1.2)</td>
<td>3.7 (1.3)</td>
</tr>
<tr>
<td>English Speaking</td>
<td>96.7 (6.8)</td>
<td>96.1 (6.4)</td>
</tr>
<tr>
<td>English Comprehension</td>
<td>97.2 (6.2)</td>
<td>96.8 (5.8)</td>
</tr>
<tr>
<td>English Reading</td>
<td>98.7 (3.8)</td>
<td>95.9 (7.5)</td>
</tr>
<tr>
<td>English Writing</td>
<td>96.3 (7.9)</td>
<td>96.3 (7.4)</td>
</tr>
<tr>
<td>French Speaking</td>
<td>-</td>
<td>86.6 (12.2)</td>
</tr>
<tr>
<td>French Comprehension</td>
<td>-</td>
<td>87.8 (11.7)</td>
</tr>
<tr>
<td>French Reading</td>
<td>-</td>
<td>91.1 (9.8)</td>
</tr>
<tr>
<td>French Writing</td>
<td>-</td>
<td>87.68 (11.1)</td>
</tr>
<tr>
<td>GSA bilingualism</td>
<td>8.0 (11.5)</td>
<td>89.5 (11.8)</td>
</tr>
<tr>
<td>Shipley English Vocabulary</td>
<td>104.9 (10.1)</td>
<td>107.0 (11.4)</td>
</tr>
<tr>
<td>Shipley Blocks</td>
<td>100.2 (12.1)</td>
<td>105.4 (9.0)</td>
</tr>
</tbody>
</table>

*a* SES based on mother’s education: 1: no high school diploma, 2: high school diploma, 3: some post-secondary, 4: post-secondary degree/diploma, and 5: graduate/professional degree.

*b* English and French proficiency based on a range from 0% to 100%.

*c* Global Self-Assessment of bilingualism from 0 to 100.

*d* Standardized scores based on the Shipley II norming.

was measured with a voice key. For both tasks, instructions were presented in both written and oral form. An illustration of the tasks is shown in Fig. 1.

Both switching tasks started with two pure blocks consisting of only one of the decisions (color or shape; English or French), with the order counterbalanced across participants. The pure blocks were followed by 6 mixed blocks that included both tasks. The task cue was a solid or dashed outline that appeared around the stimulus to indicate which task was required; for example, the solid outline indicated the color task for nonverbal switching and the English task for language switching and the dashed line signaled the opposite tasks. The assignment of cue to task was counterbalanced across participants, as was the assignment of the “z” or “m” keys to a response in the nonverbal task.

Each pure block consisted of 48 trials. The mixed condition consisted of 6 blocks of 48 trials each, for a total of 288 mixed trials for each of nonverbal and language switching. Within each mixed block, there were 24 repeat trials and 23 switch trials as the first trial could not be coded as either a switch or repeat. Therefore, the first trial for each block in both the pure and mixed conditions was removed from the analyses.

For nonverbal switching, there were 16 unique stimuli created from four colors (red, green, white, and grey) and four shapes (square, triangle, circle, and oval). Only a subset of the stimuli was presented to each participant to avoid ambiguity in the responses. For example, a green square would not be presented if a participant was responding with ‘z’ for colored and ‘m’ for grayscale (color task) and ‘z’ for corners and ‘m’ for rounded (shape task) because the correct responses for the color and shape task converged on the same keys. In that case, no judgment of accuracy could be made.

For language switching, four digits were chosen to make the task accessible to monolinguals with only minimal high school French instruction. The stimuli were ‘2’ (‘deux’), ‘4’ (‘quatre’), ‘5’ (‘cinq’), and ‘8’ (‘huit’). These digits were chosen to avoid phonemic onset overlap between English and French to keep stimuli as unique as possible.

### 2.4. Apparatus and data acquisition

EEG signals were sampled at 512 Hz and continuously recorded using 64 Ag/AgCl electrodes distributed according to the extended International 10–20 system with Biosemi. Two electrodes of the flat type (above and below the left eye) recorded the eye-blinks. Another two electrodes (external canthi of each eye) recorded horizontal eye-movements. The EEG signal was re-referenced to the mastoids (left and right; baseline).

**Fig. 1.** Task procedure for the nonverbal and language switching tasks with the decision options for each task.

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2.5. Electrophysiological analysis

For the EEG analysis, epochs of 500 ms with an additional 200 ms pre-stimulus baseline were created. The EEG signal was filtered with a high-pass filter of .01 Hz/12 dB, a low-pass filter of 40 Hz/24 dB, and a notch filter of 60 Hz. Ocular artifacts were corrected using Independent Component Analysis (ICA). Non-ocular artifacts were removed based on the following criteria: trials with amplitudes below − 200 μV, above + 200 μV, voltage step of 50 μV within 200 ms, or activity below .5 μV. The event-related potential (ERP) grand averages were time-locked to the onset of the target stimulus and calculated separately for each condition over all participants.

To avoid a priori bias with respect to choosing time windows and localization for ERP analyses, and given the large number of possible comparisons, a multivariate statistical tool, Partial Least Squares (PLS) was used (Lobauh et al., 2001; McIntosh et al., 1996). Based on all experimental conditions, singular value decomposition reveals a set of latent variables (LVs) representing specific contrasts that account for a percentage of the cross-block covariance. Each LV is associated with a singular value that indicates how much variance is explained by that LV. The estimate of obtaining a singular value by chance (similar to a p-value) was computed by one thousand permutations. The reliability of electrode saliences at each time point was assessed by 200 bootstrap resamplings, which apply random sampling with replacement. The relation between the experimental design contrasts (represented by design scores of the LV) and the spatiotemporal pattern of ERP amplitude changes is represented by the electrode saliences. Electrode saliences above 1.7 (p < .05) were considered reliable, because the ratio of the salience to the standard error is approximately equal to a z-score. Thus, PLS uses data-driven analyses to determine the overall structure of the brain signal, making it more objective than is the case for pre-selection of regions of interest. (For examples of how PLS can be applied to EEG data, see Duxel et al., 2003; Grundy and Shedden, 2014; Hay et al., 2002; Itier et al., 2004; Lobauh et al., 2001 and for examples of PLS specifically applied to speech production ERP data, see Christoffels et al., 2016; Timmer and Chen, 2017. For more detailed explanation of applications and formulas see McIntosh and Lobauh, 2004). In this way, PLS analyses allowed us to narrow the time windows and locations of experimental effects in order to perform conventional ERP statistics. The mean amplitudes of ERPs were submitted to repeated-measures ANOVAs. The Greenhouse–Geisser correction was applied to all repeated measures to correct for possible violations of sphericity. Follow-up analyses were corrected using Bonferroni and adjusted p-values are reported.

3. Results

3.1. Behavioral data

Mean scores for accuracy and response latencies for pure (pure vs. mixed) and switching (repeat vs. switch) costs by language group for both tasks are presented in Table 3. Nonverbal and language switching data were analyzed separately.

3.1.1. Nonverbal task switching

Accuracy scores for switching effects were examined in a 3-way ANOVA for trial type (repeat, switch), task (color, shape), and group (monolingual, bilingual). A main effect of trial type, F(1,41) = 73.95, MSe = 47.53, p < .001, ηp2 = .643, indicated better performance for repeat than switch trials, a main effect of task, F(1,41) = 17.07, MSe = 75.70, p < .001, ηp2 = .294, indicated better performance for color than shape decisions, and a main effect of group, F(1,41) = 4.14, MSe = 307.43, p < .05, ηp2 = .092, indicated better performance by bilinguals than monolinguals. The effects of trial type and task were qualified by an interaction between them, F(1,41) = 15.09, MSe = .27, p < .001, ηp2 = .269, because the switch cost was larger for the shape task than color task, t(41) = −3.95, p < .001. None of the other interactions reached significance, all Fs < 1.63.

A similar analysis examined accuracy for mixing effects by comparing performance in pure blocks and repeat trials in the mixed blocks in a 3-way ANOVA for trial type (pure, repeat), task, and group. A main effect of trial type showed better performance for pure block than repeat trials, F(1,41) = 59.34, MSe = 210.68, p < .001, ηp2 = .591, and a task effect indicated more accurate performance on color than shape decisions, F(1,41) = 6.80, MSe = 2.88, p < .05, ηp2 = .142. There were no differences between groups, F(1,41) = 2.10, n.s., and none of the interactions reached significance, all Fs < 3.20.

For the RT analyses, trials with incorrect responses and outliers (2.5 SD from the average per participant) were discarded. This left 98.23% of the pure, 88.39% of the repeat, and 81.44% of the switch trials in the analysis. The analysis of switching effects was conducted with a 3-way ANOVA for trial type, task, and group. There were faster responses for repeat than switch trials, F(1,41) = 87.72, MSe = 7682.84, p < .001, ηp2 = .681, and for color than shape decisions, F(1,41) = 7.99, MSe = 78.38, p < .01, ηp2 = .163. There were no group differences, F(1,41) = 1.19, n.s., or interaction effects, all Fs < 1.73.

To examine RT for mixing effects, a 3-way repeated measures ANOVA revealed an effect of trial type with faster responses for pure than repeat trials, F(1,41) = 407.87, MSe = 875.43, p < .001, ηp2 = .909. There were no effects for task, F < 1, or group, F(1,41) = 1.03, n.s., and none of the interactions reached significance, all Fs < 1.35.

3.1.2. Language switching

The analysis of accuracy scores for switching effects showed better performance for repeat than switch trials, F(1,41) = 13.21, MSe = 10.01, p = .001, ηp2 = .244, and better performance for English than French naming, F(1,41) = 7.79, MSe = 366.20, p < .01, ηp2 = .160, but no overall group differences, F < 1. There was an interaction of group and task, F(1,41) = 13.12, MSe = 27.91, p = .001, ηp2 = .242, in which monolinguals were more accurate in English than French, F(1,41) = 18.00, MSe = 34.29, p < .001, ηp2 = .450, but bilinguals showed no difference between languages, F < 1. None of the other interactions reached significance, all Fs < 1.17.

The analysis of accuracy for mixing effects revealed better performance for pure than repeat trials, F(1,41) = 6.81, MSe = 10.22, p < .05, ηp2 = .142, and for English than French digit naming, F(1,41) = 9.62, MSe = 233.95, p < .005, ηp2 = .190, but no effect of group, F < 1. Again there was an interaction of task and group, F(1,41) = 12.44, MSe = 18.81, p = .001, ηp2 = .233, in which monolinguals were more accurate in English than French, F(1,41) = 28.99, MSe = 15.31, p = .001, ηp2 = .569, but bilinguals showed no difference between languages, F < 1. None of the other interactions reached significance, all Fs < 1.

For the RT analyses, trials with incorrect responses, voice-key errors, and outliers (2.5 SD from the average per participant) were discarded, leaving 94.83% of the pure, 91.80% of the repeat, and 90.05% of the switch trials in the analysis. The analysis of switching effects revealed faster responses for repeat than switch trials, F(1,41) = 93.52, MSe = 2127.30, p < .001, ηp2 = .695, faster responses for English than French digit naming, F(1,41) = 21.00, MSe = 96656.12, p < .001, ηp2 = .339, and faster naming by bilinguals than monolinguals, F (1,41) = 4.56, MSe = 29.636.20, p < .05, ηp2 = .100. An interaction between task and group, F(1,41) = 48.81, MSe = 1980.44, p < .001, ηp2 = .543, demonstrated that monolinguals named digits faster in English than French, F(1,41) = 49.72, MSe = 2865.26, p < .001, ηp2 = .693, but bilinguals named digits faster in French than English, F(1,41) = 5.59, MSe = 955.91, p < .05, ηp2 = .227.

The ANOVA of RT for mixing effects revealed main effects of trial type, F(1,41) = 227.69, MSe = 8139.37, p < .001, ηp2 = .847, task, F (1,41) = 59.24, MSe = 157.025.11, p < .001, ηp2 = .591, and group, F (1,41) = 11.39, MSe = 14,899.08, p < .005, ηp2 = .217. These main effects were qualified by interactions of trial type by task, F(1,41) =
Monolinguals showed faster response latencies for the pure than repeat trials, \( F(1,22) = 110.82, \text{MSe} = 2399.11, p < .001, \eta^2_p = .834 \), and faster response latencies for English than French digit naming, \( F(1,22) = 43.03, \text{MSe} = 1962.23, p < .001, \eta^2_p = .662 \). However, the mixing cost was larger in English (152 ms; SE = 14.44) than French (86 ms; SE = 13.06), \( t(22) = 6.53, \text{SE} = 10.16, p < .001 \), presumably because French was slower overall so less

Table 3
Mean response latencies in ms (and standard error) and mean accuracy in percentages (and standard error) for nonverbal task switching and language switching for each condition by language group.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Pure blocks</th>
<th>Mixed blocks</th>
<th>Pure</th>
<th>Repeat</th>
<th>Switch</th>
<th>Mixing cost</th>
<th>Switch cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonverbal task switching</td>
<td>Color</td>
<td>Shape</td>
<td>Color</td>
<td>Shape</td>
<td>Color</td>
<td>Shape</td>
<td>Color</td>
</tr>
<tr>
<td>RT (ms) M</td>
<td>503 (12.6)</td>
<td>494 (16.9)</td>
<td>795 (21.1)</td>
<td>803 (25.1)</td>
<td>895 (30.5)</td>
<td>921 (31.3)</td>
<td>292</td>
</tr>
<tr>
<td>B</td>
<td>475 (13.5)</td>
<td>484 (18.2)</td>
<td>763 (22.6)</td>
<td>780 (26.9)</td>
<td>841 (32.7)</td>
<td>866 (33.5)</td>
<td>288</td>
</tr>
<tr>
<td>ACC (%) M</td>
<td>98 (.5)</td>
<td>98 (.9)</td>
<td>89 (1.8)</td>
<td>84 (2.2)</td>
<td>83 (1.9)</td>
<td>74 (2.6)</td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>99 (.5)</td>
<td>98 (1)</td>
<td>92 (2)</td>
<td>90 (2.3)</td>
<td>88 (2)</td>
<td>82 (2.8)</td>
<td>7</td>
</tr>
<tr>
<td>Language switching</td>
<td>English</td>
<td>French</td>
<td>English</td>
<td>French</td>
<td>English</td>
<td>French</td>
<td>English</td>
</tr>
<tr>
<td>RT (ms) M</td>
<td>504 (11.2)</td>
<td>654 (15.1)</td>
<td>656 (17.0)</td>
<td>739 (16.5)</td>
<td>715 (19.9)</td>
<td>789 (21.7)</td>
<td>152</td>
</tr>
<tr>
<td>B</td>
<td>497 (12.0)</td>
<td>507 (16.1)</td>
<td>658 (18.3)</td>
<td>639 (17.7)</td>
<td>695 (21.3)</td>
<td>682 (23.3)</td>
<td>161</td>
</tr>
<tr>
<td>ACC (%) M</td>
<td>97 (1.0)</td>
<td>92 (1.3)</td>
<td>94 (1.5)</td>
<td>90 (1.5)</td>
<td>92 (1.5)</td>
<td>86 (1.7)</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>95 (1.0)</td>
<td>95 (1.4)</td>
<td>91 (1.6)</td>
<td>92 (1.6)</td>
<td>89 (1.6)</td>
<td>90 (1.8)</td>
<td>4</td>
</tr>
</tbody>
</table>
| Note: M = monolingual; B = bilingual; Mixing cost (repeat – pure); Switch cost (switch – repeat).
These two factors interacted, response latencies were similar for English and French digit naming, \( t(19) = 3.52, p < .005 \), than French (132 ms; SE = 12.53), \( \eta^2 = .853 \). However, the mixing cost was again larger in English (161 ms; SE = 15.88), and French, \( \eta^2 = .882 \), but monolinguals showed no difference (repeat: \( \mu V = 2.38, SE = .79 \); switch: \( \mu V = 2.64, SE = .75 \); \( F < 1 \) (see Fig. 4).

To summarize, bilinguals showed sensitivity to the switch effect at the N2 but monolinguals did not, indicating earlier processing for bilinguals. At the P3/LPC, both groups showed the expected sensitivity to the N2 but monolinguals did not, indicating earlier processing for bilinguals. At the P3/LPC, both groups showed the expected sensitivity to the N2 but monolinguals did not, indicating earlier processing for bilinguals. At the P3/LPC, both groups showed the expected sensitivity to the N2 but monolinguals did not, indicating earlier processing for bilinguals. At the P3/LPC, both groups showed the expected sensitivity to the N2 but monolinguals did not, indicating earlier processing for bilinguals.
variables. Fig. 7 presents the ERP waveforms for the mixing effect by language group.

3.2.1.2.1 N1 (125–175 ms time window). The repeated-measures ANOVA revealed a main effect of trial type, $F(1,41) = 24.81, MSe = .16, p < .001, \eta^2_p = .377$, which interacted with localization, $F(2,82) = 4.19, MSe = 4.41, p < .05, \eta^2_p = .093$, and with localization and group, $F(2,82) = 5.34, MSe = 4.41, p < .05, \eta^2_p = .115$. To explore the interactions, separate ANOVAs were run for the monolinguals and bilinguals.

For monolinguals, there was a main effect of trial type, $F(1,22) = 9.65, MSe = 19.42, p = .005, \eta^2_p = .305$, that interacted with localization, $F(2,44) = 8.69, MSe = 3.48, p < .005, \eta^2_p = .283$. Pure trials showed larger negative amplitudes than repeat trials in the parietal (pure: $\mu V = - .85; SE = .58$ vs. repeat: $\mu V = .45; SE = .63$).
than pure trials ($\mu V = -1.33; SE = .63$), $F(1,22) = 315.90, MSe = 11.92, p < .005, \eta^2 = .546$, with no differences in the parietal and occipital regions. Bilinguals also showed an interaction of trial type and localization, $F(2,38) = 45.32, MSe = 6.98, p < .001, \eta^2 = .705$. Similar to monolinguals, bilinguals showed a smaller N2 for repeat ($\mu V = 1.04; SE = .88$) than pure trials ($\mu V = -.89; SE = .90$), $F(1,19) = 10.04, MSe = 22.33, p < .01, \eta^2 = .346$, in frontal regions. Unlike monolinguals, bilinguals showed an additional difference in the occipital region with a smaller N2 for pure than repeat trials, $F(1,19) = 23.13, MSe = 15.40, p < .005, \eta^2 = .549$ (see Fig. 7). There were no significant effects in the parietal region.

3.2.1.2.3. P3/LPC (300–375 ms time window). There was a main effect of trial type, $F(1,41) = 17.03, MSe = 57.55, p < .001, \eta^2 = .293$. Localization interacted with trial type, $F(2,82) = 5.90, MSe = 11.23, p < .01, \eta^2 = .126$, trial type interacted with group, $F(1,41) = 5.13, MSe = 57.55, p < .05, \eta^2 = .111$, and task interacted with group, $F(1,41) = 7.81, MSe = 12.24, p < .01, \eta^2 = .160$, so separate ANOVAs were run for monolinguals and bilinguals.

Monolinguals revealed an interaction between trial type and localization, $F(2,44) = 4.09, MSe = 7.71, p < .05, \eta^2 = .157$. There was an effect of trial type with greater positive amplitudes for pure ($\mu V = 4.81; SE = .53$) than repeat trials ($\mu V = 1.77; SE = .69$), $F(1,22) = 7.79, MSe = 11.29, p < .05, \eta^2 = .261$, only in the occipital region, and no amplitude differences in the frontal or parietal regions. In contrast, bilinguals revealed both a main effect of trial type, $F(1,19) = 15.62, MSe = 70.35, p < .001, \eta^2 = .451$, and task, $F(1,19) = 7.30, MSe = 13.60, p < .05, \eta^2 = .278$, with no effect of localization or interactions of localization with other factors, $p > 2.36$. The trial type effect indicated more positive amplitudes for pure ($\mu V = 5.24; SE = .67$) than repeat trials ($\mu V = 2.77; SE = .88$); the task effect showed more positive amplitudes for color ($\mu V = 4.38; SE = .70$) than shape decisions ($\mu V = 3.63; SE = .75$).

To summarize, the nonverbal switching task revealed mixing effects in three ERP components, N1, N2, and P3/LPC, with more distributed effects over the scalp for bilinguals than for monolinguals.

3.2.2. Language switching

After data adjustments similar to those used for nonverbal switching, 93.42% of the pure, 90.99% of the repeat, and 90.97% of the switch trials were left in the analysis.

3.2.2.1. Switching effect. PLS analysis for switch effects in language switching revealed one significant LV which accounted for 61.04% of the variance, $p < .001$, indicating a switch effect for French but not English and a task effect only in bilinguals (see Fig. 8). This effect was only present in the 325–400 ms time window. Therefore, this window was analyzed with trial type (repeat vs. switch), group, task, and localization (central: C1, Cz, C2; central-parietal: CP1, CPz, CP2; parietal: P1, Pz, P2; parietal-occipital: PO3, POz, PO4) as independent variables. Fig. 9 presents the ERP waveforms of the switching effect for both language groups.

3.2.2.2.1. P3/LPC (325–400 ms time window). The main effect of task showed greater positive amplitudes for French ($\mu V = 8.30; SE = .71$) than English trials ($\mu V = 7.33; SE = .66$), $F(1,41) = 14.66, MSe = 33.40, p < .001, \eta^2 = .263$. The interaction between localization and trial type was significant, $F(3,123) = 5.17, MSe = 1.02, p < .01, \eta^2 = .112$, and the four-way interaction between all factors was marginally significant, $F(3,123) = 3.26, MSe = 1.35, p = .055, \eta^2 = .074$. We initially ran separate ANOVAs for each group, but this approach was unable to account for the four-way interaction. Thus, separate ANOVAs were run for the central, central-parietal, parietal and parietal-occipital regions. In brief, the switching effect was evident in bilinguals at central-parietal, $F(1,19) = 4.86, MSe = 5.03, p < .05, \eta^2 = .204$, parietal, $F(1,41) = 4.79, MSe = 4.09, p < .05, \eta^2 = .105$, and parietal-occipital regions, $F(1,41) = 6.04, MSe = 3.83, p < .05, \eta^2 = .128$, but was only evident for monolinguals at parietal, $F(1,41) =

To summarize, only the P3/LPC component reflected the switch effect during the language task, and was distributed over a larger scalp region for bilinguals than monolinguals.

3.2.2.2. Mixing effects. For mixing effects, PLS analysis revealed two latent variables. LV1 showed a mixing cost for both language groups and accounted for 45.27% of the variance, *p* < .001. This effect was most reliable within the 200–300 ms time windows throughout the parietal-occipital region (electrodes: PO7, PO3, O1, POz, Oz, Iz, PO8, PO4, and O2) (see Fig. 10). LV2 accounted for 34.92% of the variance, *p* < .001, and showed a mixing effect for bilinguals but not monolinguals in the same region as LV1 but in the 350–400 ms time window (see Fig. 11). Both time-windows were analyzed with trial type (pure vs. repeat), task (English vs. French), group (monolinguals vs. bilinguals), and localization (left: PO7, PO3, O1; central: POz, Oz, Iz; right: PO8, PO4, O2) as independent variables. Fig. 12 presents the ERP waveforms of the mixing effect for both language groups.

3.2.2.2.1. N2 (200–300 ms time window)

There was a main effect of trial type, *F*(1,41) = 69.88, *MSe* = 21.54, *p* < .001, *η^2^ = .630, and an interaction of trial type and localization, *F*(2,82) = 6.03, *MSe* = 1.21, *p* = .005, *η^2^ = .128. However separate analyses for each region revealed a main effect of trial type in all regions (see Fig. 12), left: *F*(1,41) = 62.74, *MSe* = 8.14, *p* < .005, *η^2^ = .605; central: *F*(1,41) = 60.84, *MSe* = 6.43, *p* < .005, *η^2^ = .597; right: *F*(1,41) = 67.85, *MSe* = 9.07, *p* < .005, *η^2^ = .623, with larger negative amplitudes for repeat (left: µV = 1.47; SE = .49; central: µV = 1.37; SE = .43; right: µV = 2.14; SE = .48) than pure trials (left: µV = 3.46; SE = .49; central: µV = 3.12; SE = .46; right: µV = 4.33; SE = .49). Consistent with the findings of LV1, this pattern held for both language groups.

3.2.2.2.2. P3/LPC (350–400 ms time window)

There was a main effect of task with larger positive amplitudes for French (µV = 4.59; SE = .61) than English (µV = 3.30; SE = .57), *F*(1,41) = 17.00, *MSe* = 37.32, *p* < .001, *η^2^ = .293. There were interactions of trial type and localization, *F*(2,82) = 4.15, *MSe* = 1.73, *p* < .05, *η^2^ = .092, and trial type and group, *F*(1,41) = 5.76, *MSe* = 46.44, *p* < .05, *η^2^ = .123. The trial type by group interaction indicated no difference between pure and repeat trials for bilinguals, *F*(1,19) = 2.32, n.s., but monolinguals showed more positive amplitudes for pure than repeat trials, *F*(1,22) = 4.40, *MSe* = 22.21, *p* < .05, *η^2^ = .167.

To summarize results of mixing costs for language switching, the N2 revealed similar mixing effects for both language groups. An additional late component, P3/LPC, was present for monolinguals but not bilinguals.

4. Discussion

The present study examined nonverbal task switching and language switching processes in monolinguals and bilinguals using event-related potentials. Bilinguals were more accurate than monolinguals in the mixed block during nonverbal task switching, and monolinguals were, not surprisingly, slower than bilinguals during language switching in French. An overview of the modulations of ERP components and their relation to findings in the previous literature are presented in Table 1. Bilinguals showed more distributed processes than monolinguals for both nonverbal task and language switching. In nonverbal task switching bilinguals also showed earlier processing effects for the switch cost; in language switching, monolinguals showed additional late processing that captured the mixing effect. Further, the ERP components for the two tasks appeared to be more similar for bilinguals than for monolinguals, suggesting that there might be more processing overlap for bilinguals. Such a finding would be consistent with the interpretation that life-long practice of language switching modifies these processes for both verbal and nonverbal domains. However, this effect could not be tested directly and so remains speculative. This point is discussed further below.

In the nonverbal task there was a typical switch cost indicated by faster response times and higher accuracy for repeat than switch trials. The magnitude of the switch cost was similar for monolinguals and bilinguals, but bilinguals were more accurate than monolinguals on both types of trials in the mixed blocks.

The ERP components associated with switch costs in task switching
are the N2 and P3/LPC (e.g., Barceló et al., 2007; Kieffaber and Hetrick, 2005), although some studies report only P3/LPC modulations (Friedman et al., 2007; Scisco et al., 2008; Swainson et al., 2006). Periáñez and Barceló (2009) showed that N2 amplitudes are influenced by cue updating and not by task updating. The N2 revealed greater negativity for repeat than switch cues. This ERP pattern has been attributed to cue repetition and sensory priming of the cue, leading to an enduring memory for the repeated stimulus (Moulden et al., 1998; Periáñez and Barceló, 2009; Rushworth et al., 2002). This pattern was found for the bilingual group only and may reflect cue updating and reactivation of the decision rule at early stages of processing. Monolinguals did not show a distinction between trial types at these early stages in processing. Periáñez and Barceló (2009) disentangled cue- from task-processing by having the cue indicate whether the participants had to repeat or switch the current task they were performing. This is in contrast to the present study, where the cue indicates which task they are performing. Our interpretation is that the results of the current study most likely reflect cue-updating.

In contrast to the N2, there was a P3/LPC modulation for both groups. Previous research suggests that the P3/LPC modulation on switch trials is associated with reconfiguration of S-R mappings in working memory and the application of the appropriate rule to the target stimulus (Barceló et al., 2006, 2007, 2002; Jost et al., 2008; Periáñez and Barceló, 2009; Watson et al., 2006).

Bilinguals distinguished between repeat and switch trials at the N2 but monolinguals did not. This difference indicates that bilinguals were more sensitive to cue-updating and showed earlier attentional processing of the cue than monolinguals. Importantly, not all studies investigating ERPs of task switching have found N2 modulations (Friedman et al., 2007; Scisco et al., 2008; Swainson et al., 2006). Studies investigating the effects of cognitive training in attentional processes and reasoning have shown a substantial increase of the N2 for the switch trials during task switching compared to a relaxation and no-contact group (Gajewski and Falkenstein, 2012; Gajewski et al., 2017). Therefore, experience in switching between languages may act as a type of cognitive training that enhances sensitivity to cue-updating reflected by N2 modulations. In a bilingual environment with interlocutors from different languages, bilinguals have experience using cues to adjust the task. This practice could help bilinguals reactivate cue-mappings quicker than monolinguals and may lead to earlier attentional processing of the difference between repeat and switch trials. Earlier attention to cue processing for bilinguals has also been supported by behavioral evidence showing reduced restart costs (i.e., comparing the first and second trial after a repeat cue) for bilinguals compared to monolinguals (Hernández et al., 2013). This earlier attention to cue-updating could be reflected in higher accuracy rates for bilinguals than monolinguals on non-linguistic tasks.

The switch cost results from the language switching task were similar to those from task switching: there were switch costs in both response latencies and accuracy, with faster and better naming on repeat than switch trials. The modulations observed at the P3/LPC mirrored the behavioral results with greater positive amplitudes for switch than repeat trials in the 325–400 ms time window for both monolinguals and bilinguals. This finding is in line with other language switching studies that have reported modulations of the P3/LPC (Hernández et al., 2013; Jackson et al., 2001; Liu et al., 2016, 2014). In the current study the P3/LPC is present for both groups through the parietal and parietal-occipital regions, but extends to the central-parietal region only for bilinguals. This finding is in line with other language switching studies that have reported modulations of the P3/LPC (Hernández et al., 2013; Jackson et al., 2001; Liu et al., 2016, 2014).
language group differences have been reported, fewer studies have found behavioral differences between groups on mixing costs (but see Wiseheart et al., 2016). Consistent with this trend, both monolinguals and bilinguals showed similar behavioral mixing costs on accuracy and RT.

ERPs revealed more distributed networks for bilinguals than monolinguals on three ERP components: N1, N2, and P3/LPC. Previous literature has only looked at the P3/LPC component, but the PLS analyses show two earlier components that were sensitive to mixing costs that have not been studied in previous research. The modulation for N1 was present in parietal and occipital regions for both groups and extended to frontal regions for bilinguals. This initial component has been related to early attentional processing in other visual tasks like the flanker task (Beste et al., 2008; Johnstone et al., 2009). Greater
sensitivity to the N1 has been found for participants with more experience in interpreting and translation (Dong and Zhong, 2017). This is in line with the present sensitivity to cue processing for bilinguals. Modulation on the second component, N2, could potentially reflect attentional processing for both groups in the frontal region and an additional sensitivity for bilinguals throughout the occipital region. The occipital sensitivity for bilinguals but not monolinguals could be indicative of additional visual attention to all stimuli (Hillyard and Anllo-Vento, 1998; Mangun, 1995). In line with previous research, the current study also found modulation of the P3/LPC reflecting attentional allocation to non-stimuli during memory updating (Goffaux et al., 2006; Gomer et al., 1976; Jost et al., 2008; Kamijo and Takeda, 2010; Kok, 2001; Wijers et al., 1989). This effect was present in the occipital region for both groups and extended to the frontal and parietal regions for bilinguals. Thus, bilinguals displayed a more distributed network for the N1, N2, and P3/LPC components than monolinguals.

For the language switching task, participants were faster and more accurate on pure than repeat trials in mixed blocks, revealing a mixing cost. For both groups the mixing cost was larger in the dominant than in the non-dominant language. However, this mixing cost difference was greater for monolinguals than bilinguals. This is in line with previous studies that demonstrated a greater switch cost to the dominant than non-dominant language for unbalanced bilinguals (Christofels et al., 2007; Gollan and Ferreira, 2009; Philipp et al., 2007; Prior and Gollan, 2007; Wijers et al., 1989). This effect was present in the occipital region for both groups and extended to the frontal and parietal regions for bilinguals. Thus, bilinguals displayed a more distributed network for the N1, N2, and P3/LPC components than monolinguals.

Critically, the BAPSS model proposes that these adaptations lead to more efficient processing of both verbal and nonverbal stimuli through reliance on more perceptual and motor regions. It takes a lot of effort to learn a new language and this effort requires substantial contributions from the frontal lobes. At the beginning, learners over-recruit frontal resources to deal with competition between the two languages, but to promote efficiency over time, one must recruit different regions and networks to help with task demands. Bilingual children often show over-recruitment of frontal resources compared to monolinguals (e.g. Jasinska and Petitto, 2013; Kobayashi et al., 2008; Mohades et al., 2014) in the same regions that are engaged more efficiently by bilingual adults. Similarly, less proficient bilinguals require more neural resources to manage two languages than more proficient bilinguals (Abutalebi et al., 2013; Perani and Abutalebi, 2005). However, lifelong bilingualism eventually leads to greater white matter volume and integrity (e.g. Coggins et al., 2004; Felton et al., 2017; Luk et al., 2011; Platsiakas et al., 2015), greater functional connectivity between different brain regions (e.g. Costumero et al., 2015; Grady et al., 2015; Li et al., 2015), and a general shift to rely more on visual, perceptual, and subcortical processes than mostly frontal (reviews in Grundy et al., 2017a). These structural and functional changes promote efficient processing in the bilingual brain for all stimuli.

The BAPSS model proposes that when first learning a new language, top-down control processes are required, but that with second-language mastery comes earlier and more efficient processing of both verbal and nonverbal stimuli through reliance on more perceptual and motor regions. It takes a lot of effort to learn a new language and this effort requires substantial contributions from the frontal lobes. At the beginning, learners over-recruit frontal resources to deal with competition between the two languages, but to promote efficiency over time, one must recruit different regions and networks to help with task demands. Bilingual children often show over-recruitment of frontal resources compared to monolinguals (e.g. Jasinska and Petitto, 2013; Kobayashi et al., 2008; Mohades et al., 2014) in the same regions that are engaged more efficiently by bilingual adults. Similarly, less proficient bilinguals require more neural resources to manage two languages than more proficient bilinguals (Abutalebi et al., 2013; Perani and Abutalebi, 2005). However, lifelong bilingualism eventually leads to greater white matter volume and integrity (e.g. Coggins et al., 2004; Felton et al., 2017; Luk et al., 2011; Platsiakas et al., 2015), greater functional connectivity between different brain regions (e.g. Costumero et al., 2015; Grady et al., 2015; Li et al., 2015), and a general shift to rely more on visual, perceptual, and subcortical processes than mostly frontal (reviews in Grundy et al., 2017a). These structural and functional changes promote efficient processing in the bilingual brain for all stimuli.
earlier and more automatic ERP processes for bilinguals than monolinguals on non-verbal executive function tasks (Grundy et al., 2017a), consistent with the present findings of earlier processing for bilinguals.

To summarize, monolinguals and bilinguals revealed similar behavioral switching and mixing costs on the nonverbal task switching paradigm but bilinguals performed better in all conditions of the mixed blocks. The switch effect for both language switching and task switching was indexed by the P3/LPC for both language groups, but only bilinguals demonstrated sensitivity to the switch effect through a deflection in the N2 waveform. In other words, bilinguals showed earlier attentional cue processing, possibly due to their longer experience with paying attention to contextual cues informing them about the language to be used. This earlier sensitivity of bilinguals to the processing of repeat and switch trials may have led to their improved behavioral performance in these conditions. In addition, bilinguals revealed more distributed networks for all components involved during the nonverbal mixing effect than monolinguals. For the language mixing effect, monolinguals needed an additional late control component; bilinguals did not need this additional control component during language switching.

The results of the present study are consistent with the view that the ongoing experience of language switching that is associated with bilingualism modifies the neural networks involved in switching more broadly. The nonverbal and language switching tasks were structurally similar but based on stimuli from different domains. The activations for bilinguals were earlier and more distributed across the scalp than was found for monolinguals. Specifically, bilinguals demonstrated processing based on earlier attention, better monitoring, and possibly more integrated networks than monolinguals performing the same tasks. Our interpretation is that bilingualism modifies crucial brain networks, possibly by integrating pathways generally used for different domains and influencing performance across a broad range of tasks.

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References


Grundy, J.G., Chung-Fat-Yim, A., Friesen, D.C., Mak, L., Bialystok, E., 2017b. Sequential congruence effects reveal differences in disengagement of attention for monolingual


