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Language and cognitive control networks in bilinguals and monolinguals

John A.E. Anderson[a,1], Ashley Chung-Fat-Yim[a,1], Buddhika Bellana[b], Gigi Luk[c], Ellen Bialystok[a,*]

[a] Department of Psychology, York University, Toronto, Ontario, Canada
[b] Department of Psychology, University of Toronto, Toronto, Ontario, Canada
[c] Graduate School of Education, Harvard University, Cambridge, MA, USA

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ABSTRACT

Neuroimaging studies have reported overlapping neural circuits for cognitive control when engaging in tasks that involve verbal and nonverbal stimuli in young adult bilinguals. However, no study to date has examined the neural basis of verbal and nonverbal task switching in *both* monolinguals and bilinguals due to the inherent challenge of testing verbal task switching with monolinguals. Therefore, it is not clear whether the finding for overlapping networks is unique to bilingualism or indicative of general cognitive control. To address this question, the current study compared functional neural activation for young adults who were bilingual speakers of English and French or monolingual English speakers who had limited French learning experience ("functional monolinguals") on verbal and nonverbal task switching. Analyses showed common variance explaining general cognitive control in task switching across verbal and nonverbal domains for both groups, in line with the explanation that task switching involves general cognitive control, as well as unique brain regions recruited by monolinguals and bilinguals. Specifically, beyond the processing common to the tasks, monolinguals also recruited distinct networks for each of verbal and nonverbal switching but bilinguals used a common shared network. Thus, the domain-general aspect of switching is different for monolinguals and bilinguals.

1. Introduction

A growing body of research reports domain-general changes in nonverbal cognitive control for bilinguals that are frequently associated with enhanced performance on some types of executive function tasks (review in Bialystok, 2017). When other socio-demographic variables are considered, these effects of bilingualism persist into older age as protective factors; for example, bilinguals have been shown to display symptoms of dementia at a significantly older age than monolinguals, (review in Bak and Alladi, 2014). Furthermore, recent research has identified a set of structural and functional brain differences between monolinguals and bilinguals that may reveal the neural substrate of the mechanism reflected in the behavioral effects (reviews in Grundy et al., 2017; Li et al., 2014; Pliatsikas, 2017; Tu et al., 2015). However, the brain-behavior relationship that connects these types of evidence to identify the relevant mechanism is not well-documented.

One activity that is unique to bilinguals and provides an opportunity to probe this mechanism is language switching. Highly proficient bilinguals are constantly required to switch between languages in response to cues from the environment, such as the context of the situation or the language of their interlocutors (Green and Abutalebi, 2013). In the bilingual mind, both languages are simultaneously active and compete for attention in all contexts (Kroll et al., 2014, 2012; Misra et al., 2012; but see Costa et al., 2017 for a counterpoint), creating a selection challenge that requires continuous monitoring of available cues and planning to select the appropriate language. Over time, this challenge potentially modifies the associated cognitive processes responsible for language selection and language switching. Moreover, these processes involved in monitoring and selecting the target language may be generalized beyond language and partly account for domain-general enhancements in bilinguals when engaging in nonverbal cognitive tasks. However, this exercise may not be specific to bilinguals. Monolinguals also need to monitor the environment for cues and select from competing alternatives during communication, even when the alternatives exist within the same language (Allopenna et al., 1998; Schriefers et al., 1990). Nonetheless, selecting alternatives within a language is not equivalent to selecting alternatives from different representational structures. In a study by Friesen et al. (2016), monolingual and bilingual young adults performed a lexical selection task in English in the context of competing alternatives. Analysis of event-related potentials showed that the two language groups performed this task differently. Therefore, language selection for bilinguals is

* Correspondence to: Department of Psychology, York University, 4700 Keele Street, Toronto, Ontario, Canada M3J 1P3.
E-mail address: ellenb@yorku.ca (E. Bialystok).

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fundamentally different than it is for monolinguals, even within the same language.

In the present study, we examined the neural correlates of switching behavior for functional monolinguals and bilinguals. The task designed for the study requires processes such as monitoring the available options and flexibly switching between choices. The purpose is to compare the processes used by bilinguals for verbal and nonverbal switching and determine whether similar processes are recruited by monolinguals. Differences in these processes for the two language groups would support the interpretation that language switching for bilinguals is a viable candidate for an experience-dependent mechanism that underlies difference in cognitive control observed in behavior.

One paradigm that can be adapted to investigate this question is task switching. In a task switching paradigm, participants switch between performing two tasks, such as classifying verbal stimuli that are proper names or common nouns (Vallesi et al., 2015) or classifying pictures based on nonverbal cues, like shape and color (Wiseheart et al., 2016). Typically, participants complete pure blocks of trials containing only one of the tasks and a mixed block where the two tasks are randomly interspersed, creating switch trials and non-switch trials. The behavioral indices of performance are *switch costs*, reflecting slower responses to switch than non-switch trials in the mixed block, and *mixing costs*, reflecting slower responses to non-switch trials in the mixed block than to the same trials in the pure block (Monsell, 2003). Previous behavioral studies have shown smaller costs for bilinguals than monolinguals on switch costs (Garbin et al., 2010; Prior and Gollan, 2013; Prior and MacWhinney, 2010; Qu et al., 2016; Stasenko et al., 2017) or mixing costs (Wiseheart et al., 2016). Other studies using behavioral measures have failed to find group differences in either cost (Paap and Greenberg, 2013; Paap and Sawi, 2014). Language switching is typically assessed by tasks in which bilinguals are required to switch between naming stimuli (usually pictures) in their two languages by responding to a cue associated with each language (Abutalebi et al., 2008; Crinion et al., 2006; Hernandez et al., 2000; see Declerck and Philipp, 2015 for a review).

Neuroimaging studies have demonstrated that bilinguals typically recruit brain regions associated with domain-general executive control when switching between languages (for review see Hervais-Adelman et al., 2011), although these regions appear to be more involved for language switching in laboratory settings than in naturalistic contexts (Blanco-Elorrieta and Pylkkanen, 2017). A meta-analysis by Luk et al. (2012) examined 10 language switching studies with bilinguals and found that relative to single-language tasks, language switching was associated with increases in activation in left inferior frontal gyrus, left middle temporal gyrus, left middle frontal gyrus, right precentral gyrus, right superior temporal gyrus, middle pre-supplementary motor area and bilateral caudate nuclei. These regions have been associated with monitoring and planning (Bush et al., 2000; Nachev et al., 2008), suggesting similar cognitive processes for verbal and nonverbal switching in bilinguals. Furthermore, de Baene et al. (2015) included a verbal picture-naming task in which participants were asked to switch between naming pictures in Spanish, Basque or English and a nonverbal switching task that required participants to switch between judging color, gender, or motion. The tasks were similar but differed in response modality with one based on spoken response and the other on button press. The results showed that regions in the fronto-parietal network were recruited for both language switching and nonverbal switching. Similar findings were reported by Weissberger et al. (2015), supporting the notion that common brain regions are recruited for language switching and task switching in bilinguals.

In a related study that did include monolinguals, Coderre et al. (2016) examined the functional overlap between language processing, non-linguistic executive control, and linguistic executive control in English monolinguals and Spanish-English bilinguals. Linguistic and non-linguistic executive control was assessed with a modified flanker task where the distractors appeared above and below four arrows pointing in the same direction that were either verbal in English (right or left) or Spanish (izquierda or derecha), nonverbal (→ → → → or ← ← ← ←), or semantically-related (down or up). The English monolingual participants did not perform the Spanish verbal condition. Language processing was measured using a semantic categorization task where participants had to make living or non-living judgments for words. Bilinguals performed the semantic categorization task in both languages. The results from a conjunction analysis of the flanker and semantic categorization tasks showed functional overlap in the left inferior frontal gyrus for bilinguals, but no such overlap in monolinguals. The authors concluded that monolinguals use separate brain regions for linguistic and non-linguistic processing, while bilinguals recruit executive control for both.

The language switching processes involved in bilingual language selection have been proposed as part of the mechanism that modifies control processes for bilinguals and leads to enhancements in nonverbal cognitive control (Bialystok et al., 2009). However, this explanation would be undermined if the same control processes were found in monolingual switching performance. Since monolinguals do not routinely switch between languages, it is not clear whether task switching in monolinguals would be similar for different types of stimuli, particularly, verbal material. One attempt at obtaining comparative evidence for monolinguals and bilinguals performing a verbal switching task was conducted by Abutalebi et al. (2012). Italian monolinguals and German-Italian bilinguals performed a verbal task and a flanker task. For the verbal task, bilinguals switched between naming pictures in their two languages depending on the cue, but monolinguals were asked to switch between generating nouns or verbs in response to a picture. However, switching between form class *within* a language may not rely on the same processes as switching *between* languages, so the task may be more accurately described as task switching with verbal stimuli rather than language switching. Reduced activation in the dorsal anterior cingulate cortex was found for bilinguals compared to monolinguals on the flanker task; this brain structure is associated with monitoring for conflict and allocating attentional resources for dealing with conflict, indicating more efficient processing by bilinguals (Botvinick et al., 2001).

Only one study to date has directly compared monolinguals and bilinguals in task switching and language switching. Timmer et al. (2017) had English-speaking functional monolinguals with limited school knowledge of French and English-French bilinguals perform a verbal (digit naming in English/French) and nonverbal (color/shape) switching task while EEG was recorded. The data were analyzed using Partial Least Squares (PLS), a whole-brain multivariate approach that highlights coherent spatial network of activity (McIntosh et al., 1996; McIntosh and Lobaugh, 2004; Krishnan et al., 2011). Results revealed that for both the verbal and nonverbal switching tasks, bilinguals used a more spatially distributed network across the brain than monolinguals, with earlier peak waveforms. Furthermore, the bilinguals showed greater overlap in the recruited brain regions for the two tasks than did monolinguals.

The current study extended these preliminary results by using fMRI to examine the neural networks recruited by monolinguals and bilinguals while they performed verbal and nonverbal switching paradigms. fMRI can provide spatial information regarding the neural network involved in verbal and nonverbal switching, thereby clarifying the issue of overlapping selection processes for verbal and nonverbal stimuli.

To address the problem of language switching for monolinguals, we identified individuals who had knowledge of a second language through formal education but have not used that language in naturalistic settings for communication. Thus, the monolinguals functioned only in English but had brief exposure to French instruction in school to the extent that they had basic knowledge of letters and numbers. Therefore, we describe these participants as functional monolinguals. The bilinguals, in contrast, used English and French on a daily basis since a young age and were able to converse in both languages fluently.

Participants in both groups performed an English-French verbal switching task and a color-shape nonverbal switching task that were designed to reduce the number of methodological differences across domains by making the responses for both tasks via button press. The purpose was to determine whether selection and switching mechanisms for verbal and nonverbal stimuli were similar across groups and across task domains. Evidence for the overlap of these processes in bilinguals would be consistent with the notion that language switching constitutes part of the mechanism for adaptations in behavioral and brain outcomes for bilinguals reported elsewhere.

Two objectives were incorporated into the study. The first objective was to determine the similarity in these tasks across domains by comparing brain activity for the verbal and nonverbal task switching contexts. The hypothesis was that distinct networks will be identified for switching in each of these tasks. The second objective was to determine the similarity in processing across language groups by comparing performance in the two domains for each group. The hypothesis was that functional monolinguals and bilinguals will use similar networks, the language network, for switching between languages, but that monolinguals and bilinguals will recruit different networks while performing nonverbal task switching (Coderre et al., 2016; Timmer et al., 2017). Specifically, bilinguals were expected to show more overlapping activity across verbal and nonverbal domains than monolinguals, even though both tasks also include unique neural correlates. Evidence for language group differences in processing in these domains would be consistent with the interpretation that nonverbal processing for bilinguals has been shaped by language experience.

2. Method

2.1. Participants

Fifteen functional monolingual and 17 English-French bilingual young adults participated in the study. Participants' language experience and self-rated language proficiency were obtained from the *Language and Social Background Questionnaire* (LSBQ; Anderson et al., 2018) and *French Language Experience Questionnaire* (FLEQ; Chung-Fat-Yim, 2013). One functional monolingual had Tagalog in the home and reported using that language approximately 10% of the time, so this participant was excluded from further analyses. Two bilingual participants did not have pre-scan normalization activated during the acquisition of the functional runs and were thus removed from subsequent analyses. The final sample, therefore, consisted of 14 functional monolinguals and 15 English-French bilinguals. Bilinguals indicated they were also biliterate and used both languages daily and reported being highly proficient in both. Eight bilinguals indicated that French was their more fluent language and the remaining seven indicated that English was their more fluent language. Bilingual participants indicated they learned French in the home, through a French immersion program, or by attending a school where French was the medium of instruction. For bilinguals, the mean age of acquisition for English and French was 4.47 (3.96) and 1.67 (2.35) years old, respectively. The bilinguals indicated that they used English and French in different social and professional contexts throughout their development. Functional monolinguals had basic knowledge of French from a compulsory school language course and had the ability to correctly spell digits 1–10 in French. Demographics of the participants are presented in Table 1. All participants provided informed consent prior to participating and filled out an MRI prescreen questionnaire before each session. None of the participants reported history of head injuries or neurological disorders. The University Research Ethics Committee approved all study procedures. From the LSBQ and FLEQ, composite proficiency scores were created as the average ratings across speaking, understanding, reading and writing in English for the functional monolinguals and in English and French for the bilinguals. The groups differed in self-rated proficiency and usage in French (see Table 1).

Table 1
Mean score (SD) of demographic and language background measures by language group.

	Monolingual	Bilingual	*t*-value
Age	21.8 (4.3)	22.6 (4.2)	0.52
Mother's Education	3.2 (0.7)	3.6 (1.0)	1.21
CCFIT	105.9 (10.7)	113.0 (9.0)	1.96
PPVT	106.4 (9.4)	109.4 (11.7)	0.77
English Self-Rated Proficiency			
Speaking	100.0 (0.0)	91.5 (12.1)	2.61*
Understanding	100.0 (0.0)	92.2 (13.5)	2.15*
Reading	100.0 (0.0)	91.8 (14.4)	2.12*
Writing	100.0 (0.0)	91.2 (15.1)	2.19*
Composite English Proficiency	100.0 (0.0)	91.7 (13.3)	2.33*
French Self-Rated Proficiency			
Speaking	17.0 (11.4)	90.7 (12.5)	16.55***
Understanding	22.1 (13.6)	94.8 (9.4)	16.89***
Reading	23.5 (13.5)	94.8 (9.4)	16.62***
Writing	16.5 (12.5)	86.7 (16.5)	12.83***
Composite French Proficiency	19.8 (10.1)	91.8 (10.2)	19.02***
Level of Bilingualism (1–5)	1.4 (0.5)	4.6 (0.5)	16.75***
Bilingual Language Usage (%)	0.38 (1.11)	32.47 (17.03)	7.03***
Accuracy (%)			
English Digit Naming	98.4 (5.9)	99.7 (1.0)	0.85
French Digit Naming	99.0 (2.5)	100.0 (0.0)	1.53
English Picture Naming	95.1 (5.7)	94.9 (5.1)	0.10
French Picture Naming	11.3 (8.5)	78.7 (17.8)	12.87***
French Picture Matching	53.0 (11.8)	99.3 (1.2)	15.14***

Note. Level of Bilingualism was computed from 1 to 5 with 1 representing "Not Bilingual" and 5 representing "Fluent Bilingual". Composite proficiency scores are the average ratings across speaking, understanding, reading and writing within each language. * *p < .01.
* p < .05.
*** p < .001.

2.2. Materials

Participants completed a 1½ hour behavioral testing session and returned approximately two weeks later for a one-hour scanning session. The following tasks were administered during the behavioral testing sessions:

2.2.1. Peabody picture vocabulary test-III (PPVT-A; Dunn and Dunn, 1997)

This is a standardized test of receptive English vocabulary. Four black and white pictures and a verbal prompt were presented and participants were asked to identify which of the four pictures corresponded to the verbal prompt. Raw scores represent the number of correct responses between the first item of a base set and the last item of a ceiling set. Raw scores were transformed to age-corrected standard scores with a population mean of 100 and a standard deviation of 15.

2.2.2. Cattell culture fair intelligence test (CCFIT; Cattell, 1957)

CCFIT is a standardized measure of nonverbal reasoning. The test includes four subtests that require participants to solve abstract reasoning problems by choosing a response from six alternatives. Raw scores were converted to age-corrected standard scores with a mean of 100 and a standard deviation of 15.

2.2.3. English and French digit naming task

The English and French versions were administered in separate blocks in counterbalanced order across participants. In each block, participants named digits 1 through 9 by speaking into a microphone. Digits were presented one at a time on the screen with each digit shown three times for a total of 27 trials. A blank screen was shown for 1500 ms after each trial. The purpose was to confirm that participants could name digits in both languages. The task was untimed, accuracy rates of digit naming in French and English were the outcome variables with a possible maximum of 27 for each language.

2.2.4. English and French picture naming task

The two language tasks were administered in separate blocks with order counterbalanced across participants. In each block, participants named 24 common objects that were presented as line drawings one at a time either in English or French. If participants did not know the name of the picture, they were instructed to say “pass”, which was later coded as an incorrect response. Following each response, a blank screen appeared for 1500 ms. The pictures were selected from the Cycowicz et al. (1997) compendium. This task measured basic vocabulary knowledge in each language and was used to supplement scores from the other measures and the self-report ratings on the LSBQ. The dependent variable was accuracy with a possible maximum of 24 in each language. Similar to the digit naming task, the picture naming task is untimed.

2.2.5. French picture matching task

Participants were given an 8-page booklet with six pictures on each page. The pictures were again selected from the Cycowicz et al. (1997) database and included some of the same images they had seen in the picture-naming task. Participants were required to match each picture with its corresponding name in French. The French picture matching task was included to assess ability to recognize pictures in French.

2.3. In-scanner task

2.3.1. Verbal and nonverbal switching task

In the verbal switching task, a cue for English (Ontario flag) or French (Quebec flag) was presented simultaneously above a digit and letter. These cues are highly familiar to all participants and associated with English and French languages, respectively. Participants were asked to indicate whether the digit began with that letter in the language indicated by the flag by pressing the corresponding button. The stimuli included the digits 1 through 9 and the letters a, c, d, e, f, h, j, n, o, q, r, s, t, u, and w (see Fig. 1a). In the nonverbal switching task, two stimuli appeared below a color or form cue and participants had to indicate whether the stimuli matched on the cued dimension. The shapes used were circle, triangle, square, and hexagon, and the colors used were blue, yellow, red, and green (see Fig. 1b). This design allows the comparison of bilinguals and monolinguals within the same paradigm, something not previously possible. Both the nature of the judgement for each task (match-mismatch) and the response method (button press) were identical. Proportions of match and mismatch trials was 50%. For the verbal task, the proportion of trials that were a match between the letter and the number in the irrelevant language was 25% in both the pure and mixed block (e.g., judgment carried out in English, and the number “1” is paired with the letter “u”). Similarly for the nonverbal task, the proportion of trials where the two objects matched on the irrelevant dimension was 25% (e.g., when making a judgment for shape, the objects were the same color).

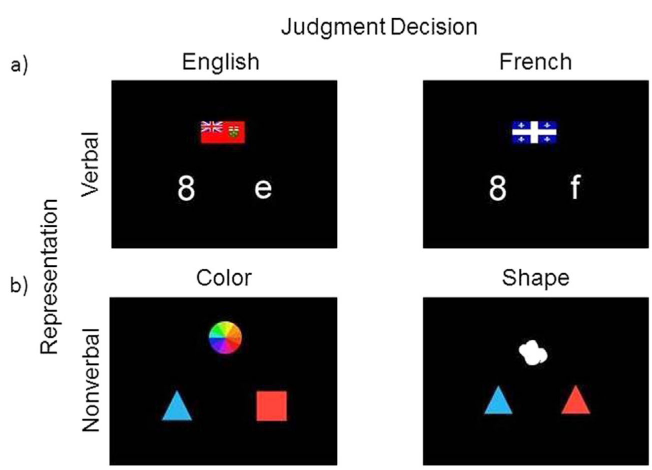

Fig. 1. Sample stimuli from the verbal and nonverbal task. (a) Verbal task: The image on the left depicts a trial where the participant had to make a judgment in English (8 = eight, a match trial). The image on the right depicts a trial where the participant had to make a judgment in French (8 = huit, a mismatch trial). (b) Nonverbal task: The image on the left depicts a trial where the participant had to make a judgment for color (blue vs. red, a mismatch). The image on the right depicts a trial where the participant had to make a judgment for shape (triangle vs. triangle, a match trial).

Each trial was preceded by a fixation cross for 500 ms and followed by a blank screen that was jittered randomly between 0, 500, and 1000 ms. The stimuli remained on the screen until the participant made a response or until 2000 ms had elapsed. To avoid excessive motion in the scanner associated with overt naming, the tasks were implemented as a match/mismatch judgment requiring a button press. Match and mismatch responses were each mapped to a response box on each hand, with the assignment counterbalanced across participants.

2.4. Procedure

In the behavioral session, participants first completed the LSBQ and FLEQ. The remaining tasks were assigned to two sets and administered in one of two pre-determined orders counterbalanced across participants within each language group. The sets consisted of English or French Digit Naming Task, Verbal or Nonverbal Task Switching, CCFIT or PPVT, English or French Picture Naming Task. The French Picture Matching task was always administered last.

The scanning session began with participants practicing the two switching tasks to familiarize themselves with the keypress and instructions. In the scanner, participants completed two verbal switching runs and two nonverbal switching runs. Each run consisted of two single judgment blocks of 24 trials each (using only either English or French in verbal task and only color or shape in the nonverbal task) and two mixed blocks with 48 trials in each (switching between English and French in verbal task and between color and shape in the nonverbal task). The first run presented the two pure blocks followed by two mixed blocks and the second run began with two mixed blocks followed by two pure blocks. In each mixed block, 48 trials were arranged in pseudorandom order to create 24 switch trials and 24 non-switch trials. In total, there were 96 non-switch trials in the pure block, 96 switch trials in the mixed block, and 96 non-switch trials in the mixed block across the two runs. Each run took approximately 7 min to complete. In addition to the functional scans, a six-minute high-resolution T1-weighted anatomical scan was performed for registration purposes. At the end of the session, participants received monetary compensation and were debriefed about the purpose of the study.

2.5. Data acquisition

Participants were scanned using a Siemens Trio 3 T scanner with a 32-channel head coil. Head movement was constrained with foam padding. Functional runs were acquired with an echo planar imaging sequence of 204 volumes for each run TR = 2 s, TE = 30 ms, flip angle = 70°, FOV = 19.2 cm^2, 64 × 64, 30 slices of 4-mm thickness. High-resolution, T1-weighted, anatomical scans were acquired with a magnetized-prepared rapid gradient echo sequence under the following parameters: TR = 1.9 s, TE = 2.52 ms, FOV = 25.6 cm^2, 256 × 256 matrix, 192 slices of 1-mm thickness.

2.6. Data preparation and analysis

Preprocessing of fMRI data was conducted using FSL (Jenkinson et al., 2012). We chose not to use slice-time correction as the benefits when using fast TRs are minimal (Sladky et al., 2011). Standard preprocessing steps were used, including: (1) six-parameter rigid body motion correction and affine registration of the functional image to

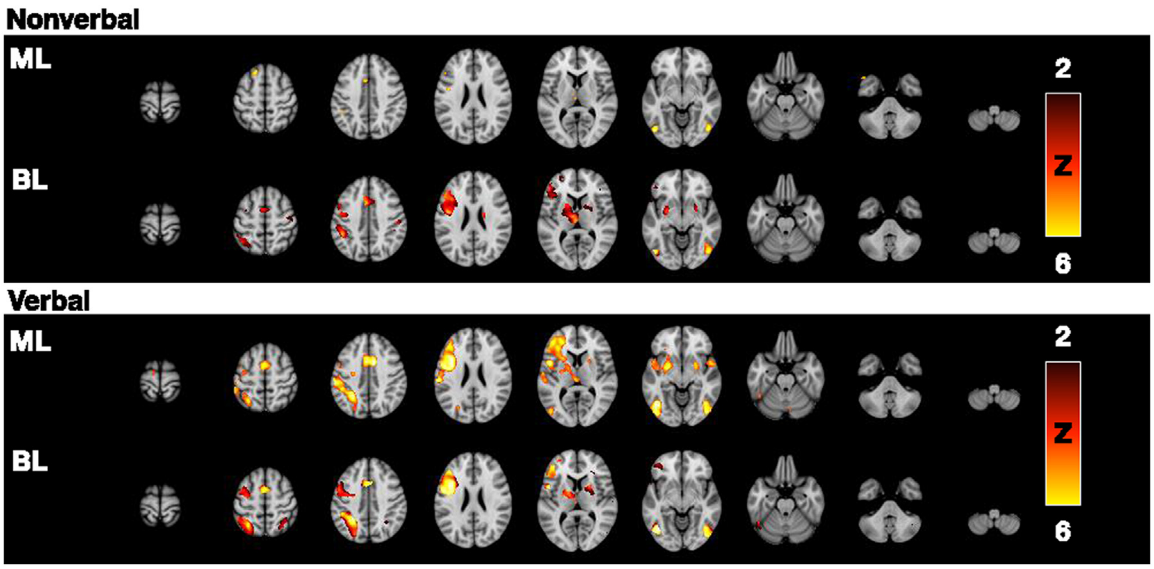

Fig. 2. Univariate contrasts for the verbal and nonverbal task from FEAT. Z-score images were thresholded using the false-discovery correction method with an α level of 0.001 to control for the number of comparisons. No higher-level contrasts survived. Monolingual means are indicated by panels with ML, bilingual means are indicated by panels with BL.

each individuals T1 scan, (2) spatial smoothing with an eight mm Gaussian kernel, (3) high-pass filtering to remove low frequency temporal drifts (> 100 s), (4) regression of white matter and cerebrospinal fluid-related time-series, using subject specific one voxel eroded tissue masks generated by segmentation of T1 scans using FAST (Zhang et al., 2001), an approach similar to ANATICOR (Jo et al., 2010), and (5) registration to the MNI-152 2 mm template, and (6) resampling to 4 × 4 × 4 mm (Jenkinson et al., 2012; Jo et al., 2010). An additional motion-scrubbing procedure (Anderson et al., 2014; Bellana et al., 2016; Campbell et al., 2013) was included at the end of the preprocessing pipeline to correct for the effects of motion that are known to persist despite standard preprocessing steps (for discussion, see Power et al., 2012). Using a conservative multivariate technique, time points that were outliers in both the six-parameter rigid-body motion estimates and the average fMRI BOLD signal were removed, and the BOLD signal was interpolated across adjacent data points. This process minimizes the effects of motion-induced spikes in the BOLD signal without leaving sharp discontinuities due to the removal of outlying volumes (for details, see Campbell et al., 2013).

Functional data were analyzed using two approaches. The first approach used FEAT to model the univariate task and group differences using a standard general linear model (GLM) approach. A gamma function was convolved with a box-car design to model activity for each trial type per participant. At the individual subject-level, our GLM included the three trial types: 1) pure, 2) non-switch, and 3) switch trials. Variables of no interest were not added to the model at this stage given the aggressive preprocessing had already been applied. Whole-brain maps were then calculated for task performance overall (i.e., averaging across all trial types), mix-cost (i.e., non-switch trials – pure trials) and switch-cost (i.e., switch trials – non-switch trials). This model was fit per subject for the verbal and non-verbal tasks separately, and two additional within-participant contrasts were calculated for 1) nonverbal > verbal trials and 2) verbal > nonverbal trials. Thus, at the group level we submitted participant-level z-maps to 3 (mean effect, mixing cost, switching costs) x 4 (verbal, nonverbal, verbal > nonverbal, nonverbal > verbal) x 4 (BL, ML, BL > ML, ML > BL) separate contrasts using FEAT's FLAME 1 model (FMRIB's Local Analysis of Mixed Effects). To control for the number of contrasts (48) the familywise alpha value was set to 0.05/48 = 0.001, and this value was used to correct the unthresholded z-statistic images post-hoc using the FDR algorithm in FSL.

Given the large number of contrasts, we also planned a multivariate analysis using Partial Least Squares (PLS), which affords greater power and can answer questions about *networks* of regions showing covarying activation across time rather than isolated activations. PLS can be used to identify patterns of activity across the entire brain and does not require a priori contrasts typical of univariate techniques (e.g., subtraction method), and thus provides a data-driven approach to characterizing patterns of brain activity associated with multiple task conditions. To accomplish this, PLS utilizes both the covariance between brain voxels and the experimental design across subjects to identify latent variables (LVs) that optimally describe the data in a single analytic step. Crucially, since the LVs are estimated in one step across all voxels, conditions, and subjects, there is no need to correct for multiple comparisons post-hoc. In this way, PLS is conceptually similar to a principal component analysis, though simultaneously rotating two matrices from which it derives LVs. Each LV contains a spatial activity pattern of voxels that shows the strongest relation to (i.e., are covariant with) a specific task contrast. Each brain voxel has a weight, also known as a salience that is proportional to the covariance of activity with the task contrast on each LV. The significance for each LV was determined by using a permutation test (McIntosh et al., 1996) with 500 permutations, affording a minimum *p*-value for each LV at $p < 0.002$. In addition to the permutation test, a second and independent step was to determine the reliability of the saliences for the brain voxels characterizing each pattern identified by the LVs. To do this, all saliences were submitted to a bootstrap estimation of the standard errors (SEs; Efron and Tibshirani, 1986) using 500 bootstraps.

LVs calculated using PLS are orthogonal to one another and may consist of dissociable positive and negative valences. The positive or negative assignment of valences are arbitrary but the difference in valence represents opposing patterns of brain activity associated with the task contrast of a particular LV (i.e., the positive regions seen in Figs. 2–4). The reliability of each voxel's association with either the positive or negative valence of an LV was determined by their bootstrap ratio (BSR), which is calculated by dividing the voxel's salience score by its standard error that has a positive or negative value. Thus, the positive or negative attributions do not correspond to "activation" or "deactivation" but reflect two distributions of voxels that covary with one another. BSR ratio thresholds were selected as half of the maximum BSR for the peak cluster. For the three significant LVs, peak voxels with a BSR exceeding ± 2.5 ($p \le .00124$) were considered reliable.

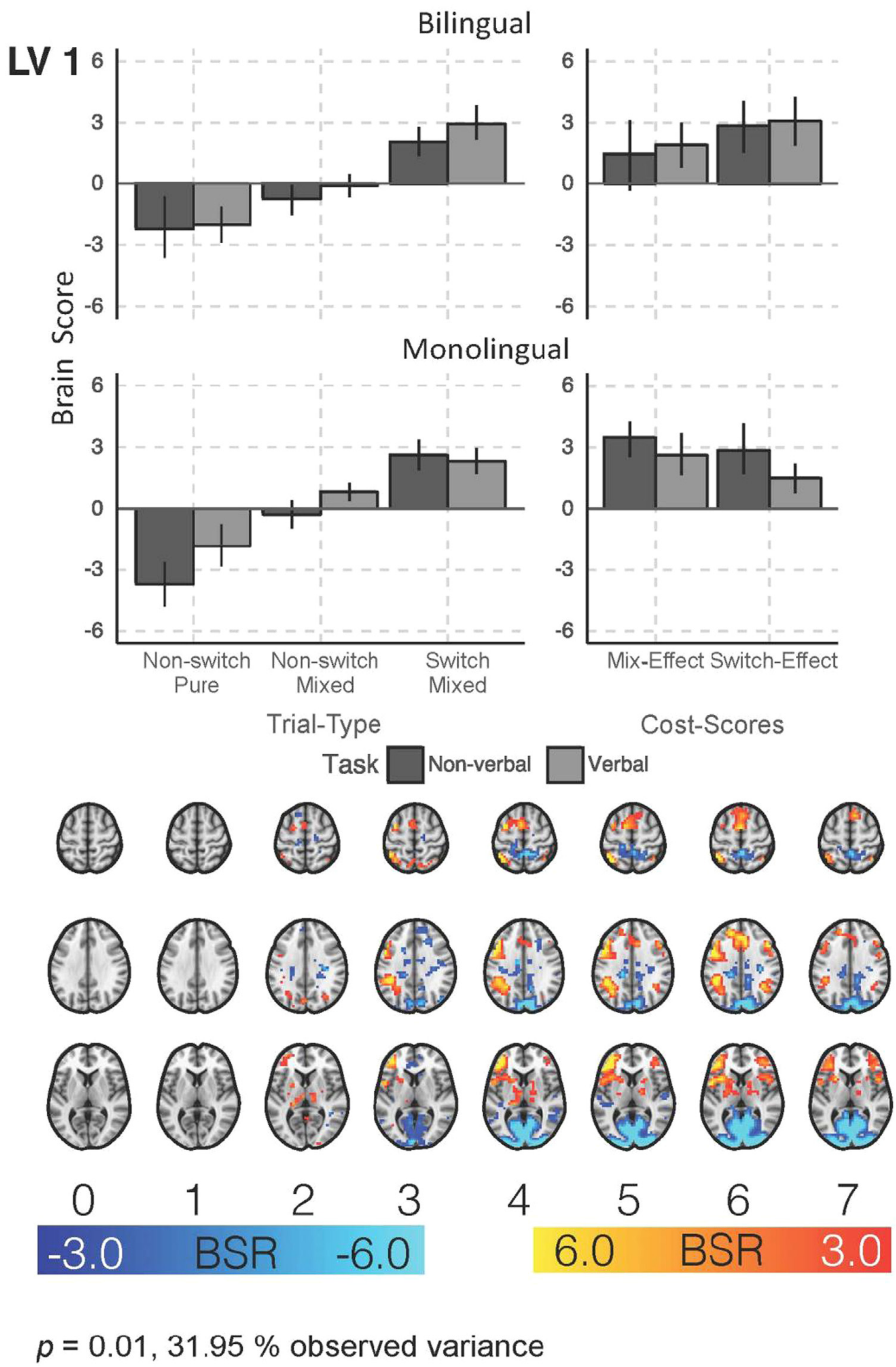

Fig. 3. Results from the task-PLS shown on a high resolution MNI152 axial image. The pattern identified by this LV (at bottom) shows areas that all participants activated relative to the non-switch pure trials (positive colors) or where there was more activity during the non-switch pure condition (negative colors). The bar graphs (at top) shows the mean-centered mean brain scores for each group on this LV (error bars represent the 95% confidence intervals). Positive brain scores during the tasks correspond to more activity in warm colored areas relative to overall mean activity (0 in the graph) and negative brain scores are associated with more activity during fixation (cool colors). A bootstrap ratio threshold of 3.0 was used to form the brain image.

Significant clusters were defined as having at least 10 contiguous voxels. Coordinates are reported in MNI space.

Two condition factors, trial type (non-switch trials from pure blocks, non-switch trials from mixed blocks, and switch trials from mixed blocks) and task (verbal, nonverbal) and one group factor (monolingual, bilingual) were included in the present mean-centered event-related PLS model, implemented in Matlab (Mathworks Inc). The degree to which each participant expressed each LV pattern was calculated by multiplying each voxel's salience by the BOLD signal in the voxel and summing over all brain voxels. The resulting summary measure, or brain score, was produced for each participant by trial-type, task, and language group. Bootstrapped means and confidence intervals (95%) for the brain scores by trial-type, task, and group, were calculated in R using 500 bootstraps (R Core Team, 2016).

Estimates of mixing costs and switch costs were derived post-hoc. This was possible because of the event-related design that allowed us to model switch and non-switch trials separately within the mixed block. Mixing costs were calculated by subtracting brain-scores of the non-switch trials in the pure block from brain-scores of the non-switch trials from the mixed block per subject. Switch costs were calculated by subtracting the non-switch trial brain-scores from the switch trial brain scores in the mixed block. We calculated bootstrapped means and 95%

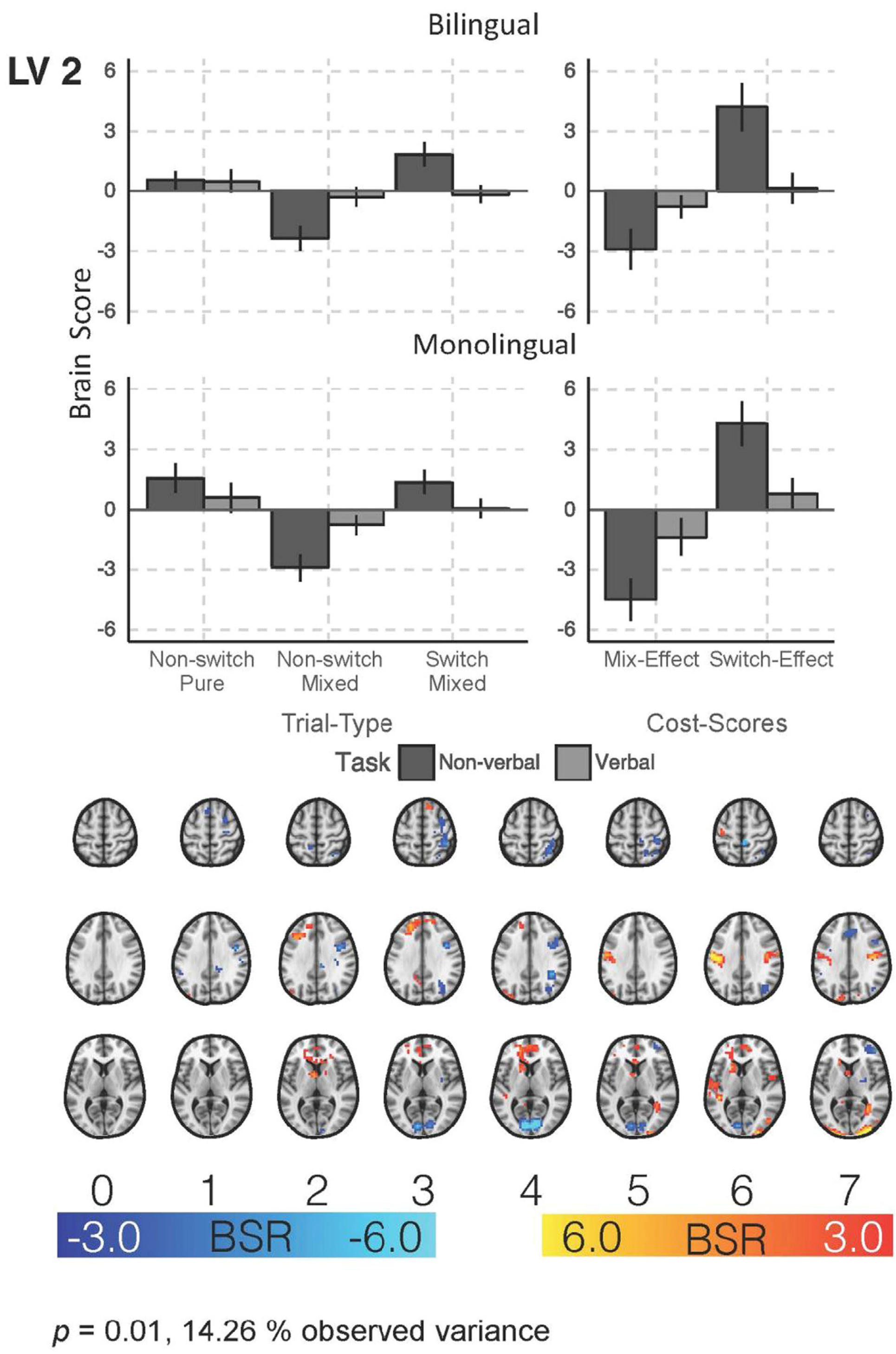

Fig. 4. Results from the task-PLS shown on a high resolution MNI152 axial image. The pattern identified by this LV (at bottom) shows areas that all participants activated for the contrast between the non-switch pure and switch mixed (warm colors) versus non-switch mixed conditions (cool colors). The bar graphs (at top) shows the mean-centered mean brain scores for each group on this LV (error bars represent the 95% confidence intervals). Positive brain scores during the tasks correspond to more activity in warm colored areas relative to overall mean activity (0 in the graph) and negative brain scores are associated with more activity in cool colored areas. A bootstrap ratio threshold of 3.0 was used to form the brain image.

confidence bands for these difference scores as described above. These cost scores reflect *relative differences* in the magnitude of the salience loadings across trials and tasks. An analogous procedure in a univariate design would be to perform a higher-level analysis to derive a contrast between conditions, each of which might have been modeled in a separate first-level analysis. Finally, to identify peak regions, we exported the thresholded PLS cluster-report MNI coordinates to Talairach Client (Talairach and Tournoux, 1988), coordinates were first transformed from MNI to Talairach using Ginger Ale (Eickhoff et al., 2009).

3. Results

3.1. Behavioral results

3.1.1. Background measures

Table 1 displays the mean scores from the background measures by language group. Monolinguals and bilinguals were equivalent on age, maternal education, CCFIT, and PPVT, all *ps* > 0.06. Groups were similar in accuracy for naming digits in English, $F < 1$, and French, $F(1, 27) = 2.33$, $p = .14$. As expected, bilinguals were more accurate than monolinguals in naming pictures in French, $F(1, 27) = 165.61$, $ps < 0.0001$, $\eta_p^2 = 0.86$, but similar in naming pictures in English, $F < 1$. In

Table 2
Mean reaction times (SD) and mean accuracy rates (SD) by Language group, block, and trial type in verbal and nonverbal switching task.

Task	Block	Trial type	Accuracy rates (%)		Reaction times (ms)	
			Monolingual	Bilingual	Monolingual	Bilingual
Nonverbal	Pure	Non-Switch Trials	98.4 (1.4)	98.1 (1.8)	573 (66)	623 (91)
	Mixed	Non-Switch Trials	95.7 (3.1)	95.7 (3.1)	812 (116)	865 (125)
		Switch Trials	96.3 (2.6)	93.5 (4.7)	815 (108)	878 (129)
		Switch Costs	0.7 (3.5)	− 2.2 (3.1)	3 (21)	13 (27)
		Mixing Costs	− 2.7 (2.7)	− 2.4 (2.0)	240 (77)	243 (61)
Verbal	Pure	Non-Switch Trials	98.1 (1.8)	97.3 (2.1)	704 (66)	776 (99)
	Mixed	Non-Switch Trials	96.7 (3.6)	95.0 (2.5)	797 (97)	905 (136)
		Switch Trials	95.6 (2.7)	93.4 (4.5)	807 (97)	923 (133)
		Switch Costs	− 1.1 (2.4)	− 1.6 (3.2)	10 (24)	18 (44)
		Mixing Costs	− 1.4 (3.1)	− 2.4 (2.0)	93 (49)	129 (71)

addition, bilinguals were more accurate than monolinguals in matching the French word to its corresponding picture, $F(1, 27) = 229.19$, $p < .0001$, $\eta_p^2 = .89$.

3.1.2. Task switching

Mean reaction times and accuracy rates from the switch tasks are reported in Table 2. Switch cost was analyzed by comparing the switch trials to the non-switch trials in the mixed block. A three-way ANOVA was performed on correct mean reaction times with task (verbal, nonverbal) and trial type (switch, non-switch) as the within-subject factors and language group (monolingual, bilingual) as the between-subjects factor. The main effect of trial type was significant, $F(1, 27) = 5.94$, $p = .02$, $\eta_p^2 = .18$, with non-switch trials producing faster response times than switch trials. There was also a main effect of language group, $F(1,27) = 4.32$, $p = .04$, $\eta_p^2 = .14$, in which monolinguals produced faster responses than bilinguals. There was no effect of task and no significant interactions, $ps > 0.10$. Similar analyses were performed for accuracy. A main effect of trial type was found, $F(1,27) = 5.30$, $p = .03$, $\eta_p^2 = .16$, in which non-switch trials were more accurate than switch trials. No other main effects or interactions reached significance, $ps > 0.09$.

Mixing cost was analyzed by comparing the non-switch trials in the mixed block to the trials in the pure block, all of which were non-switch. A three-way ANOVA was performed on correct mean reaction times with task (verbal, nonverbal) and block (pure, mixed) as the within-subjects factors and language group (monolingual, bilingual) as the between-subjects factor. The main effect of block was significant, $F(1, 27) = 340.07$, $p < .001$, $\eta_p^2 = .93$, such that responses to trials in the pure block were faster than were those to non-switch trials in the mixed block. There was also a main effect of task, $F(1, 27) = 35.21$, $p < .001$, $\eta_p^2 = .57$, with faster responses to the nonverbal task than to the verbal task. There was a significant main effect of language group, $F(1,27) = 4.38$, $p = .05$, $\eta_p^2 = .14$, indicating faster responses by monolinguals than bilinguals. The task by block interaction was significant, $F(1, 27) = 74.27$, $p < .001$, $\eta_p^2 = .73$; faster responses to the nonverbal task were found only in the pure block, $p < .001$, with no task difference in the mixed block, $p = .47$. No other main effects or interactions reached significance, all $ps > 0.148$. Similar analyses were performed for accuracy. There was a main effect of block, $F(1,27) = 37.21$, $p < .001$, $\eta_p^2 = .58$, in which responses to the pure block were more accurate than were those in the mixed block. No other main effects or interactions reached significance, $ps > 0.11$.

3.2. Univariate analysis

From the FEAT analysis of average effects, the main effects of verbal and nonverbal stimuli reached significance for each group separately (see Fig. 2). When presented with nonverbal material, both groups activated the fusiform gyrus bilaterally, the cingulate gyrus, the left inferior frontal gyrus, and the left superior parietal lobule. Bilinguals additionally recruited subcortical regions including bilateral putamen and left thalamus. Verbal stimuli activated a similar set of regions with generally more robust activation in both groups. In addition to the regions activated for the nonverbal task, activation was also observed in the left temporal lobe regions. Neither the direct comparisons between conditions (i.e. verbal > nonverbal) nor the differences between groups survived FDR thresholding. None of the contrasts in the cost-score analyses survived thresholding.

3.3. Task PLS

Task PLS was run to examine the patterns of brain activity that covaried with performance and language group. Three latent variables reached significance. The first LV, $p < .001$, explained 31.95% of the cross-block covariance and primarily reflected activation patterns associated with relative difficulty of the trial type. The second LV, $p < .001$, explained 14.26% of the cross-block covariance and primarily reflected differences in the nonverbal task domain in that it was most strongly associated with nonverbal stimuli, thereby distinguishing between the domains. The third LV, $p = .01$, explained 10.93% of the cross-block covariance and primarily reflected differences in activation patterns attributable to language group effects. The results for each LV are explained by first reporting the outcomes based on the three individual trial types (pure block, nonswitch, switch) and then the outcomes based on the derived cost scores (switch costs, mixing costs).

3.3.1. LV1: effect of trial type

The results for LV1 are shown in Fig. 3. Note that the spatial pattern for this LV overlaps with most of the regions described by the univariate contrasts, and that the interpretation is similar in that there is no difference between groups or conditions. The first latent variable can thus be thought of as roughly synonymous with a typical univariate set of results. The advantages of using PLS are that all conditions are modeled at once, and subsequent orthogonal latent variables can reveal group or condition differences to which univariate analyses may be insensitive. The pattern of brain scores for this LV indicated reliable differences in activation that varied with trial difficulty and were equivalent for both language groups. The non-switch trials in the pure block, the simplest trials, covaried most strongly with activation in the mid occipital gyrus, the cuneus, lingual gyri, and medial prefrontal gyrus, a set of regions that constitute part of the default-mode network (e.g., Raichle et al., 2001, see negative regions in Fig. 3). Brain regions covarying with the two trial types in the mixed block trials were largely representative of the frontoparietal network and included bilateral mid-frontal gyri, left insula, precentral gyrus, medial frontal gyrus, cerebellum, and bilateral inferior parietal lobule (see positive regions in Fig. 3). These regions are predominantly involved in "adaptive task control", including working memory, attention control, and task execution (Dosenbach et al., 2007; Vincent et al., 2008). Both groups increased recruitment of this network with task difficulty, with strongest recruitment for the switch trials in the mixed block, the most difficult trials. Mixing costs and switch costs both relied heavily on the frontoparietal regions. Based on the overlap of the 95% bootstrapped confidence intervals, there were no reliable cost-score differences between groups or across task-type.

3.3.2. LV2: effect of nonverbal task

The results for LV2 are shown in Fig. 4. This LV distinguished between domains in that it primarily captured the variance affiliated with the nonverbal task. Accordingly, the nonverbal task for both the non-switch pure trials and the switch-mixed trials loaded onto the positive brain regions, right insula, anterior cingulate, left caudate nucleus, and visual and motor cortices (red regions in Fig. 4). This contrasted with the non-switch trials in the mixed block, which loaded onto the negative regions, namely, dorsal anterior cingulate cortex, calcarine gyrus, right frontoparietal network, and cerebellum (blue regions in Fig. 4). The non-switch trials in the mixed block loaded orthogonally to the other trials across both groups, so this LV describes the unique variance associated with non-switch trials in the mixed block. Examining the cost-scores revealed that the mixing costs covaried most with the negative brain regions, while switch costs covaried most strongly with the positive set of regions. Thus, this LV also captures the difference in brain-network recruitment between the two types of cost-scores, and this was driven by the nonverbal task. As with LV1, these effects did not differ between groups. The patterns associated with the verbal task were not revealed in this LV.

3.3.3. LV3: effect of language group

The third LV (Fig. 5) revealed a difference between language groups. For the nonverbal task, bilinguals recruited cerebellum, bilateral occipital cortex, left precuneus, anterior cingulate cortex, right medial frontal gyrus, left insula and precentral gyrus, and right dorsolateral PFC (red regions in Fig. 5, see supplementary tables for clusters https://figshare.com/s/02172d217a18e7d0fb74) for the switch trials in the mixed block, and left inferior frontal gyrus, right lentiform nucleus, and left parahippocampus and culmen of the cerebellum, for the non-switch trials in the mixed block (blue regions in Fig. 5). Both the verbal and nonverbal tasks loaded in the same direction, with stronger loading from the nonverbal task (note that the 95% CI includes 0 for the verbal condition). That is, for bilinguals, the difference between verbal and nonverbal tasks was relative to brain score magnitude in the network, not differential spatial regions.

In contrast, monolinguals recruited one set of regions for the non-switch trials in the pure and mixed trial block in the nonverbal task, as well as the switch trials in the mixed block for the verbal task and a different set of regions for all the non-switch trials in the verbal task, and the switch trials in the non-verbal task. This pattern suggests that for monolinguals this LV captured the difference between the switch trials in the mixed block and the two non-switch trials. Importantly, task-type (verbal or non-verbal) was differentiated, indicating a difference of both degree and kind. Therefore, there is greater overlap in processing verbal and nonverbal content for bilinguals than for monolinguals.

The cost scores revealed that the relevant network for bilinguals included the right insula and putamen and covaried with mixing costs and the more distributed network of another set of regions with the switch costs for both tasks. However, for monolinguals, these relations depended on the task domain. In this case, one network covaried with mixing cost in the non-verbal task and switch cost in the verbal task, whereas a spatially distinctive network covaried with switch-cost for the nonverbal task. In sum, bilinguals recruited similar sets of brain regions for both verbal and non-verbal tasks, while monolinguals switched network recruitment depending on the task domain.

4. Discussion

The present study used comparable verbal and nonverbal tasks to examine possible differences in language and task-switching between functional English-speaking monolinguals and highly proficient English-French bilinguals. The designation of functional monolingual is novel and was initially determined by self-report; a battery of language tasks in both languages was included to assess the language proficiency of participants and validate assignment to the language groups. The results confirmed that the bilinguals were well balanced in their knowledge of both languages and that functional monolinguals had only basic knowledge of French. All other background measures indicated comparability between the groups.

The behavioral results showed the expected task effects in which non-switch trials were performed faster and more accurately than switch trials for both task domains. For the mixing costs, participants were slower to respond to the verbal task (this was driven by the single block with only verbal stimuli). Likely, this last effect results from participants having to convert a numeric stimulus into a written form in order to evaluate the cue onscreen, creating a demanding multi-step process. Surprisingly, monolinguals performed faster than bilinguals on these trials, a difference that did not interact with any other factors. Notably, the group differences were not tied directly to either switch-costs or mix-costs as has been shown in the literature, but rather revealed itself as overall faster responding by monolinguals. One possible explanation is that both tasks make substantial demands on verbal knowledge, a situation that generally favors monolinguals (Bialystok and Luk, 2012). Despite being functionally monolingual and not being able to switch between languages, our novel task successfully elicited a comparable switch-like performance for each group (accuracy being at ceiling).

The PLS analysis on the functional data revealed three LVs, each associated with one of the three primary factors in the design. The first LV reflected variance associated with differences between the three trial types. Together they formed a progression in which increasing difficulty was associated with greater activation of brain regions and these regions shifted from more posterior to anterior regions as trial type difficulty increased. Brain regions associated with the non-switch single task were the lingual gyrus and occipital cortex. Activation of these regions is consistent with participants attending to visual stimuli but not necessarily being cognitively taxed by them. Brain regions associated with the difficult switch trials are those involved in cognitive control and executive functions and could be characterized as the fronto-parietal network. The pattern for trial type activations was similar for both language groups.

The second LV reflected variance associated with task domain, particularly the nonverbal task. As with the first LV, the pattern for trial type activations did not differ by language group. There were two networks associated with the non-verbal task. The network depicted in hot colors, including Brodmann area 10, bilateral caudate, and bilateral insula, is consistent with part of the salience network – a set of regions involved with selecting and detecting stimuli that are relevant for the task (Uddin, 2016). The two trial types that were associated with this network were the non-switch-pure and the switch-mixed trials. The non-switch-pure trials were always presented first, so it possible that participants were concentrating harder on mastering the task and selecting the appropriate stimuli to respond to. During the more difficult mixed-block, the switch trials were those requiring more discernment and careful selection relative to those trials where the goal is to maintain the same strategy (i.e. non-switch-mixed trials). The other network, depicted in blue, involved the lingual gyrus, the dorsal anterior cingulate, the right parietal lobe and inferior frontal gyrus, a set of regions (with the exception of the lingual gyrus) resembling the right fronto-parietal network. The fronto-parietal network is crucial for shaping "goal directed cognition", and it flexibly couples with either the default mode network (involved in internally directed attention, mind wandering, and autobiographical memory), or the dorsal attention network (which governs externally focused attention to stimuli; Spreng et al., 2010). In the context of the non-switch mixed trials, the fronto-

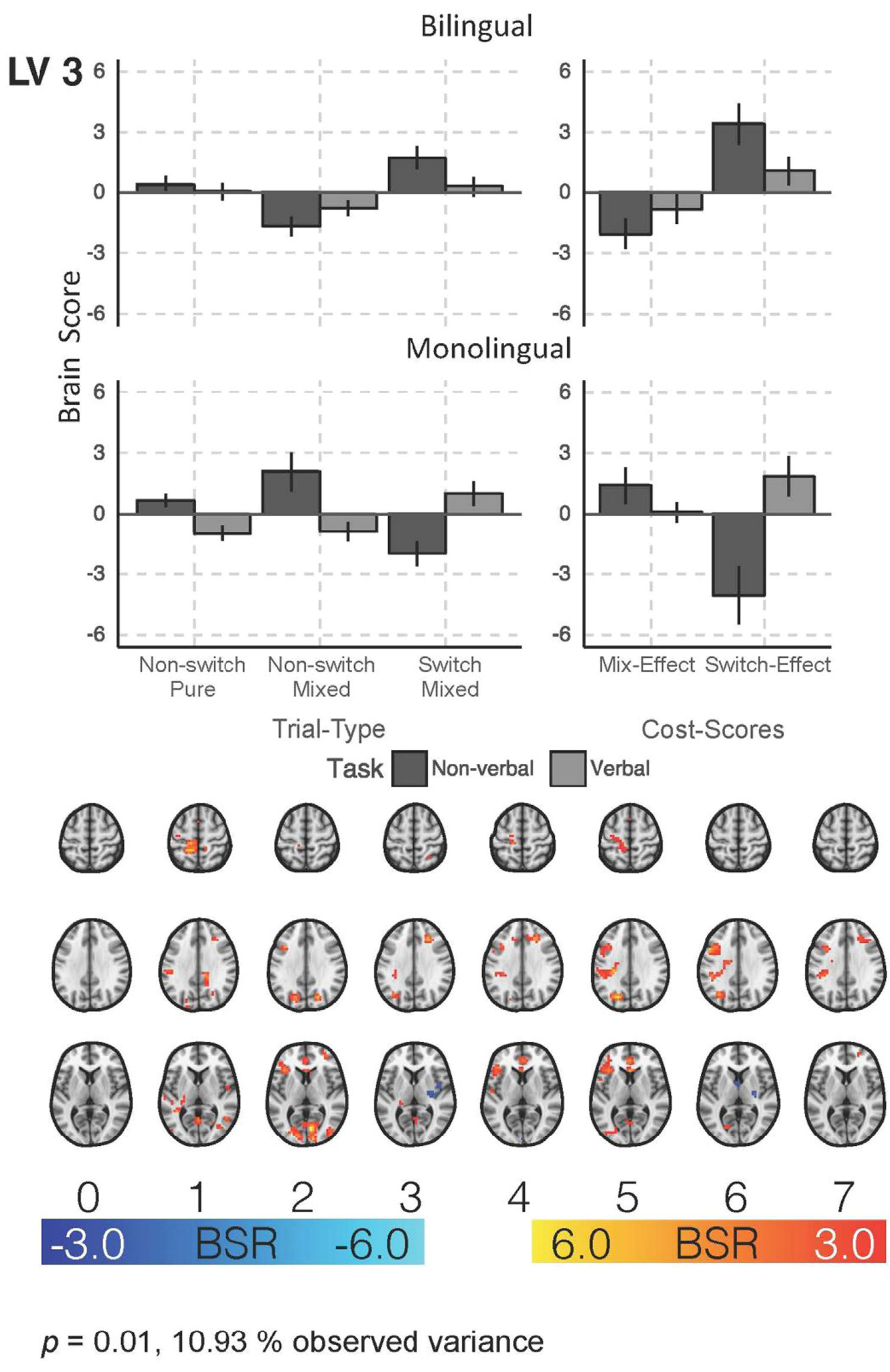

Fig. 5. Results from the third LV shown on a high resolution MNI152 axial image. The pattern identified by this LV in (a) shows areas with increased activity primarily during the switch-effect conditions for Bilinguals (warm colored regions) and mix-effect conditions (cool colors). Note that for bilinguals, verbal and nonverbal tasks load in the same direction. The pattern for monolinguals differs by both task (verbal/nonverbal) and trial (non-switch pure, non-switch mixed, switch mixed). Broadly, for monolinguals, non-switch nonverbal trials load onto the warm regions, while non-switch verbal trials load onto the cool regions. Monolingual verbal switch mixed trials load onto the positive regions, while the nonverbal switch mixed trials load onto negative regions. The bar graph (at top) shows the mean-centered mean brain scores for both groups on this LV (error bars represent the 95% confidence intervals). Group differences are indicated by a lack of overlap in the confidence intervals. A bootstrap ratio threshold of 3.0 was used to form the brain image.

parietal network's role would be to maintain attention to the task and prevent errors.

The third LV indicated differences between language groups. The key pattern was that for bilinguals, the two tasks were associated with similar brain regions for each of the three trial types, although they differed in the degree of activation, for monolinguals, the two tasks recruited different networks for each of the trial types.

These results will be discussed in terms of the two primary objectives for the study. The first objective was to establish the extent to which verbal and nonverbal switching reflect domain-general processes of selection and shifting. The results, particularly those from LV1, indicate a substantial common basis for these processes across domains (e.g., similarly graded recruitment of the frontoparietal network with increasing task-demand).

The second objective was to determine whether there were differences between language groups in how switching was performed for verbal and nonverbal domains, beyond what was common in these processes. The motivating assumption was that experience with language switching in bilinguals changes how switching is carried out, and that this change extends to switching in nonverbal domains. Such an effect would provide a possible clue to why other aspects of nonverbal processing, for example, executive functioning, is different for bilinguals.

The results of LV3 identified language-specific patterns for each group with the largest differences found for the nonverbal task. Broadly the two networks that were affiliated with LV3 can be divided into a distributed network of cortical (positive regions) and subcortical (negative regions). The primary foci of the positive network were the lingual gyrus and occipital regions, and the anterior cingulate and left inferior and right mid frontal gyri (see supplementary tables https://figshare.com/s/02172d217a18e7d0fb74 for a full set of regions). The negative network was more closely affiliated with subcortical regions including bilateral caudate nucleus, right thalamus, bilateral hippocampus and parahippocampus, and right lentiform nucleus/putamen. Bilinguals recruited the positive, cortical, network for both non-switch pure and switch mixed trials, and this effect was stronger for the nonverbal task; they recruited the negative, subcortical network for non-switch mixed trials. Subcortical regions including the caudate nucleus are often referenced for withholding motor responses and gating information to the frontal lobes, an interpretation which fits well with bilinguals "staying" on task in the non-switch-mixed trials (Haber, 2016). Consistent with the previous literature, bilinguals showed overlap between language control and cognitive control (Coderre et al., 2016; see Hervais-Adelman et al., 2011 for review). In contrast, monolinguals recruited the negative, subcortical, network for non-switch pure and non-switch mixed *verbal* trials, and non-verbal switch-mixed trials; they recruited the distributed cortical network for non-verbal non-switch pure, non-switch mixed and verbal switch mixed trials. This can be summarized as monolinguals recruiting the positive cortical network for the nonverbal mix-effect and verbal switch-effect, and the negative, subcortical regions for the nonverbal switch-effect. Thus, while bilinguals are able to recruit a consistent set of regions across tasks (verbal/nonverbal), network recruitment by monolinguals is dictated by the interaction of both task *and* trial type.

There is considerable commonality across tasks that can be attributed to the underlying processing involved in switching. These common processes are found for both groups. However, there were also clear differences in how monolinguals and bilinguals carried out these switching tasks. For monolinguals, as exemplified by LV3, each of the domains recruited distinct processes for each of the three trial types. For bilinguals, however, the additional processing resources for the two task domains were comparable, even though they varied in intensity. Thus, for bilinguals, there has been a harmonization of the processes responsible for task switching that generalizes across domains, presumably as a consequence of constant use of switching in ordinary language use. Ironically, this experience in switching in a linguistic context led to the largest changes in terms of discrepancies from monolinguals in a nonverbal context.

In summary, we showed that while bilinguals and monolinguals have similar brain responses to increasing task difficulty across trial types, and similarly distinguish between verbal and nonverbal task, the interaction of the two reveals unique network recruitment. Bilinguals recruit overlapping sets of regions for language and executive functions. In contrast, monolingual recruitment of these regions was sensitive to the task *and* trial type. Bilingual experience with switching in everyday life appears to have furnished them with a superior and more efficient mechanism that extends beyond language and into switching between tasks.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2018.06.023.

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