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Multifaceted multilingual experiences modulate neurocognitive mechanisms of task switching

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Research Article

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Abstract

This study explored the relationship between multifaceted multilingualism and cognitive shifting through a task-switching paradigm using fMRI. Multilingualism was modeled from both convergent (i.e., integrated multilingual index) and divergent (i.e., L2 proficiency, interpreting training, language entropy) perspectives. Participants identified letters or numbers based on task cues, with Repeat trials maintaining the same task and Switch trials requiring a different task. Switch cost (Switch–Repeat) was used to reflect shifting demands. Better task-switching performance was associated with a higher integrated multilingual index and interpreting training. Neuroimaging indicated that multilinguals predominantly engaged left-hemisphere regions for switching, with extensive multilingual experience requiring fewer neural resources for switch cost (i.e., more efficient processing for cognitive control). During task switching, brain connectivity was regulated locally by L2 proficiency, and globally by interpreting training. These findings underscore the importance of considering multifaceted multilingual experience to understand its impact on cognitive function and brain activity.

Highlights

1. Multilingual experience captured by convergent and divergent variables.
2. Interpreting training enhanced task-switching performance.
3. Higher multilingual index associated with enhanced performance and neural efficiency.
4. Multilinguals engaged left-lateralized brain regions for task switching.
5. L2 proficiency locally, interpreting training globally, regulated task connectivity.

1. Introduction

Multilinguals are individuals who speak at least two languages in daily life, including bilinguals, trilinguals, or professionals. A common practice for multilinguals is to switch among various languages in different contexts. With this practice, previous research has shown that multilinguals exhibit advantages over monolinguals in cognitive switching flexibility, which is an important aspect of cognitive control (Bialystok, 2017; Miyake et al., 2000). However, there are conflicting viewpoints regarding the cognitive benefits of multilingualism, which are often associated with the diverse language profiles of multilingual individuals. To start with, non-native language proficiency varies across individuals. Additionally, in some circumstances, multilinguals must keep their languages separate and use only one language. In other situations, they are required or choose to switch among different languages. It is not yet clear how various types of multilingual experience produce different effects on cognitive ability. Therefore, this study investigated the effects of multilingual diversity across several dimensions on task switching in multilinguals, gathering evidence from behavioral and multimodal neuroimaging domains.

Previous research has indicated that even when multilinguals are speaking only one of their languages, the other languages are still activated in parallel (e.g., Thierry & Wu, 2007; Wu & Thierry, 2013). Thus, multilinguals' language production involves a higher level of competition which is expected to be resolved via the inhibition of the nontarget language (Guo et al., 2011; Kroll & Stewart, 1994). Neural evidence has also shown that multilinguals and monolinguals display different underlying brain networks during language production tasks (e.g., Abutalebi & Green, 2007), with multilinguals involving cognitive control regions to a greater extent than monolinguals (Abutalebi & Green, 2007; Abutalebi & Green, 2008; Wong et al., 2016). Therefore, robust evidence has shown that multilinguals' experience of using different languages entails greater involvement in executive function than that of monolinguals.

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The persistent requirement for additional cognitive control resources may enhance multilinguals' executive function. Many studies have revealed that multilinguals (most focused on bilinguals) show benefits over monolinguals on a variety of executive function tasks measuring inhibition, conflict monitoring, or task switching (Bialystok, 2017; Bialystok & Craik, 2022; Bialystok et al., 2012). Neuroimaging studies have also consistently reported differences between bilinguals and monolinguals performing cognitive control tasks. These studies have indicated that bilinguals recruit neural resources differently than monolinguals on domain-general cognitive control tasks (Abutalebi et al., 2012; Bialystok et al., 2005; Cargnelutti et al., 2019; Garbin et al., 2010; Luk et al., 2011; Olulade et al., 2015; Pliatsikas et al., 2015; Stein et al., 2014; Zhang et al., 2020). While extensive research supports the cognitive benefits of multilingualism (mostly in bilinguals), it is important to recognize that the advantages multilinguals have on executive functions are not an absolute certainty. Some studies did not find any cognitive advantages linked to bilinguals (e.g., Dick et al., 2019; Paap & Greenberg, 2013), and it has been argued that the reported cognitive benefits are the result of publication bias (de Bruin et al., 2015). The mixed effects might be related to the fact that different studies have tested multilinguals with various language profiles.

The conventional approach categorizes multilingualism as a binary variable based only on the number of languages spoken. However, this approach is impractical, because there is substantial variation in both the quantitative and qualitative nature of multilingual experiences. This divergence includes ability-based variables (e.g., number of languages spoken, language proficiency), usage-based variables (e.g., language exposure, age of acquisition [AoA], language switching frequency and contexts), and integrated variables (e.g., interpreting training, language dominance). For example, from an ability-based perspective, higher second language (L2) proficiency has been shown to enhance executive function in bilinguals of various ages, including children (Tse & Altarriba, 2014), younger adults (Coderre et al., 2013), and older adults (Gallo et al., 2023), although results are not entirely consistent (Dong & Xie, 2014). Higher L2 proficiency is also associated with higher gray matter density in the left inferior parietal gyrus, a hub for attentional processes (Mechelli et al., 2004).

From a usage-based perspective, the adaptive control hypothesis (ACH, Green & Abutalebi, 2013) proposes that multilinguals engage in different interactional contexts reflecting everyday language use (e.g., single language, dual language, or dense code-switching). These contexts demand different aspects of cognitive functions. For instance, the single-language context requires goal maintenance and interference control, whereas the dual-language context additionally demands cue detection, response inhibition, task engagement, and disengagement. To further capture how languages are used in different contexts, researchers developed measurements such as "language entropy," reflecting the extent to which various languages are used diversely (Baum et al., 2021; Gullifer et al., 2018; Gullifer & Titone, 2020; Gullifer & Titone, 2021). Language entropy was developed based on the Shannon entropy, using the equation: $H= -\sum^{n}_{i=1}P_i log_2(P_i)$ (Shannon, 1948). In this equation, n represents the number of languages used in that context and P_i represents the proportion of the language$_i$ used within a context. Studies from the contextual perspective have shown that more extensive and mixed use of multiple languages (e.g., balanced exposure to both languages, more frequent switching between languages) is associated with greater cognitive control benefits, evidenced by behavioral studies (Barbu et al., 2018; Beatty-Martinez et al., 2020; Hartanto & Yang, 2016; Sabourin & Vinetre, 2018), pupil dilation studies (van den Berg et al., 2022), as well as neuroimaging studies (Gullifer et al., 2018).

In addition to regular cases, some individuals are proficient in speaking multiple languages professionally. For instance, interpreters not only need to regulate two languages in the ways that ordinary bilinguals do (e.g., Kroll et al., 2008), but they must also comprehend the source language, internally translate the source language into the target language, and finally, produce the target language (e.g., Bajo et al., 2000; Korenar et al., 2023a, 2023c; Padilla et al., 2005). In other words, interpreting, as an extreme form of multilingualism, is far more demanding in cognitive control. Previous studies have shown that professional interpreters established superior language processing and cognitive abilities compared to ordinary bilinguals (e.g., Christoffels et al., 2006; Dillinger, 1994; Dong & Xie, 2014; Liu et al., 2004; Morales et al., 2015; Yudes et al., 2011). Neural evidence also suggests that simultaneous interpreters may differ in both brain structure and function relative to regular bilinguals (Becker et al., 2016; Elmer et al., 2014, 2016; Hervais-Adelman et al., 2015; Korenar et al., 2023a, 2023c). Even student interpreters have shown better switching and updating abilities than regular bilinguals (Dong & Liu, 2016). This supports ACH, which posits that frequent practice of using multiple languages in both single- and dual-language contexts demands and develops the ability to engage and disengage tasks.

In summary, the degree of multilingualism should be defined on a multifaceted integrated continuous spectrum. At one end of this spectrum are functional monolinguals who are less proficient in and never need to use a second language; at the other end are super bilinguals, such as simultaneous interpreters, or even multilinguals who frequently speak three or more languages. Various divergent variables highlight different dimensions of multilingual profiles, but these variables can be interconnected. For instance, as higher entropy and professional interpreting training provide more varied opportunities to use the non-native language, they often lead to higher L2 proficiency (Gullifer et al., 2021). Additionally, interpreting training can increase entropy by encouraging interpreters to use a broader range of expressions and adapt to different contexts and speakers. With these underlying relationships, empirical studies have developed methods to calculate a convergent integrated multilingual index, providing a comprehensive reflection of an individual's overall multilingual profile (Anderson et al., 2018; Gallo et al., 2021; Li et al., 2020). Studies have reported behavioral and neural changes associated with integrated bilingual experience (DeLuca, Rothman, Bialystok, et al., 2019; Gallo et al., 2021; Korenar et al., 2023b). These empirical findings have been incorporated into recent theories regarding multilingualism and neural mechanisms. Specifically, the Bilingual Anterior-to-Posterior and Subcortical Shift model (BAPSS, Grundy et al., 2017) posits that increasing bilingual experience leads to more efficient language control and executive functioning, resulting in a shift of neural activation from frontal to posterior cortical and subcortical regions. Furthermore, the Dynamic Restructuring Model (DRM, Pliatsikas, 2020) describes neurostructural changes with increasing bilingual experience, indicating a steady volumetric increase in most subcortical structures involved in language control, except the caudate nucleus. Finally, the Unifying the Bilingual Experience Trajectories (UBET, DeLuca et al., 2020) model integrates different theories on bilingualism-induced neural plasticity, mapping the relationships among various aspects of multilingual experience and neurocognitive adaptations.

In addition to the multifaced multilingual experience, executive function involves several distinct functions such as mental set

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shifting (i.e., switching), information updating and monitoring, and inhibition of prepotent responses (Miyake et al., 2000). These different components are correlated but separable. Among multilingual practices, one frequently observed experience is switching back and forth among languages based on a contextual cue. Language-specific and domain-general shifting both require multiple sub-processes, such as interference control, retrieving new task sets, and task-set reconfiguration (Monsell, 2003). Therefore, frequently engaging in this process is assumed to enhance individuals' domain-general cognitive flexibility, allowing them to shift among different tasks. This enhancement can be measured using a task-switching paradigm.

Cued task switching has been used to measure cognitive control, particularly the ability to update and activate task representations in real time to direct attention and actions for upcoming targets (Braver et al., 2021). The task involves alternating between two or more tasks in a random order, where targets are typically ambiguous and must be disambiguated based on the cue presented before the target. An important aspect of this paradigm is the switch cost, which indicates a cognitive cost when the task to be performed for the current trial is different from the task in the previous trial, reflecting the demands in task engagement and disengagement. Previous research has commonly associated the cognitive demands in task switching with the bilateral prefrontal cortex, primarily the right dorsolateral portions (Braver et al., 2021; Friedman & Robbins, 2022; Hampshire & Owen, 2006; Hyafil et al., 2009; Jamadar et al., 2015; Sohn et al., 2000).

Given the similarities between domain-general task switching and domain-specific language switching, task switching has frequently been used to investigate the effects of multilingual practice on general mental shifting ability (De Baene et al., 2015; Garbin et al., 2010; Hartanto & Yang, 2016; Prior & Macwhinney, 2010; Soveri et al., 2011; Weissberger et al., 2015; Yang et al., 2016a, 2016b). Most of these studies have reported that bilinguals showed enhanced cognitive flexibility and better switching performance with more efficient neural processing than monolinguals. However, some studies failed to report a bilingual advantage in task switching (Paap et al., 2017). As mentioned earlier, multilingual experience is multifaceted, and it is important to acknowledge the specific language experience in a multilingual population (Yang et al., 2016a, 2016b). For example, bilinguals immersed in a dual-language context showed a smaller switch cost compared to those in a single-language context (Hartanto & Yang, 2016). Some studies have also investigated the effects of interpreting experience on task switching (Babcock et al., 2017; Babcock & Vallesi, 2017; Zhao & Dong, 2020). For instance, interpreters have been found to exhibit comparable switch costs but smaller mixed costs (i.e., sustained control in maintaining two task sets) compared to regular multilinguals (Babcock & Vallesi, 2017). Despite these findings, behavioral studies on this topic are limited, and research into the neural mechanisms underlying these effects is even scarcer, leaving much of the neural basis of these phenomena elusive. Specifically, it remains uncertain how multilingual experience might modulate neural allocation during task switching.

To summarize, when investigating the cognitive and neural consequences of multilingualism, only a few studies have focused on specific language experiences and explored how the diversity in multilingual profiles can influence the behavioral and neural bases of cognitive function. Therefore, focusing on cognitive shifting in this study, we examined the relationship between a multifaceted multilingual profile and domain-general task switching. The multilingual profile was captured with an overall convergent multilingual index (modified from the dominance score from the Language History Questionnaire, Li et al., 2020; see method section for details), as well as several divergent dimensions separately, including L2 proficiency reflecting ability, language entropy reflecting usage, and interpreting training reflecting both ability and usage. Additionally, multimodal neuroimaging data were analyzed, not only focusing on fMRI functional activation but also investigating functional connectivity. For the analysis of functional activation during task switching, a conventional whole-brain approach was used. We examined the patterns of functional activation while participants performed task switching. A seed-to-voxel approach was utilized to explore the task and resting state functional connectivity. Specifically, the bilateral lateral prefrontal cortex (LPFC) was used as the seed region since previous research has highlighted its critical role in task switching (Dove et al., 2000; Miller, 2000; Monsell, 2003). ROIs were defined in CONN based on the Independent Component Analysis of the data from the Human Connectome Project (Nieto-Castanon & Whitfield-Gabrieli, 2022). A network approach analysis on connectivity was also presented in Supplementary Materials. According to the existing literature, we predicted that more extensive multilingual experience including higher ability and more usage (reflected by higher proficiency, higher entropy, or interpreting training) would be associated with enhanced task-switching performance and more efficient neural processing. Additionally, multilingual experience might modulate the neural organization of the brain during task switching, as well as the resting state.

2. Methods

2.1. Participants

Forty-two participants took part in this experiment (31 female, mean age = 23.5 years, SD = 2.4 years, range = 21–32 years). They were all multilinguals with diverse language experience (i.e., multilinguals speaking at least two languages, including Cantonese, Mandarin, English, Portuguese, or others). Furthermore, half of the participants in this study were regular multilinguals who used languages nonprofessionally, whereas the other half were students who majored in interpreting and actively immersed in interpreting training courses. The self-assessed proficiency levels for each language across all participants were rated on a scale of 0–1, with the following scores: L1 (N = 42, mean = .85, SD = .13), L2 (N = 42, mean = .70, SD = .15), L3 (N = 29, mean = .62, SD = .10), and L4 (N = 8, mean = .42, SD = .15). More information regarding multilinguals' language profiles can be found in Table 1. All participants were right-handed with normal or corrected-to-normal vision and no one reported neurological or other mental health conditions. All experimental procedures were approved by the Research Ethics Committee at the University of Macau.

2.2. Procedure

Before coming to the lab, participants completed the Online Language History Questionnaire (LHQ3) measuring their language background including AoA, language proficiency, language use contexts, language immersion, and so forth (Version 3.0, Li et al., 2020).

During fMRI sessions, participants first practiced the domain-general task-switching task in an MRI simulator, before completing the formal task in the MRI scanner. This task measures the speed and accuracy where individuals switch back and forth

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Table 1. Language profile of participants in this study

	Interpreting Training	No Interpreting Training	Group Difference (*p* level)
Sample size (*N*)	21	21	
Number of languages spoken	3.10 (.70)	2.67 (.66)	*
L1 proficiency (0–1)	.87 (.12), *N* = 21	.83 (.14), *N* = 21	
L2 proficiency (0–1)	.73 (.15), *N* = 21	.67 (.14), *N* = 21	
L3 proficiency (0–1)	.65 (.12), *N* = 17	.59 (.05), *N* = 12	
L4 proficiency (0–1)	.39 (.17), *N* = 6	.50 (.10), *N* = 2	
L1 age of acquisition (years)	.43 (.93)	.33 (.91)	
L2 age of acquisition (years)	5.76 (4.39)	7.90 (2.86)	
L3 age of acquisition (years)	11.40 (6.57)	15.20 (4.62)	
L4 age of acquisition (years)	20 (2.68)	14 (5.66)	
Mean entropy	.84 (.31)	.59 (.36)	*

*$p < .05$. When not marked, $p > .05$.

between two tasks (Kiesel et al., 2010). The current version was adjusted from the dual mechanisms of cognitive Control project (DMCC, Braver et al., 2020). In each trial, participants saw a number-letter pair, following a cue to indicate whether they should respond to the letter or the number (see Figure 1 for demonstration). Participants needed to judge whether the number was odd (right button) or even (left button), or to judge whether the letter was a consonant (right button) or vowel (left button). Each participant completed a total of 54 trials presented in a randomized order. These included 3 filler trials and two critical types of trials: (1) Switch trial, where the cue in the current trial was different from the previous trial (21–36 trials); (2) Repeat trial, where cue in the current trial was the same as the previous trial (30–15 trials). The task was divided into three blocks, each separated by a 28 s fixation period, with the first trial in each block being a filler trial. The switching cost was defined as the performance difference (reaction time [RT] and accuracy [ACC]) between switch trials and repeat trials.

2.3. Image Acquisition

Structural and functional images were acquired using a Siemens MAGNETOM Prisma 3 T MRI scanner and a 32-channel head coil. Sagittal T1-weighted localizer images were collected and used to define a volume for data collection, higher-order shimming, and alignment to the anterior commissure and posterior commissure (AC–PC). Blood-oxygen level dependent (BOLD) resting state and task-based functional images were sequentially collected using an echo-planar imaging sequence (TR = 1200 ms; TE = 33 ms; flip angle = 63°; echo spacing = .58 ms; acceleration factor = 4; field of view (FOV) = 216 mm^2; voxel size = 2.4 × 2.4 × 3.4 mm; matrix size = 90 × 90 voxels; 60 contiguous axial slices, parallel to the AC–PC, interleaved ascending acquisition; 500 volumes for the resting state scan and 650 volumes for the task scan, respectively). Eight dummy volumes were acquired and discarded at the beginning of each functional run to reach steady state equilibrium.

T1-weighted anatomical images were collected using a Magnetization-Prepared 2 Rapid Acquisition Gradient Echo (MP2RAGE) sequence (TR = 2,300 ms; TE = 2.26 ms; TI = 900 ms; flip angle = 8°; echo spacing = 6.8 ms; acceleration factor = 3; FOV = 256 × 256 mm^2; voxel size = 1× 1× 1 mm; 256 contiguous axial slices). A field map sequence was also collected using a double-echo spoiled gradient echo sequence (TR = 446 ms; TE = 4.92 ms; flip angle = 63°; FOV = 216 mm^2; voxel size = 2.4 × 2.4 × 2.4 mm; 60 contiguous

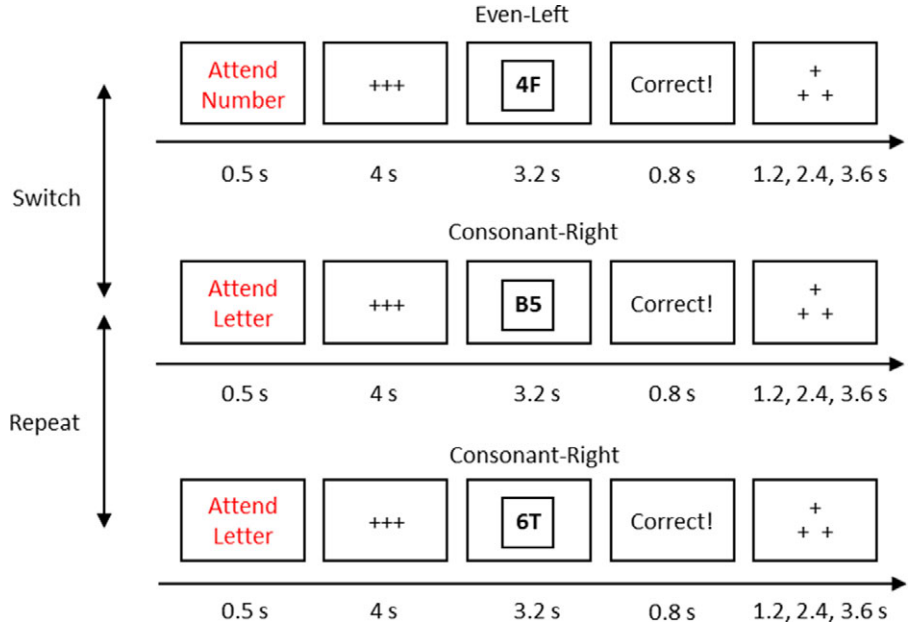


Figure 1. Task Switching Demonstration. Each row is a cued (in red) number-letter pair trial (attended stimulus and corresponding response are indicated on top, e.g., Even-Left). The second row represents a switch trial where the cue (attend letter) is different from the previous trial (attend number), while the third row represents a repeat trial where the cue (attend letter) is the same as the previous trial (attend letter).

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axial slices; phase encoding = anterior to posterior, fat saturation = off) that generated 2 magnitude images and 1 phase image.

2.4. Behavioral Data Analyses

In the LHQ, participants were asked to rate their proficiency in each language. Not all participants had an L3 or L4, but they all reported speaking L1 and L2. Compared to L1 (range from .57 to 1, SD = .12), L2 proficiency received a larger variation (range from .43 to 1, SD = .15); therefore, we consider L2 proficiency better reflecting non-native language proficiency across the current sample. The interpreting training experience was monitored as another language experience factor, with half of the participants had interpreting training experience while the other half did not. Furthermore, to measure language usage, we used self-rated scores from a few questions in the LHQ. These questions asked participants' language use in 17 different communicative contexts either via the time spent in each language (watching TV, listening to the radio, reading for fun, reading for school/work, using social media and internet, and writing for school/work; speaking with family members, speaking with friends, speaking to classmates, and speaking to other people), or the frequency to use each language on a 7-point scale (thinking, talking to self, expressing emotion, dreaming, arithmetic, remembering numbers, and praying). The diversity of language use was purely reflected by a measurement named language entropy, using the equation: $H = -\sum_{i=1}^{n} P_i log_2(P_i)$ (Shannon, 1948), where n represents the number of languages used and P_i represents the proportion of the language$_i$ used within a context. The calculation was conducted using the *languageEntropy* package (Gullifer et al., 2018) in the R environment (RStudio Team, 2022). For each participant, language entropy was first calculated for each context, and then the mean entropy was calculated by averaging across all contexts. A lower entropy value indicates compartmentalized use of each language, whereas a higher entropy value represents a more balanced and mixed use of multiple languages, independent from language proficiency.

In addition to the divergent dimensions mentioned above, a convergent integrated multilingual index was calculated to capture individuals' overall multilingual profile. Initially, a dominance score was computed using the LHQ3 online calculator (Gullifer & Titone, 2019; Li et al., 2020). For the *i*th language reported by a participant, LHQ3 calculates an aggregated dominance score (Dominance$_i$) based on self-reported proficiency and frequency of usage across various language contexts. Subsequently, LHQ3 determines a Proportion of Dominance for each language, and the participant's dominance level is determined by the Shannon Entropy of these proportions. To derive the overall multilingual index for the current sample, interpreting experience was numerically coded. For participants with interpreting experience, a specific value ([max Dominance − min Dominance]/2) was added to their dominance score. No additional value was added for participants without interpreting experience. This method integrates both the Dominance score and interpreting experience into a single comprehensive convergent index (i.e., multilingual index) for the study.

Task-switching performance was evaluated by analyzing both RT and ACC separately using mixed-effect modeling. In addition, the Inverse Efficiency Score (IES, RT/ACC) incorporates both RT and ACC and has been shown sensitive to speed-accuracy tradeoffs (Liesefeld & Janczyk, 2019; Townsend & Ashby, 1983; Vandierendonck, 2017). Therefore, as a supplementary analysis, IES was also calculated and reported in the Supplementary Materials. Participants' RTs were trimmed before further analysis. Any RTs for incorrect responses, and RTs longer or shorter than 2.5 standard deviations from the individual's overall mean or less than 250 ms were excluded (5.51% of trials were excluded across all participants). After trimming, accuracy and RTs were analyzed based on trial-level data employing the *glmer* and *lmer* function respectively in the *lme4* package (Bates et al., 2014) in the R environment (Venables & Smith, 2006). The *p* values for regression coefficients were obtained using the *lmerTest* package (Kuznetsova et al., 2017). For accuracy and RT, two sets of regressions were conducted. The first set of analyses focused on convergent language experience by including the task condition (Switch vs. Repeat), the integrated multilingual index (coded continuously), and their interaction as predictors. The second set of analyses focused on the divergent language experience by including the task condition, all three language factors (L2 proficiency, language entropy, and interpreting training), and their interactions with the task condition as separate predictors. The L2 proficiency and Language entropy were modeled as continuous variables, while Interpreting training was modeled as a categorical variable (*Yes* coded as .5 vs. *No* coded as −.5). Full models including the maximal random-effects structure were used as recommended by Barr et al. (2013). A caveat is that when initially running the ACC model with separate language factors, the full model failed to converge, leading to the removal of the participant-level random intercept from the analysis. Marginal and conditional R-squared were calculated using the *MuMIn* package to assess effect sizes (Barton & Barton, 2015). However, interpreting these effect sizes in mixed-effects regressions should be done cautiously due to the complexities introduced by random effects.

2.5. MRI Data Analyses

Anatomical and functional images were visually inspected for artifacts and signal drop-out. The functional images during task switching were then analyzed using FSL (Version 6.0.5), with FEAT (fMRI Expert Analysis Tool) version 6.0 (Smith et al., 2004; Woolrich et al., 2004), to carry out preprocessing and statistical analyses. Non-brain tissue of the anatomical images was removed using the skull-stripping tool in FreeSurfer (Fischl, 2012; Ségonne et al., 2004). The data preprocessing pipeline involved various steps to enhance the quality of the functional brain images. These steps included motion correction (FSL MCFLIRT), B0 unwarping with field mapping correction, slice timing correction, spatial smoothing (FWHM = 5 mm), high-pass filtering, coregistration (first to the brain-extracted structural image, then to the MNI space), and normalization. A double-gamma hemodynamic response function was used to model the BOLD signal for each event, and only correct trials were included in the analyses. First-level analyses were performed on individual runs, and motion parameters were incorporated as confound explanatory variables. Finally, analyses from previous steps were combined across participants in group-level analyses using FMRIB's local analysis of mixed effects (FLAME 1 + 2, Beckmann et al., 2003; Woolrich et al., 2004). Specifically, we identified regions that were responsive to basic trial types (i.e., Switch condition, Repeat condition, and Switch vs. Repeat masked with Switch condition), and then we compared the modulation effects on different trial types from the integrated multilingual index, along with various language factors separately (i.e., L2 proficiency, language entropy, and interpreting training). Similar to the behavioral analyses, interpreting training was modeled

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categorically, whereas other factors were modeled parametrically. All significant activations were determined using a two-step process. First, *Z* (Gaussianised T/F) statistical images were initially thresholded at the voxel level ($p < .01$). Second, clusters of identified voxels were corrected for multiple comparisons ($p < .05$, corrected) based on Gaussian random field theory (Worsley, 2001) in which each cluster's estimated significance level was compared with the cluster probability threshold, and then only clusters whose estimated significance exceeded the threshold were included in the results (Hayasaka & Nichols, 2003). Clusters with less than 10 voxels were further excluded. All reported comparisons among individuals were masked with regions that showed positive activation at the group level to ensure the reported results are practically meaningful.

Functional connectivity during the task switching and resting state scans were analyzed using the CONN functional connectivity toolbox version 22a in MATLAB (Whitfield-Gabrieli & Nieto-Castanon, 2012). Data preprocessing steps involved various procedures to ensure the quality of the functional and anatomical brain images. First, functional realignment and unwarping were performed to estimate and correct for any head motion during scanning. Distortion correction was applied using a voxel-displacement map based on the field map. Additionally, a slice-timing correction was employed to account for the maturation of the BOLD signal over time (Huettel et al., 2004). To identify and address functional outliers, an Artifact Detection Tools-based identification method was utilized (Whitfield-Gabrieli et al., 2009). Outliers were defined using a conservative threshold (i.e., 97th percentile) and subsequently removed from the dataset. Both the anatomical and functional images were then normalized to the standard Montreal Neurological Institute (MNI) space. The anatomical images underwent segmentation into gray matter, white matter, and cerebral spinal fluid (CSF) tissue classes using the SPM12 unified segmentation and normalization procedure. These tissue masks were subsequently applied to the functional images (Ashburner & Friston, 2005). During registration, the functional images were aligned to the anatomical images, and both were normalized to the standard MNI space. To enhance the signal-to-noise ratio and reduce spurious activations of single voxels, a smoothing kernel of 6 mm was applied.

After processing, further denoising pipelines were applied to the data. Specifically, representative noise signals from white matter (5 components) and CSF (5 components) were extracted. Any signal correlated with these noise components was removed from the BOLD signal using the CompCor approach (Chai et al., 2012; Liu et al., 2017; Liu et al., 2021). Data were filtered to eliminate frequencies of less interest, with a band-pass filter of .008–.09 for resting-state scan (Davey et al., 2013; Gohel & Biswal, 2015; Hallquist et al., 2013), and a high-pass filter at .008 for task switching scan (Gonzalez-Castillo & Bandettini, 2018).

Quality assurance parameters were considered during data analysis, including the number of outlier and non-outlier volumes, maximum and mean motion, and maximum and mean global BOLD signal changes. For resting-state scan, the average number of invalid scans was 2.7 out of 500 volumes (.5%, SD = 5.3), and the mean amount of motion was .11 mm (SD = .04 mm). For the task-based scan, the average number of invalid scans was 4.4 out of 650 volumes (.7%, SD = 12.1), and the mean amount of motion was .12 mm (SD = .04 mm). The aforementioned quality control parameters, along with the confounding effects from task conditions were addressed in a single linear regression step, where the effects were controlled for by removing their associated variance. The resulting residualized BOLD signal was then used for further statistical analyses.

For the resting-state data, seed-to-voxel functional analysis was conducted using bivariate correlations without weighting, using two seeds from the CONN toolbox: the left (MNI coordinates, −43, 33, 28) and right (MNI coordinates, 41, 38, 30) lateral prefrontal cortex (LPFC) from the frontoparietal network (Figures 4 and 5), well representing the dorsal LPFC. The connectivity of each seed was presented separately. Negative connectives were not included in further analysis due to uncertainty regarding the meaning of negative correlations (Hallquist & Hillary, 2018). After obtaining basic seed-to-voxel connectivity, the effects of different language factors on these connectivities were examined. For task switch functional connectivity, the same ROIs were used and the generalized psychophysiological interactions (gPPI) approach was utilized to investigate whether the seed-to-voxel connectivity would be modulated by different task conditions and language-related factors (McLaren et al., 2012).

3. Results

3.1. Behavioral Results

To explore the effect of convergent multilingual experience on performance, mixed-effect logistic regressions were conducted on trial level accuracy, which focused on the effects of task condition (Switch vs. Repeat) and the integrated multilingual index (Theoretical, R^2 Marginal = .01, R^2 Conditional = .17; Delta, R^2 Marginal = .001, R^2 Conditional = .02; Figure 2A). Results showed that the accuracy in the Switch condition (M = .96, SD = .19) was not different from the Repeat condition (M = .96, SD = .18; β = −.11, SE = .33, $z = -.33$, $p = .74$). There was no significant main effect of multilingual index or its interaction with task condition either ($ps > .1$).

In addition, to explore the effects of divergent multilingual experiences on behavioral performance, mixed-effect logistic regressions were conducted on trial-level accuracy to explore the effect of task condition (Switch vs. Repeat) and separate language factors including L2 proficiency, language entropy, and interpreting training (Theoretical, R^2 Marginal = .04, R^2 Conditional = .04; Delta, R^2 Marginal = .005, R^2 Conditional = .005). The main effect of task condition was not significant, as previously reported (β = .07, SE = .24, $z = .30$, $p = .76$). There was a significant effect of Interpreting training, such that participants with interpreting training (M = .97, SD = .16) showed significantly higher accuracy than others with no training (M = .95, SD = .21; β = .53, SE = .26, $z = 2.06$, $p = .04$; Figure 2C). Other main effects of language factors or the interactions between language factors and task conditions were not significant ($ps > .1$, Figure 2, top panel).

In addition to accuracy, participants' processing speed on task switching was also analyzed (Figure 2, bottom panel). A linear mixed-effect model was conducted on reaction times including the main effects of the task condition and integrated multilingual index, and their interaction (R^2 Marginal = .04, R^2 Conditional = .39). The main effect of the task condition on RT was significant such that Repeat trials (M = 1,050 ms, SD = 387 ms) were responded faster than Switch trials (M = 1,114 ms, SD = 392 ms; β = 67.33, SE = 14.73, $t = 4.57$, $p < .001$). Additionally, the main effect of multilingual index was significant (β = −77.78, SE = 36.41, $t = -2.14$, $p = .04$; Figure 2E). Specifically, higher multilingual index

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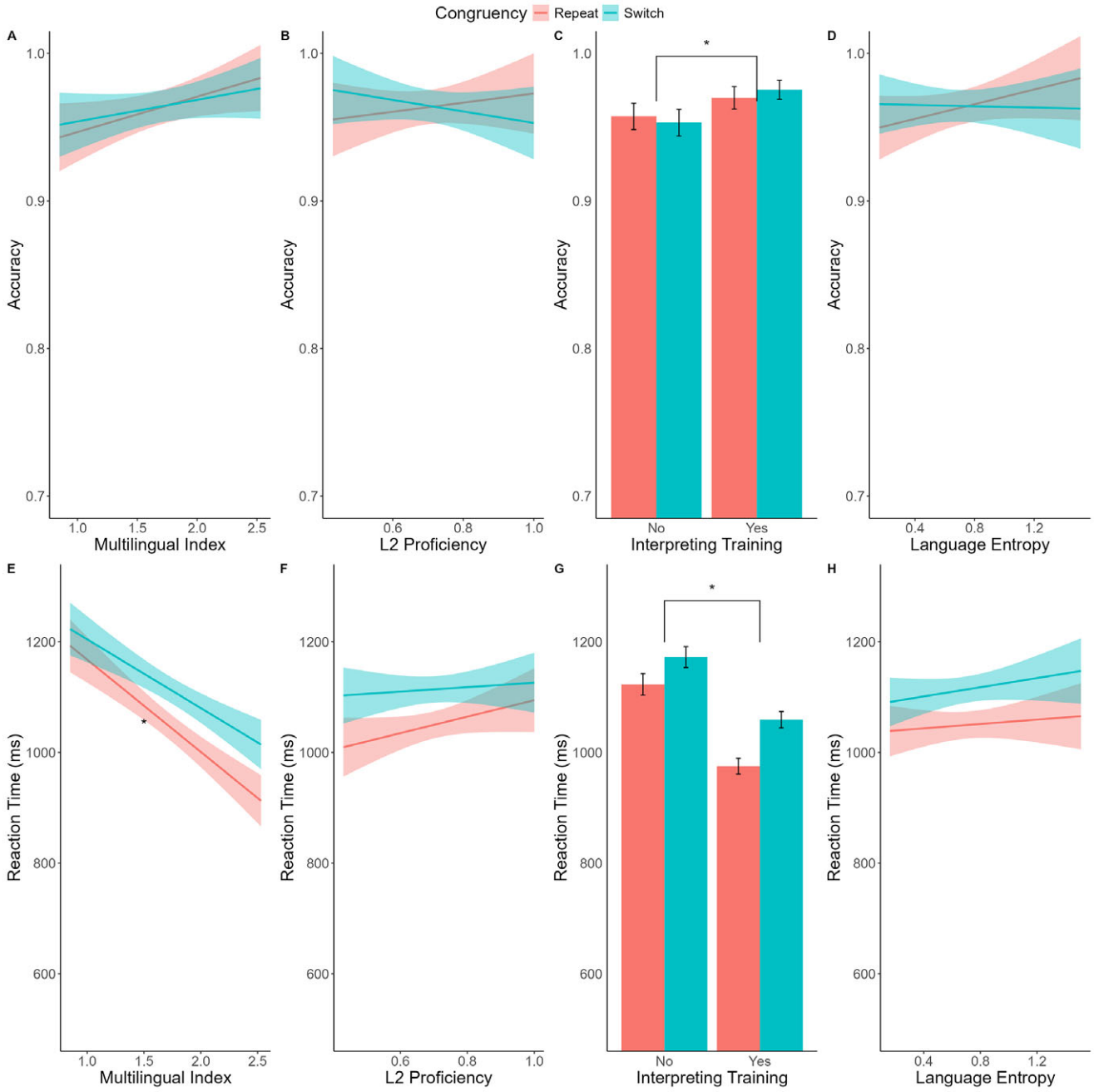


Figure 2. Effects of task condition and language factors on accuracy (top panel) and reaction time (bottom panel) during task switching. Top panel: The effect of the multilingual index on accuracy was not significant (A). Although the effects of L2 proficiency (B) and language entropy (D) were not significant, individuals with interpreting training showed significantly higher accuracy than individuals with no training (C). Bottom panel: The Switch condition (blue) elicited longer reaction times than the Repeat condition (red). A higher multilingual index was significantly associated with faster responses (E). There was no significant effect of L2 proficiency (F) or language entropy (H) on RT. Individuals with interpreting training showed significantly faster RT than people with no training (G).

individuals showed faster response times. Yet, the interaction between task condition and multilingual index was not significant (β = 16.30, SE = 14.82, t = 1.10, p = .28).

Additional analyses on RTs were conducted to explore the effect of task condition, and its interaction with separate language factors (R^2 Marginal = .05, R^2 Conditional = .40). The main effect of task condition remained to be significant (β = 67.33, SE = 15.25, t = 4.41, p < .001). In terms of the effects of language factors on RT, the main effect on RT of L2 proficiency was not significant (β = 17.99, SE = 40.97, t = .44, p = .66; Figure 2F). The main effect of entropy on RT was not significant either (β = 29.81, SE = 42.85, t = .70, p = .49; Figure 2H). Yet, there was a significant main effect of interpreting training experience on RT (β = −166.78, SE = 79.91, t = −2.09, p = .04; Figure 2G). Specifically, individuals with interpreting training experience (M = 1020 ms, SD = 333 ms) showed faster reaction time on task switching than individuals with no training (M = 1148 ms, SD = 432 ms; Figure 2G). No interaction between language factors and task effect was significant (ps > .1).

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3.2. Task Switching fMRI Results

The Switch and Repeat conditions elicited very similar patterns of activation, throughout many brain regions such as the left frontal pole, bilateral insular cortex extending to frontal operculum cortex and central opercular cortex, bilateral anterior cingulate gyri extending to paracingulate gyri, bilateral precentral gyri, left postcentral gyrus extending to bilateral supramarginal gyri and superior parietal lobule, bilateral lateral occipital cortex and cerebellum (Supplementary Figure 1A,B and Supplementary Table 1). Additionally, compared with the Repeat condition (Supplementary Figure 1C and Supplementary Table 1), the Switch condition elicited greater activation in the left middle and inferior frontal gyri, left angular gyrus extending to supramarginal gyrus, left precentral and postcentral gyri, left precuneus, and occipital cortex (i.e., Switch cost = Switch – Repeat, masked with Switch).

Looking at the convergent integrated multilingual index, we observed a positive relationship between the index and brain activation in the left frontal pole (Figure 3A and Table 2). Although there was no significant effect of the continuous integrated multilingual index on switch cost (i.e., interaction), we further categorized the participants into the high versus low multilingual index group using a medium split (Figure 3B and Table 2). Results showed that individuals in both the high and low multilingual index groups engaged the left middle frontal gyrus, left superior parietal lobe extending to the left supramarginal gyrus, and right occipital fusiform gyrus during switch cost, while those in the low multilingual index group recruited these regions more extensively and additionally engaged left angular gyrus.

We also explored the effect of divergent language factors (L2 proficiency, language entropy, and interpreting training) on the task switching activation (i.e., the main effects of each language factor, and their interactions with the switching conditions). The interpreting training experience was modeled categorically while L2 proficiency and language entropy were modeled continuously using the demeaned values, to explore the parametric effects on task switching. Results showed that higher L2 proficiency was associated with greater activation in right frontal pole extending to the right inferior frontal gyrus, left frontal orbital cortex, left superior and middle frontal gyri, right precentral gyrus, left precuneus cortex, and bilateral insular (Figure 3C and Table 2). Individuals who had interpreting training showed greater involvement of the left frontal pole than individuals who did not (Figure 3D and Table 2). Additionally, higher entropy was associated with greater activation in the right inferior frontal gyrus extending to the right frontal pole (Figure 3E and Table 2). There was neither a negative relationship found between continuous language factors and brain activation, nor region showing greater activation in individuals with no interpreting training compared to those who had training.

In terms of the interaction effects of divergent language factors and task switching, only the effect of language entropy on switch cost was significant (Figure 3F and Table 2). Specifically, higher entropy individuals showed a smaller switch cost in the right middle frontal gyrus, bilateral precuneus, left middle and inferior temporal gyri, and bilateral occipital cortex, after masking with switch costs.

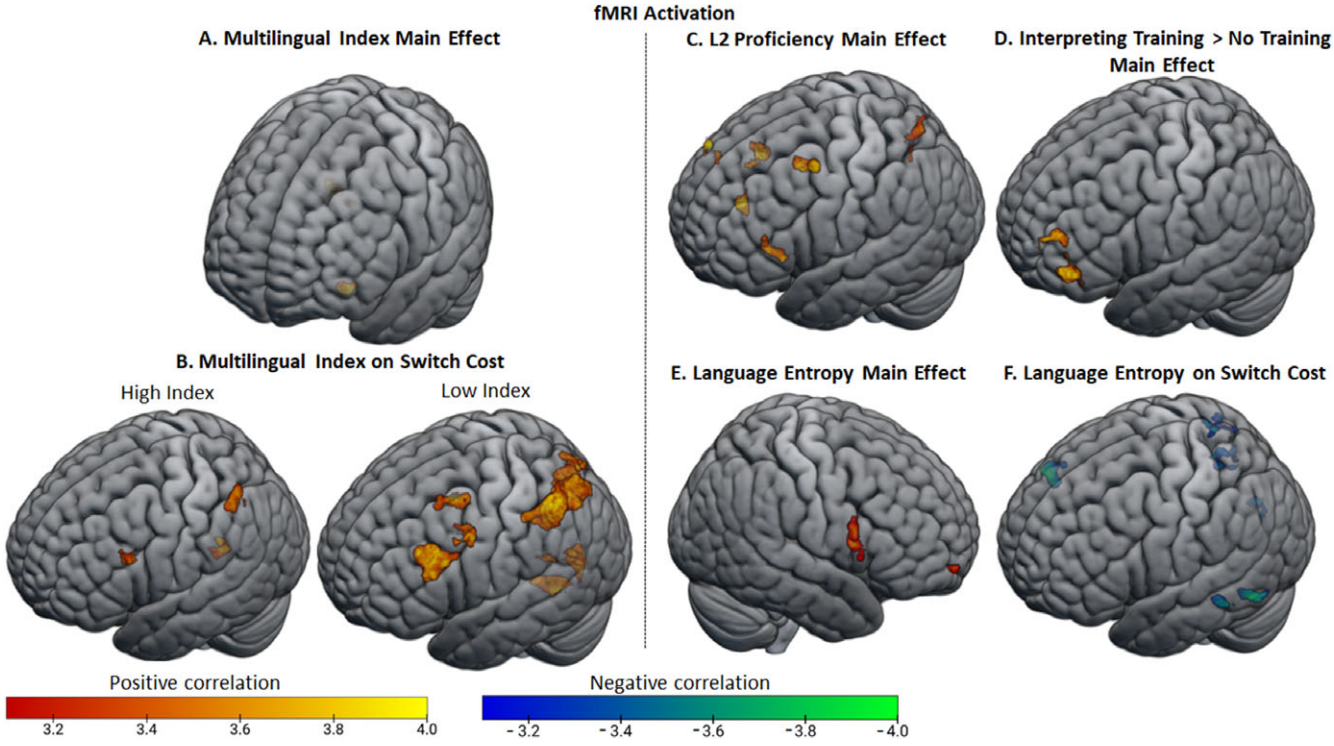


Figure 3. Effect of language factors on fMRI activation. Left panel figures are (A) Regions showed stronger activation with higher multilingual index, and (B) Activation patterns regarding switch cost in the high versus low multilingual index group. Right panel figures are (C) Regions showed stronger activation with higher L2 proficiency, (D) Regions showed stronger activation in individuals with interpreting training than individuals with no training, (E) Regions showed stronger activation with higher language entropy, and (F) Regions where higher Language entropy associated with smaller switch cost. Red/yellow suggests a positive correlation, whereas blue/green suggests a negative correlation. The color bar ranges from Z = 3.1 to Z = 4.

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Table 2. Effect of language factors on fMRI activation

		BA		Coordinates (mm)			
	Hemisphere	Label	Voxels	*x*	*y*	*z*	*Z* value
Multilingual Index Main Effects							
Frontal pole	Left	BA10	88	−44	48	−2	4.78
High Multilingual Index Switch Cost							
Middle frontal gyrus	Left	BA9	109	−44	22	32	3.52
Supramarginal gyrus	Left	BA40	191	−48	−48	48	3.7
Superior parietal lobule	Left	NA		−40	−52	62	3.48
Occipital fusiform gyrus	Right	NA	170	36	−70	−24	4.09
Low Multilingual Index Switch Cost							
Middle frontal gyrus	Left	BA9	651	−48	24	36	4.29
Middle frontal gyrus	Left	BA6	182	−32	0	60	4.12
Supramarginal gyrus	Left	BA40	1794	−48	−46	54	4.72
Angular gyrus	Left	BA39		−48	−52	54	4.62
Lateral occipital cortex	Left	BA7		−28	−74	48	4.86
Lingual gyrus	Right	NA	331	2	−78	−14	4.09
Occipital fusiform gyrus	Right	BA18		14	−86	−16	4.06
L2 Proficiency Main Effects							
Frontal pole	Right	BA9	23	50	36	24	4.17
Frontal orbital cortex	Left	BA45	116	−28	30	2	3.73
Insular cortex	Right	BA13	107	32	24	−2	4.63
Insular cortex	Left	BA13		−30	18	−8	4.3
Inferior frontal gyrus	Right	BA44	236	48	16	14	4.03
Precentral gyrus	Right	BA6		54	4	16	4.26
Middle frontal gyrus	Left	BA6	171	−34	2	52	5.6
Superior frontal gyrus	Left	BA6		−22	4	49	4.16
Precuneous cortex	Left	BA7	140	−6	−70	50	3.88
Lateral occipital cortex	Left	BA7		−6	−76	58	3.46
Interpreting Training > No Training							
Frontal pole	Left	BA10	295	−44	50	−2	4.79
Language entropy main effects							
Frontal pole	Right	BA10	15	22	68	−6	4.25
Inferior frontal gyrus	Right	BA44	108	54	18	6	3.33
Language Entropy × Switch cost							
Middle frontal gyrus	Right	BA9	144	48	34	32	−4.08
Middle temporal gyrus	Left	BA21	107	−62	−34	−10	−3.96
Precuneous cortex	Left	BA7	116	−4	−50	68	−3.69
Precuneous cortex	Right	BA7		4	−52	64	−3.6
Inferior temporal gyrus	Left	BA37	114	−54	−54	−16	−4.03
Precuneous cortex	Right	BA7	127	8	−62	44	−3.56
Lateral occipital cortex	Right	BA39	119	30	−76	32	−3.74
Occipital fusiform gyrus	Right	BA18	103	22	−90	−8	−3.66
Occipital pole	Right	BA18		34	−92	−12	−3.66

Abbreviation: BA, Broadmann area.

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3.3. Task Switching Functional Connectivity

Using the gPPI approach, seed-to-voxel analyses were conducted using the bilateral LPFC (Figure 4) as seeds, as these regions could represent the dorsal LPFC.

With left LPFC as the seed, there was a main effect of task condition on several clusters. On the left temporal pole, extending to the left middle temporal gyrus, the Switch condition showed positive connectivity, whereas the Repeat condition showed negative connectivity (Figure 4A, in red). On the other hand, on the left frontal pole, the Repeat condition showed positive, whereas the Switch condition showed negative connectivity (Figure 4A, in blue). Yet, there was no significant effect of the congruency condition on right LPFC seed-to-voxel connectivity.

We further explored the effects of convergent and divergent language factors on connectivity. There was no significant main effect of convergent integrated multilingual index on bilateral LPFC seed-to-voxel connectivity. Looking at divergent language factors, similar to the fMRI activation analysis, L2 proficiency and entropy were modeled continuously, while interpreting training experience was coded as a categorical variable. With left LPFC as the seed, there was no main effect of either language factor on connectivity. Yet, there was a significant interaction between congruency condition and interpreting training, located at the left frontal orbital cortex (Figure 4D and Table 3). Further exploration showed that individuals with interpreting training showed negative connectivity between the left LPFC and left frontal orbital cortex during the Repeat condition, while positive connectivity during the Switch condition. The same pair of connectivity was similar between Repeat and Switch in the no-training group. With right LPFC as the seed, compared to individuals with no interpreting training, individuals with training showed significantly stronger connectivity with bilateral middle and inferior frontal gyri, precentral gyri, occipital cortex, and right superior parietal lobe (Figure 4B and Table 3). Furthermore, higher L2 proficiency was found to be significantly associated with weaker connectivity in the anterior cingulate cortex, bilateral frontal pole extending to the paracingulate gyrus, and right frontal orbital cortex (Figure 4C and Table 3). There was no significant interaction between the congruency condition and language factors on right LPFC seed-to-voxel connectivity.

3.4. Resting-State Functional Connectivity

For all participants, seed-to-voxel analyses were conducted using the bilateral LPFC as seeds. Masked with the general significant positive connectivity between the LPFC and the rest of the brain, we investigated how the convergent language factor (i.e., multilingual

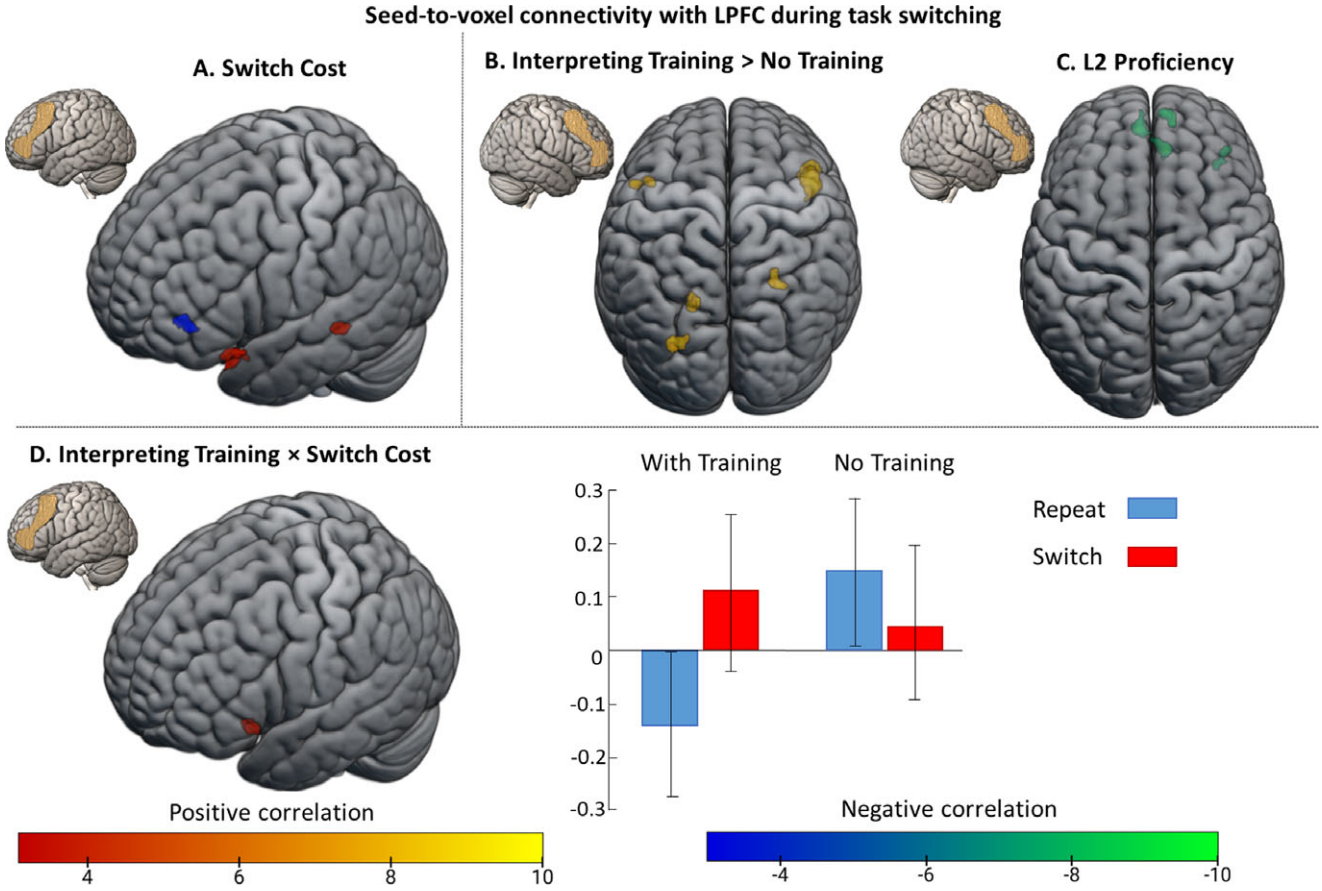


Figure 4. Seed-to-voxel task-based functional connectivity, using bilateral LPFC as seeds, is displayed in the small brown brains on the left corner. (A) Switch cost, red/yellow represents stronger connectivity in Switch than Repeat, while blue/green represents stronger connectivity in Repeat than Switch. (B) Across Switch and Repeat conditions, stronger connectivity in individuals with interpreting training than no training. (C) Across Switch and Repeat conditions, higher L2 proficiency is associated with weaker connectivity. (D) Regions that showed significant interaction with interpreting training and switch cost. Red/yellow suggests a positive correlation, whereas blue/green suggests a negative correlation. The color bar ranges from Z = 3.1 to Z = 10.

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Table 3. Seed-to-voxel task-based functional connectivity, using bilateral LPFC as seeds

		BA		Coordinates (mm)			
	Hemisphere	Label	Voxels	*x*	*y*	*z*	*Z* value
Switch Cost							
Left LPFC seed							
Frontal pole	Left	BA46	35	−48	44	4	−4.4
Temporal pole	Left	BA38	58	−50	20	−14	3.69
Middle temporal gyrus	Left	BA21	35	−64	−28	−2	4.52
Interpreting Training > No Training							
Right LPFC seed							
Middle frontal gyrus	Right	BA44	201	44	14	32	15.62
Inferior frontal gyrus	Right	BA44		43	11	29	9.28
Precentral gyrus	Right	BA44		46	10	32	13.05
Inferior frontal gyrus	Left	BA44	38	−50	14	28	10.22
Middle frontal gyrus	Left	BA8		−44	13	33	8.61
Precentral gyrus	Left	BA44		−50	12	30	8.91
Lateral occipital cortex	Right	NA	39	26	−56	38	11.8
Superior parietal lobule	Right	NA		26	−50	45	9.83
Lateral occipital cortex	Left	BA7	51	−18	−68	38	15.49
Lateral occipital cortex	Left	NA	65	−28	−80	18	13.28
L2 Proficiency							
Right LPFC seed							
Paracingulate gyrus	Left	BA10	49	−6	50	−6	−11.8
Frontal pole	Left	BA10		−6	58	−6	−8.38
Frontal pole	Right	BA10	34	9	57	0	−9.33
Frontal pole	Right	BA47	34	40	38	−18	−9.55
Frontal orbital cortex	Right	BA47		36	32	−18	−7.71
Anterior cingulate gyrus	Right	BA32	70	8	38	0	−16.77
Anterior cingulate gyrus	Middle	BA32		0	44	2	−7.66
Paracingulate gyrus	Right	BA32		5	42	−4	−7.7
Interpreting Training × Switch Cost							
Left LPFC seed							
Frontal orbital cortex	Left	BA47	45	−46	20	−6	4.28

Abbreviation: BA, Broadmann area.

index) and divergent language factors (L2 proficiency, language entropy, and interpreting training) modulated these connectivities respectively. Across both the left and right LPFC, a higher multilingual index was significantly associated with weaker positive connectivity in the occipital lobe extending to the cerebellum (Figure 5A and Table 4). With left LPFC as the seed, there was no significant effect of either language factor on the positive seed-to-voxel connectivity. With the right LPFC as the seed, higher L2 proficiency was associated with stronger positive connectivity in the right frontal pole (Figure 5B and Table 4). Higher language entropy was also associated with weaker positive connectivity in the left cerebellum (Figure 5C and Table 4). There was no significant main effect of interpreting training on the bilateral LPFC seed-to-voxel connectivity.

4. Discussion

The interplay between multilingualism and cognitive brain functions is intricate and influenced by multiple factors. This study advances our understanding by examining the effects of diverse language experiences on cognitive switching and brain activity. Our findings provide compelling evidence for overlapping and distinct impacts of convergent and divergent language experiences on cognitive and brain functions, particularly in relation to cognitive shifting assessed through the task-switching paradigm, as well as resting-state and task-based functional connectivity. These findings are discussed in detail in the following sections.

To start with, during the task switching task in this study, the Switch condition, compared with the Repeat condition, resulted in

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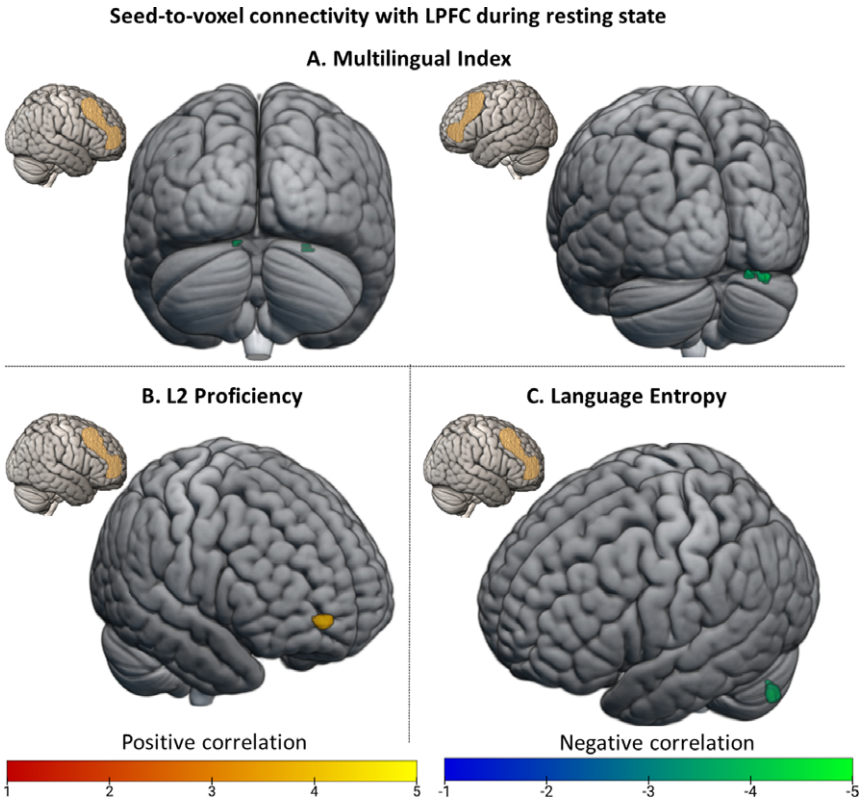


Figure 5. Seed-to-voxel resting-state functional connectivity, using bilateral LPFC as seeds, is displayed in the small brown brains on the left corner. (A) Regions showed weaker connectivity with higher multilingual index; (B) Regions showed stronger connectivity with higher L2 proficiency; (C) Regions showed weaker connectivity with higher language entropy. Red/yellow suggests a positive correlation, whereas blue/green suggests a negative correlation. The color bar ranges from Z = 1 to Z = 5.

longer response times and stronger fMRI activation in left-dominant brain regions typically involved in higher-order cognitive control (e.g., left superior and middle frontal gyri, and superior parietal lobe) and language processing (e.g., inferior parietal lobe including supramarginal and angular gyri, precentral and postcentral gyri, and left precuneus). The switch cost, which reflects the additional mental effort required for task switching, has been consistently associated with the bilateral frontoparietal brain network (Braver et al., 2003; Dove et al., 2000; Friedman & Robbins, 2022; Hampshire & Owen, 2006; Hyafil et al., 2009; Jamadar et al., 2015; Kim et al., 2012; Periáñez et al., 2022; Sohn et al., 2000). For instance, a meta-analysis on task switching identified consistent neural associations, including the bilateral dorsolateral prefrontal cortex, premotor cortex, superior and inferior parietal lobule, precuneus, left anterior cingulate, and right ventrolateral prefrontal cortex (Jamadar et al., 2015). The neural patterns associated with the switch cost in the current study (Supplementary Figure 1C) partially align with the findings reported in the meta-analysis.

Differently, our study observed a predominantly left-lateralized activation pattern in regions associated with switch costs on fMRI. Task-related connectivity results further supported this left-dominant pattern, revealing switch costs between the left LPFC and left frontal-temporal regions (Figure 4A), but not the right LPFC. The left-lateralization associated with switch cost contrasts with the commonly reported bilateral engagement reported in previous meta-analyses (Jamadar et al., 2015; Kim et al., 2012) and other task-switching studies (Braver et al., 2003; Dove et al., 2000; Friedman & Robbins, 2022; Hampshire & Owen, 2006; Hyafil et al., 2009; Periáñez et al., 2022; Sohn et al., 2000). The left-dominant activation pattern may theoretically be related to the language processing demands of the letter-number task used in our study. However, since both the Switch and Repeat conditions entail similar language demands, the observed switch costs should primarily reflect cognitive shifting demands, independent of language processing. Previous fMRI studies employing the letter–number task or other language tasks have generally reported bilateral or right-lateralized distributions during switch costs (Kimberg et al., 2000; Sohn et al., 2000), consistent across different task-switching versions. Therefore, the left-lateralized activation observed during switch costs in our study likely reflects the specific multilingual profiles of our participants. Prior research contrasting language switching and task switching has indicated overlap in left hemisphere regions such as the dorsolateral prefrontal cortex, pre-supplementary motor area, precuneus, and cerebellum (e.g., Jiao et al., 2022; Tao et al., 2021). Even in nonlanguage task switching alone, multilingual individuals predominantly recruited left hemisphere regions (Tao et al., 2021). The left-lateralized effects observed during the task can be attributed to the left hemisphere language network, which shares overlapping nodes with the frontoparietal executive control network (Abutalebi & Green, 2016; Geranmayeh et al., 2014). This overlap supports the integration of language processing and executive functions in multilinguals. Thus, multilingual may engage language control resources more extensively, even for nonlanguage tasks, showing greater left-dominant brain region engagement with increasing multilingual experience.

A distinctive aspect of this study is the examination of specific language experiences on behavioral and neural mechanisms in

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Table 4. Seed-to-voxel resting-state functional connectivity, using bilateral LPFC as seeds

	BA		Coordinates (mm)				
	Hemisphere	Label	Voxels	*x*	*y*	*z*	*Z* value
Multilingual Index							
Left LPFC seed							
Lateral occipital cortex	Right	NA	82	28	−84	−22	−5.22
Cerebellum	Right	NA		28	−84	−26	−3.93
Right LPFC seed							
Occipital fusiform gyrus	Left	NA	102	−28	−70	−20	−4.76
Occipital fusiform gyrus	Right	NA	72	28	−72	−20	−5.02
Cerebellum	Right	NA		29	−74	−22	−3.71
Occipital pole	Left	BA18	66	−6	−102	−6	−4
L2 Proficiency							
Right LPFC seed							
Frontal pole	Right	BA10	99	20	64	0	5.09
Language Entropy							
Right LPFC seed							
Cerebellum	Left	NA	71	−34	−74	−54	−5.03

Abbreviation: BA, Broadmann area.

task switching, from a convergent perspective with an integrated multilingual language index, and a divergent perspective focusing on L2 proficiency, interpreting experience, and language entropy. First, the convergent multilingual index calculated in the current study integrates various aspects of multilingual experience, including language proficiency and language use experience, aligning with similar measures in previous studies (Anderson et al., 2018; Gallo et al., 2021). Importantly, our study uniquely incorporates interpreting training experience into the multilingual index, enhancing its comprehensiveness for our participant cohort. Higher values of the multilingual index were associated with faster response times, suggesting that more extensive multilingual experience generally improves task-switching performance (Figure 2E). While informative, further investigation is needed to explore how task switching is affected by different multilingual language variables.

Regarding the effects of divergent language factors, controlling for other types of language experience, the interpreting experience positively facilitated cognitive switching, reflected by the overall higher accuracy and faster response time (Figure 2C and 2G), and lower inversed efficiency score (reported in Supplementary Materials). Compared with other types of multilingual experience, interpreting training is more intensive and demands higher involvement of cognitive abilities such as attention, switching, or working memory. This result supports the idea that professional training enhances attentional focus and information processing, consistent with some previous studies (Babcock & Vallesi, 2017; Hernández et al., 2013).

In addition to the observed behavioral effects, our study explored the effects of multilingual experience on neural mechanisms of task switching. Individuals with more extensive multilingual experience exhibited heightened activation in frontal regions extending to the insular and precuneus, consistent with prior findings (Van de Putte et al., 2018). The significance in subcortical regions supports recent theories such as BAPSS (Grundy et al., 2017), DRM (Pliatsikas, 2020), or UBET (DeLuca et al., 2020), which proposes a subcortical shift accompanying more extensive multilingual experience. However, the BAPSS and UBET also suggest a posterior shift with increased multilingual experience, which contracts with our finding of predominant anterior activation. One plausible explanation is that while proficient and balanced multilinguals may shift to posterior regions for demanding cognitive tasks, the multilinguals in the current study were mostly unbalanced, being late learners of non-native languages, dominant in L1, and living in a native language environment. It is possible that the posterior shift observed in BAPSS has not manifested in the current group of multilinguals. Future studies could recruit multilinguals with more prolonged multilingual experience to further test the effects of convergent and divergent language factors on task switching.

Different language factors are also associated with distinct lateralization patterns. Specifically, higher L2 proficiency, and interpreting training predominantly activate the left hemisphere activation, whereas higher language entropy additionally engages regions in the right hemisphere. These findings suggest a divergent role of the left versus right hemisphere during task switching based on language experience. Specifically, multilingual individuals with enhanced language abilities, similar to the efficiency factor proposed in the UBET (DeLuca et al., 2020), as indicated by proficiency and professional training, demonstrated increased activation in left hemisphere regions such as the insular, superior and inferior frontal gyri, and superior parietal lobule. These areas are crucial for language-specific control in bilinguals (Calabria et al., 2018; Sulpizio et al., 2020; Tao et al., 2021), and for managing lexical competition in monolinguals (Fedorenko & Thompson-Schill, 2014; Hickok & Poeppel, 2007; Indefrey & Levelt, 2000; Price, 2010). Thus, in this study, multilingual participants effectively utilized these left hemisphere neural resources to enhance

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task-switching performance with minimal language-specific demands. On the other hand, multilinguals with more flexible language use, resembling the executive control demands factor in UBET, indicated by higher entropy, tended to rely more on right hemisphere domain-general neural resources, such as the inferior frontal gyrus.

Regarding switch cost, individuals with a lower multilingual index exhibited greater recruitment of left-lateralized frontal–parietal neural resources (Figure 3B). Similarly, multilinguals with more flexible language use experience, reflected by higher entropy, recruited less neural resources when dealing with the switching demands in the task (Figure 3F). Recall that there were no significant interactions between language factors and task conditions behaviorally, suggesting that multilinguals were comparable in terms of the performance to flexibly shifting between tasks. Thus, these combined results suggest that experienced multilinguals may utilize neural resources more efficiently during task disengagement and engagement (i.e., using less neural resources while achieving the same level of performance). Yet, this result needs to be interpreted with caution because the effect of multilingual index was only found when modeling the variable categorically but not continuously.

The modulation effects of multilingualism on behavior and task-related activation were further supported by analyses of task-based functional connectivity. Specifically, higher L2 proficiency was linked with reduced connectivity between the right LPFC and bilateral frontal pole extending to the right frontal orbital cortex and paracingulate gyri (Figure 4C). On the other hand, individuals with interpreting training exhibited enhanced connectivity between the right LPFC and bilateral middle and inferior frontal gyri, extending to the right superior parietal lobe, bilateral precentral gyri, and bilateral occipital cortex (Figure 4B). These findings suggest that the influence of L2 proficiency on brain connectivity remained to be local while the effect of interpreting training exerted a broader effect across the whole brain. Additionally, there was a notable interaction between interpreting training experience and task congruency conditions in the connectivity between the left LPFC and left frontal orbital cortex (Figure 4D). Specifically, individuals with interpreting training demonstrated more efficient regulation of connectivity in response to task demands (i.e., down-regulate the connectivity when the switching demand is low while maintaining high performance), compared with those with no professional training.

Finally, during the resting state, more experienced multilinguals (e.g., those with higher multilingual index or language entropy) exhibited weaker connectivity between bilateral LPFC and occipital cortex extending to the cerebellum (Figure 5A and 5C). This finding underscores the involvement of the cerebellum in response to multilingual experience, even during periods without an explicit task, aligning with empirical studies (DeLuca, Rothman, & Pliatsikas, 2019; Gullifer et al., 2018), as well as recent theories such as DRM (Pliatsikas, 2020). Some empirical studies have suggested that more experienced multilinguals typically demonstrate stronger connectivity within cortical structures bilaterally (Berken et al., 2016; Gullifer et al., 2018) or within subcortical structures (Gullifer & Titone, 2019). Together with our results, these patterns suggest that individuals with extensive multilingual experience may exhibit reduced interaction between cortical and subcortical regions and enhanced communication within subcortical structures. However, further detailed network analyses are needed to fully elucidate these relationships. While such network analyses are interesting, they extend beyond the central focus of this study; interested readers can refer to the Supplementary Materials for more comprehensive details. Conducting additional analyses that directly compare functional connectivity between task and resting states would also be valuable. This approach could reveal common changes in connectivity relevant to multilingual experience and identify distinct patterns associated with specific task demands.

A potential limitation of our study is the exclusion of AoA as a language factor in our analyses. We did collect self-report AoA data for each language via LHQ. Focusing specifically on L2 AoA, which showed the greatest variation among participants, we found that younger L2 AoA was significantly associated with higher language entropy ($p = .045$) and marginally associated with higher L2 proficiency ($p = .07$) and interpreting training experience ($p = .07$). These associations indicate that AoA is indeed relevant to the language factors considered in our study, and could potentially provide valuable insights if included. However, self-reported AoA may be prone to inaccuracies due to factors such as underestimation of early language knowledge because of infantile amnesia or the broad age ranges available for respondents to choose from (Xu et al., 2020). Future research efforts should strive to collect more objective AoA data when feasible, as well as consider other multilingual experience factors such as the number of languages spoken, language switching frequency, and so forth Furthermore, interpreting training (yes/no) was modeled categorically due to variability in self-reported hours. Reanalysis with training as a continuous variable showed a near-significant effect on RT ($p = .057$), but not on ACC ($p = .55$). Given the unreliability of self-reported hours, we opted for a categorical approach to clearly capture the impact of having versus not having training. Future studies should collect precise training hours to enable parametric analysis and better understand the continuous effects of interpreting training. Additionally, in this study, we tested the effects of divergent language variables within the same behavioral mixed-effects model, controlling for interconnected confounding effects. However, controlling for confounding factors is more challenging in fMRI data analysis, which can be carefully considered in future studies. Last but not least, employing nonlinear modeling approaches in data analysis could further enhance our understanding of the intricate relationships between multilingual experience and cognitive function.

In summary, this study highlights the complex interplay between multilingualism and cognitive flexibility, modeling language experience from both convergent and divergent perspectives. It demonstrates that more extensive integrated multilingual experience driven by interpreting training enhances overall task-switching performance. Neuroimaging findings indicate that multilinguals engaged left-lateralized brain regions for cognitive control, with more extensive multilingual experience linked to more efficient neural resource use. Additionally, during task switching, L2 proficiency modulated the local connectivity within the frontal lobe, while interpreting training facilitated individuals to be more efficiently regulate the global connectivity across the frontal, parietal, and occipital lobes in response to task demands. These findings emphasize the significance of comprehensively assessing both divergent and convergent language experiences to fully grasp their impact on cognitive function and brain activity.

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Data availability statement. Data and analysis scripts will be available upon request.

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