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The influence of orthographic depth on multilinguals' neural networks

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Abstract

Orthographic depth, the consistency and complexity of grapheme-phoneme correspondence, influences brain activation in multilinguals' first (L1) and second language (L2). The intrinsic functional connectivity of cross-language transfer was investigated between two groups of multilinguals, those whose L2 orthography is deeper than their L1 (S-to-D group) and those whose L2 orthography is shallower than their L1 (D-to-S group). Based on previous reports, we focused on two seed regions: the Visual Word Form Area (VWFA) and the left posterior supramarginal gyrus (pSMG). Group comparisons revealed stronger connectivity for the D-to-S group between the left pSMG and the right precuneus/cuneal cortex and the right SMG/angular gyrus. Moreover, we found that the greater the linguistic orthographic distance—the less similar in orthographic depth two languages are—the greater the negative connectivity between the left pSMG and the right pSMG, middle frontal gyrus (MFG) and frontal pole, and a cluster that included the inferior frontal gyrus (IFG) pars opercularis, frontal operculum, and insular cortex. When linguistic distance was greater, there was also greater negative connectivity between the VWFA and the left precuneus. Furthermore, stronger connectivity was found between the left pSMG and the right precuneus in multilinguals who spoke at least three languages (trilinguals) compared to those who only spoke two languages (bilinguals). Follow-up analyses revealed that this difference was driven by stronger intrinsic connectivity in D-to-S trilinguals compared to the S-to-D trilinguals. Taken together, the findings of this study suggest that multilinguals' intrinsic functional connectivity is shaped by the orthographic depth of their L2 in relation to L1, as well as differences between bilingualism and trilingualism.

Keywords

Orthographic depth; Intrinsic functional connectivity; Bilingualism; Trilingualism; Resting-state functional connectivity; Multilingualism

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None.

1. Introduction

There is mounting evidence that languages are not equally easy to learn. A central question is how the orthographic characteristics of a language influence reading. Orthographies differ in the consistency and complexity of the mappings between graphemes and phonemes; this is referred to as the orthographic depth of the language (Frost, 1994; Frost et al., 1987; Katz and Frost, 1992). In shallow orthographies, such as Finnish, Italian, and Greek, the correspondences between graphemes and phonemes are consistent and unambiguous: one letter is pronounced the same across different words. In contrast, in deep orthographies, such as English, French, and Danish, the relationship between graphemes and phonemes is not consistent: one letter is often pronounced differently in different contexts (e.g., sign vs. signal) and the same sound can be spelled with different letters or groups of letters (e.g., be vs. bee).

The relative degree of grapheme-phoneme correspondence consistency that languages display has been demonstrated to be a key factor determining the rate of reading acquisition across different orthographies (Ziegler and Goswami, 2005). Children learning to read in shallow orthographies rely almost exclusively on decoding at the grapheme-phoneme level due to the high degree of letter-sound mapping consistency. In deep orthographies, however, learning grapheme-phoneme decoding is only one decoding strategy that children must master. Children learning to read a deep orthography need to develop multiple recoding strategies to decode at several different grain sizes, such as patterns of letters, rimes, syllables, or even whole words (Psycholinguistic Grain Size Theory; Ziegler and Goswami, 2005). The necessity of learning multiple decoding strategies in deep orthographies slows down the reading acquisition process, which provides one explanation for why learning to read in deep orthographies proceeds more slowly than in more transparent orthographies (e.g., Ellis et al., 2004; Marinus et al., 2015; Seymour et al., 2003). Indeed, Seymour et al. (2003) found that the reading accuracy of students learning shallow orthographies reached 100% by the end of 1st grade, while reading accuracy in the deepest orthography studied (English) only reached 34% by the end of 1st grade.

1.1. Cross-language transfer effects

Since the 1900s, a Dual Language System Hypothesis (Kecskes, 1998; Kecskes and Papp, 2000) has been the majority view among bilingual researchers due to evidence from cross-linguistic studies. Cross-language transfer refers to interactions between two language systems (e.g., Koda, 2007, 2008). While results from cross-language transfer studies largely demonstrate a language learning advantage, it is notable that the vast majority of studies focus on learning English, a very deep orthography, as a L2 (e.g., Commissaire et al., 2011; Gebauer et al., 2013; Ramirez et al., 2010). Evidence from these studies could be interpreted as learning a shallower language first facilitates learning a second language with a deeper orthography. Yet, when compared to those studies in which participants' L1 is orthographically deeper than their L2 (e.g., Geva and Siegel, 2000; Kahn-horwitz & Saba, 2018; Pasquarella et al., 2011), a different interpretation becomes evident. Indeed, Geva and Siegel (2000) studied word and pseudoword reading in children with a deeper L1 orthography (English) learning a deep L2 (Hebrew) at school. While both English and

Hebrew are considered deep orthographies, Hebrew is considered shallower than English (Liu and Cao, 2016). Geva and Siegel (2000) found that when orthographic depth is less complex, reading develops more quickly. By first grade, students already demonstrated higher accuracy in word and pseudoword reading in the relatively shallower L2 (Hebrew) compared to their deeper L1 (English). Further, cross-language transfer occurred from a deeper to a shallower orthography. Thus, as many multilinguals will attest, cross-language transfer occurs regardless of the relative orthographic depth of the first language.

What is less obvious from individual experiences is that the orthographic depth of the languages can moderate cross-language transfer effects. Indeed, when directly compared, individuals with a shallow L1 orthography (Swedish) outperformed those with a deep L1 orthography (Danish) on L2 literacy learning in a deep orthographic (English) language (van Daal and Wass, 2017). While van Daal and Wass (2017) did, as expected, demonstrate that both L1s show cross-language transfer effects, learning was greater for individuals whose L1 had a shallow orthographic depth. This is supported by evidence from several studies showing cross-language transfer to be more apparent when the language being learned is orthographically deeper than the known language(s) (e.g., Chung et al., 2019; Deacon et al., 2013).

There is also evidence of a language similarity effect (e.g., Van Assche et al., 2013). For example, Schwartz and colleagues (2014) investigated three groups of English language learners. They found that Russian-Hebrew bilingual-biliterates demonstrated greater English (L3) orthographic learning than both Russian (L1) speaking children literate only in Hebrew (L2) and monolingual Hebrew children. The authors interpreted their results by arguing that the greater similarities—closer orthographic distance—between Russian and English as compared to English and Hebrew orthographies explained the differences in performance. Thus, evidence suggests that the orthographic distance between languages influences language acquisition.

Taken together, the prior literature indicates that cross-language transfer effects occur regardless of the orthographic depth of the languages or the order of language acquisition. However, orthographic depth does appear to moderate cross-language transfer effects. Moreover, evidence suggests that languages with shallower orthographies and languages closer in orthographic distances will result in greater language learning. Language similarity effects would, therefore, be expected to be reflected in the organization and magnitude of the bilingual neurobiological system. For example, when languages' orthographic distances substantially differ, it may be advantageous to decrease the use, or brain activation, of the language not currently being employed (as suggested by Van Assche et al., 2013). In the next section, we discuss what is known about the neurobiological correlates of orthographic depth.

1.2. Neurobiological correlates of orthographic depth

Several studies have investigated orthographic depth at the neurobiological level. Perhaps most broadly, across four languages which varied in orthographies (alphabetic versus logographic) and orthographic depth (deep versus shallow), Rueckl and colleagues (2015) reported the convergence of neural organization for both speech and print, suggestive of a universal reading network. They also observed higher speech-print neural organization convergence for shallow languages in brain regions associated with phonological processing and higher convergence for deep languages in areas associated with semantic processing. This is consistent with the Orthographic Depth Hypothesis (Katz and Frost, 1992). According to Katz and Frost (1992), readers alter their reliance on the phonological route or lexical route depending upon the orthographic depth of the language. Readers of shallow orthographies rely more heavily on the phonological route, using letter-sound correspondence rules. This reliance on phonological processing corresponds to increased activation in left superior temporal regions (Paulesu et al., 2000a,b; Sakurai et al., 2000). Readers of deeper orthographies rely more heavily on the lexical route since grapheme-phoneme correspondence is often equivocal. This reliance on semantically tuned regions corresponds to increased activation in the left inferior frontal gyrus (IFG) and the Visual Word Form Area (VWFA; Chen et al., 2008; Chen et al., 2002; Paulesu et al., 2000a,b).

In bilinguals, differences in orthographic depth correspond to differences in neurobiological activation (Cherodath and Singh, 2015). This is evidenced by the increased involvement of the left superior temporal region in the shallower language, such as German in French-German bilinguals (Buetler et al., 2014), Spanish in Spanish-English bilinguals (Jamal et al., 2012), and Hindi in English-Hindi bilinguals (Das et al., 2011). Similarly, there is increased involvement of the left IFG and VWFA in the deeper language, such as Chinese in English-Chinese bilinguals (Nelson et al., 2009), Urdu in Urdu-Hindi bilinguals (Kumar, 2014), English in English-Hindi bilinguals (Das et al., 2011), English in French-English bilinguals (Berken et al., 2015), and English in Spanish-English bilinguals (Jamal et al., 2012).

Unlike behavioral studies, neuroimaging studies reflect activation differences in L2 reading as a result of both orthographic depth and the order of language acquisition. These differences are found in bilinguals whose L2 orthography is deeper than their L1 (S-to-D) and in those whose L2 orthography is shallower than their L1 (D-to-S). However, in D-to-S bilinguals, brain activation has been shown to be more similar in L1 and L2 reading. This suggests that the existing neurobiological mechanism is largely sufficient for the more consistent grapheme-phoneme mapping in the shallow L2 (e.g., Chinese-English bilinguals; Cao et al., 2013). However, in S-to-D bilinguals, additional neural resources are required, including greater activation of the left middle frontal gyrus (MFG) and the right fusiform gyrus (the homologue of the left VWFA) for L2 than L1 reading. This increase in areas of activation was posited by the authors to be needed to deal with the more sophisticated mapping between orthography and phonology in the deeper L2 (e.g., English-Chinese bilinguals; Liu et al., 2007; Nelson et al., 2009). Furthermore, Liu and Cao’s (2016) meta-analysis explored L2 activation differences between D-to-S bilinguals and S-to-D bilinguals. The meta-analysis revealed that in D-to-S bilinguals, bilateral superior/middle temporal and precentral gyri were more activated in L2 processing, whereas in S-to-D bilinguals, the left frontal gyri were more activated in L2 processing. Taken together, results suggested that the same L2 showed different brain activation patterns depending on whether it was shallower or deeper than an individual’s L1.

The use of two or more languages results in the interaction of languages (Koda, 2007, 2008). The neurobiological reflection of language order of acquisition may, in part, be the result of lexical equivalents. Learning a language requires an individual to acquire words; however, unique to multilingualism, individuals link new-language words to the vocabulary of their prior language(s) and their semantic knowledge. This process requires links to be made between lexical equivalents—-words in a multilingual speaker's vocabulary that have a corresponding word in the other language with similar meaning (Kroll and Potter, 1984). While the left posterior supramarginal gyrus (pSMG) was initially proposed to provide a neurobiological marker for the number of words learned (Lee et al., 2007), evidence from Richardson et al. (2010) suggests that the left pSMG is engaged in learning to link a new word with lexical equivalents. Structural neuroimaging studies have shown increased left pSMG density for bilinguals compared to monolinguals (Mechelli et al., 2004). Differences have even been reported between multilinguals. Increased left pSMG density has been found for multilinguals that are trilingual when compared to those that are bilingual (Grogan et al., 2012). Thus, the pSMG appears to play a role in multilingualism broadly but is likely to differentiate between multilinguals, even when no language or reading task is being performed.

Beyond the interaction of two or more languages (e.g., lexical equivalents), multilingualism requires that individuals be able to adjust utterances to facilitate both perception and production during communication. According to Green and Abutalebi's (2013) Adaptive Control Hypothesis, the language control network adapts to specific demands as imposed by differences in interaction contexts. Building on this hypothesis, Abutalebi and Green (2016) posited that multilinguals' adaptation allows them to more easily overcome linguistic interference and first language competition. To accomplish this, they argued that the language control network likely relies on both language-specific and non-specific, domain-general, mechanisms. For example, the anterior cingulate gyrus plays a role in conflict monitoring (e.g., Botvinick et al., 1999) and tracking information about others (e.g., Apps et al., 2016). Moreover, activation in the anterior cingulate gyrus is also consistently reported during fMRI language switching tasks performed by multilinguals (e.g., Abutalebi et al., 2012). As such, we would expect multilinguals to recruit both language-specific and domain-general brain regions to accommodate the needs of the languages they coordinate. Further, we expect that in multilingual adults, the long-term use of these adaptation mechanisms would impact their intrinsic functional brain organization.

1.3. Intrinsic functional connectivity of bilinguals

The intrinsic functional organization of the brain adapts to individual differences in behavior and experience (Fox and Raichle, 2007). Resting-state neuroimaging serves as a means to determine the intrinsic functional connectivity between anatomically separated brain regions at rest, with no task-driven behavior involved (Berken et al., 2017), as resting-state connectivity provides information about the functional organization of the brain reflecting the cumulative effects of bilingual experience (Berken et al., 2017). Investigations into the resting-state functional connectivity of bilinguals have centered on the brain regions associated with language processing (e.g., Chai et al., 2016; Veroude et al., 2010) and executive functioning (e.g., Grady et al., 2015; Luk et al., 2011), as well as differences in bilingual age of acquisition (e.g., Berken et al., 2016; Gullifer et al., 2018; Kousaie et al., 2017; Thieba et al., 2019) and L2 proficiency (Sun et al., 2019). However, to date, little is known about how intrinsic functional connectivity is impacted by variations in orthographic depth in the bilingual brain.

1.4. The current study

The overarching goal of the current study was to determine if differences in orthographic depth corresponded to differences in the intrinsic functional connectivity of multilinguals. Based on previous task-based investigations into orthographic depth in bilinguals, we focused on two bilateral regions of interest (ROIs): (1) the VWFA and its right hemisphere homologue, and (2) the left and right pSMG. First, we focused on the impact of orthographic depth in multilinguals' L1 and L2. L1 and L2 literacy proficiency and participant characteristics (sex, performance IQ, & Age of Acquisition [AoA]) were included as covariates. We hypothesized that differences in the intrinsic connectivity circuits connected to the VWFA and left pSMG would exist between groups of D-to-S and S-to-D multilinguals to accommodate their different needs due to the order of language acquisition. Specifically, we expected individuals with a shallower L2 (D-to-S group) to show increased reliance on phonological regions (e.g., bilateral superior/middle temporal and precentral gyri) to use a "sound-out" strategy for the more consistent L2, while individuals with a deeper L2 (S-to-D group) would show increased reliance on lexical regions (e.g., left frontal cortex) to accommodate more complex mapping between orthography and phonology in the deeper L2.

Second, we aimed to tease apart differences in intrinsic connectivity due to the linguistic distance between the two languages (e.g., the orthographic depth of English is closer to Hebrew than Italian) and the order of language acquisition by orthographic depth (e.g., L1 deep and L2 shallow). Using orthographic depth rankings from Liu and Cao (2016), we investigated multilinguals' intrinsic functional connectivity based on the linguistic distance in orthographic depth between their L2 and L1. We expected that languages further apart in orthographic depth would show increased reliance on connections between our left-hemisphere seed regions and regions of the brain in the frontal cortex and right hemisphere.

Finally, we aimed to determine if intrinsic functional connectivity differs between multilinguals who speak three languages (trilinguals) and those who only speak two languages (bilinguals). We hypothesized that trilinguals would show greater reliance on connections to the left pSMG than bilinguals, as activation in the left pSMG had been reported to correspond to the number of lexical equivalents (Richardson et al., 2010).

2. Methods

2.1. Participants

Data analyzed in the current study was publicly available (DeLuca, 2019). Of the 64 participants, 62 had Magnetic Resonance Imaging (MRI) data that could be downloaded and analyzed. This included MRI sequences for both T1 structural and resting-state scans. Thus, data analyzed in the current study included 62 healthy, right-handed multilingual adults (48 females, mean age = 32.05 years, standard deviation (SD) = 7.67, range = 18–52). Participants' first language (L1) was determined by age of acquisition (AoA). L1 was confirmed by participants' self-reported of their most proficient languages. Participants spoke a variety of L1s with different orthographic depths (e.g., Italian, Spanish, English, Mandarin) but the majority of the participants spoke English as their second most proficient language (N = 56). Of the 62 participants, 60 were born in countries outside of the United Kingdom and moved to the United Kingdom at different ages (mean age = 26.43 years, SD = 7.30, range = 14.99–50.24). The remaining 2 participants were born in the United Kingdom to non-United Kingdom parents, stayed in their parents' home country, and moved back to the United Kingdom at a later age. All participants were in the United Kingdom at the time of the study (mean length of stay = 73.50 months, SD = 74.42, range = 0.26–383.85).

2.2. Orthographic depth

Participants were divided into two groups based on the orthographic depth of their L1 and L2. Second language was determined based on AoA and confirmed via participants' self-reported most proficient languages acquired after their L1. Orthographic depth was determined by the relative depth of the L2 orthography compared to the L1 orthography. For example, English and Mandarin Chinese would both be considered orthographically deep languages; however, Mandarin is orthographically deeper than English. Thus, if a participant's L1 was Mandarin and their second most proficient language was English, the participant was considered a Deeper-to-Shallower (D-to-S) orthographic language learner. Conversely, if a participant's L1 was English and their second most proficient language was Mandarin, the participant was considered a Shallower-to-Deeper (S-to-D) orthographic language learner. The dataset included 9 D-to-S group participants (6 females, mean age = 28.22 years, SD = 7.89, range = 18–44) and 53 S-to-D group participants (42 females, mean age = 32.69 years, SD = 7.52, range = 21–52).

Given the difference in group sample size, we used propensity score matching to create a comparably sized group of S-to-D participants for matched subset analyses. In the matched subset analysis, participants were matched on age, sex, IQ, L2 AoA, and length of stay in the UK. The 18-participant matched subsample (11 females, mean age = 29.44 years, SD = 7.58, range = 18–44) included 9 D-to-S group participants (6 females, mean age = 28.22 years, SD = 7.89, range = 18–14) and 9 S-to-D group participants (5 females, mean age = 30.67 years, SD = 7.52, range = 21–43).

2.3. Linguistic distance

The linguistic distance between L1 and L2 was determined based on Liu and Cao (2016). The linguistic distance was obtained by subtracting the orthographic depth ranking of the L2 from that of the L1. Those participants who spoke a language not ranked by Liu and Cao (2016) were not included in this analysis. Table 1 presents the frequency of the linguistic distances among selected participants.

2.4. MRI data acquisition

Neuroimaging data were acquired on a 3T Siemens MAGNETOM Trio MRI scanner with a 32-channel head coil. High-resolution T1-weighted images were collected for each participant using a 3D magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence (256 sagittal slices, 0.7-mm slice thickness, acquisition matrix 246 × 256 mm, echo time (TE) = 2.41 ms, repetition time (TR) = 2400 ms, inversion time = 1140 ms, flip angle = 8°), which were used as anatomical references. Participants were instructed to keep their eyes open during the resting-state scan. Resting-state functional images were obtained in 68 2.0-mm-thick transverse slices, covering the entire brain (300 vol, field-of-view (FOV): 192 × 192, voxel size 2.1 × 2.1 × 2.0 mm, TR = 1500 ms, TE = 30 ms, flip angle = 66°).

2.5. Functional connectivity analysis

Resting-state functional connectivity data were preprocessed and analyzed using the CONN toolbox (Whitfield-Gabrieli and Nieto-Castanon, 2012) with SPM12 (Wellcome Department of Imaging Neuroscience, London, UK). Using standard spatial preprocessing steps, images were despiked, slice-time corrected, motion-corrected, realigned and resliced, normalized to the MNI 152-subject template, and smoothed using a 4 mm full width at half maximum (FWHM) isotropic Gaussian kernel, and bandpass filtered (0.01–0.08 Hz). Physiological and other spurious sources of noise were estimated using the anatomical Compcor method (aCompcor; Behzadi et al., 2007; Chai et al., 2012), and removed together with white matter, CSF, and movement-related covariates. Furthermore, artifact/outlier scans were regressed out from the analysis. Outlier scans were identified using ART (Artifact Detection Tools; https://www.nitrc.org/projects/artifact_detect/) and were defined as images with average intensity deviated more than 3 SDs from the mean intensity in the session or composite head movement exceeded 1 mm from the previous image. Functional connectivity analyses were performed using a seed-to-whole brain approach. Seed-to-voxel correlations were performed by estimating the temporal correlations between the blood oxygen level-dependent (BOLD) signal in our a priori ROIs (seed regions) and the BOLD signal in every other brain voxel. We performed the resting-state connectivity analysis on the following seed regions: Visual Word Form Area (VWFA; −45, −57, −12; Dehaene and Cohen, 2011) and its right-hemisphere homologue, as well as the left and right pSMG (+/−55, −46, 33). First-level correlation maps were produced by extracting the residual BOLD time course from each seed and computing Pearson’s correlation coefficients between that time course and the time course of all other voxels. Coefficients were converted to z-scores using Fisher’s transformation to allow for second-level analyses.

2.6. Analytical Plan

To investigate if differences in orthographic depth corresponded to differences in the strength of multilinguals’ intrinsic functional connectivity, we conducted three primary analyses. First, a one-way ANCOVA was used to investigate if differences in intrinsic connectivity existed between D-to-S and S-to-D multilinguals. Covariates included multilinguals’ sex, age, performance IQ, L2 AoA, as well as L1 and L2 reading and writing proficiency. Given the difference in sample size between the D-to-S and S-to-D multilinguals, a follow-up analysis was conducted after using propensity score matching to create a comparably sized group matched on individual characteristics. As such, the matched sample included only multilinguals' L1 and L2 reading and writing proficiency as covariates. Second, a multiple regression analysis was employed to investigate if differences in intrinsic connectivity were due to the orthographic distance between multilinguals' L1 and L2 across both groups. This was followed by two within-group (D-to-S & S-to-D) multiple regression analyses to determine if either group was driving the results. The latter allowed us to determine if multilingual's differences in intrinsic connectivity due to orthographic distance were also impacted by the order of language acquisition. Third, a 2 × 2 mixed ANCOVA determined if intrinsic connectivity differs between D-to-S and S-to-D trilinguals and bilinguals.

3. Results

3.1. Descriptive statistics

Table 2 presents the descriptive statistics for the full sample, D-to-S group, and S-to-D group. There were no significant differences between the groups in age, IQ score, length of stay in the UK, and L1 and L2 reading and writing proficiency. However, the L2 AoA for the S-to-D group was significantly higher than the D-to-S group, $t^{60} = -0.420$, $p < .001$, indicating that the S-to-D group acquired their L2 later than the D-to-S group by roughly six years (see Table 2).

3.2. Are there differences between D-to-S and S-to-D multilinguals' intrinsic connectivity?

To elucidate the neural mechanisms that underlie cross-language transfer effects, we investigated the order of language acquisition by orthographic depth in the L1 and L2 of a sample of multilinguals (N = 62). We hypothesized that individuals with a shallower L2 (D-to-S group) would show increased reliance on phonological regions while individuals with a deeper L2 (S-to-D group) would show increase reliance on lexical regions to accommodate the more complex mapping between orthography and phonology in the deeper L2.

A one-way ANCOVA revealed differences between the D-to-S and S-to-D groups, after controlling for sex, age, performance IQ, L2 AoA, as well as L1 and L2 reading and writing proficiency. For individuals with a shallower L2, greater activation was found between the left pSMG (seed region) and two right hemisphere clusters, $t^{52} > 3.49$ $p < .001$, FDR cluster corrected at $p < .05$; k > 107 (see Fig. 1). Increased connectivity was found between the left pSMG and a cluster comprised of the right SMG and right angular gyrus (k ≥ 153; cluster coordinates: 64 −44 22) and a cluster that included the right precuneus and cuneal cortex (k ≥ 107; cluster coordinates: 12 −74 26). No group differences in connectivity were found when the VWFA, its right hemisphere homologue, or the right pSMG were used as seed regions.

As no group differences were found when the VWFA was used as a seed region, within-group analyses were performed using only the left pSMG as a seed region. For those who acquired a deeper L2 than their L1 (S-to-D group), stronger connectivity was found between the left pSMG (seed region) and several left hemisphere clusters, as well as negative connectivity in a cluster in the right hemisphere, $t^{53} > 3.48$ $p < .001$, FDR cluster corrected at $p < .05$; k ≥ 70 (see Fig. 2 top panel). Stronger connectivity was found between the left pSMG and the left middle frontal gyrus (k ≥ 156; cluster coordinates: −36 20 40), par triangularis of the IFG (k ≥ 112; cluster coordinates: −52 32 18), angular gyrus (k ≥ 85; cluster coordinates: 36 −50 36), frontal pole (k ≥ 85; cluster coordinates: −8 66 −18), posterior and temporooccipital middle temporal gyrus (k ≥ 75; cluster coordinates: 66 −44 4), and anterior SMG (k ≥ 70; cluster coordinates: 58 −44 48). Negative connectivity was found between the left pSMG and the right precuneus (k ≥ 91; cluster coordinates: 14 64 16).

For multilinguals that acquired a shallower L2 than their L1 (D-to-S group), preliminary evidence indicated stronger connectivity between the left pSMG and five right-hemisphere clusters, $t^{53} > 3.48$ $p < .001$, FDR cluster corrected at $p < .05$; k ≥ 73 (see Fig. 2 bottom panel). Stronger connectivity was found between the left pSMG and a cluster that included the right pSMG and angular gyrus (k ≥ 292; cluster coordinates: 64 −42 22), the middle frontal gyrus and frontal pole (k ≥ 132; cluster coordinates: 28 38 32), precuneus, posterior cingulate gyrus, and precentral gyrus (k ≥ 110; cluster coordinates: 4 −24 48), superior frontal gyrus (k ≥ 86; cluster coordinates: 14 8 72), and the anterior cingulate gyrus (k ≥ 73; cluster coordinates: 8 24 24).

3.2.1. Matched subsample analysis—

As the D-to-S group had a smaller number of participants than the S-to-D group, propensity score matching was used to create a matched subsample of S-to-D group participants. Specifically, nine S-to-D group participants (5 females, mean age = 30.67 years, SD = 7.52, range = 21–43) were matched to the nine D-to-S group participants (6 females, mean age = 28.22 years, SD = 7.89, range = 18–44) on age, IQ, sex, L2 AoA, and length of stay in the UK. Table 3 presents the descriptive statistics for the participants included in the matched subsample analysis. As in the whole sample analysis, no differences were found between L1 and L2 reading and writing proficiency between the two groups (see Table 3).

As in our primary analysis, a one-way ANCOVA revealed differences between the D-to-S and S-to-D matched groups, after controlling L1 and L2 reading and writing proficiency. Individuals with a shallower L2 (D-to-S group) had stronger connectivity between the left pSMG (seed region) and two clusters, $t^{12} > 4.32$ $p < .001$, FDR cluster corrected at $p <.05$; k ≥ 85 (see Fig. 3). Stronger connectivity was found between the left pSMG and a central cluster including the precuneus and posterior cingulate gyrus (k ≥ 145; cluster coordinates: 0 −32 36), as well as the left anterior SMG (k ≥ 85; cluster coordinates: 54 −44 36). Again, we found no group differences in connectivity when the VWFA, its right hemisphere homologue, or the right pSMG were used as seed regions.

3.3. Does the distance in orthographic depth between multilinguals' first two languages alter their intrinsic connectivity?

To determine if the intrinsic connectivity of multilinguals differed due to the linguistic difference between languages (e.g., the orthographic depth of Italian is closer to Spanish than English), and not just the order of orthographic depth language acquisition (e.g., L1 shallower than L2), we investigated multilinguals' intrinsic functional connectivity based on the distance in orthographic depth between their L2 and L1. We hypothesized that languages further apart in orthographic depth would show greater connections between our seed regions and regions in the frontal cortex and right hemisphere.

Using only those participants whose L1 and L2 languages were included in Liu and Cao's (2016) orthographic depth rankings (N = 39, 30 females, mean age = 33.08 years, SD = 8.52, range = 18–52), we ran a multiple regression. Table 4 shows the demographic information and descriptive statistics for the sample.

We found that intrinsic connectivity differs due to the difference in orthographic depth between participants' first and second languages, even after controlling for L1 and L2 literacy proficiency, sex, age, performance IQ, and L2 AoA. The greater the linguistic distance, the more negative connectivity there was between the left pSMG (seed region) and three clusters ($t^{29} > 3.66$, $p < .001$, FDR cluster corrected at 0.001; k ≥ 76): right pSMG (k = 89; cluster coordinates: 68 −42 22), right frontal pole/MFG (k = 86; cluster coordinates: 32 42 46), and a cluster that included the right IFG pars opercularis, insular cortex, and frontal operculum cortex (k = 76; cluster coordinates: 42 20 8; Fig. 4 top panel). Further, the greater the linguistic distance, the more negative connectivity there was between the VWFA (seed region) and the left precuneus ($t^{29} > 3.66$, $p < .001$, FDR cluster corrected at 0.001; k ≥ 534; cluster coordinates: 06 −66 14; Fig. 4 bottom panel).

To determine if the linguistic distance between multilinguals' first two languages was impacted by the order of language acquisition, planned follow-up analyses were run within each group. Multiple regression revealed that intrinsic connectivity differed in the S-to-D group (N = 33, mean orthographic distance = 8.36, SD = 4.06, range = 1–17) due to the difference in orthographic depth between their L2 and L1. The greater the distance in orthographic depth between S-to-D multilinguals' L2 and L1, the stronger the connectivity between the left VWFA (seed region) and the left precuneus ($t^{29} > 3.66$, $p < .001$, FDR cluster corrected at 0.001; k ≥ 216; cluster coordinates: 8 −66 14). No differences were found in the S-to-D group when the pSMG was used as a seed region. A preliminary analysis was run to gain insight into how the distance in orthographic depth between D-to-S multilinguals' (N = 6, mean orthographic distance = 8.50, SD = 6.03, range = 2–15) L2 and L1 may alter their intrinsic connectivity. However, likely due to the small sample size, no differences were found in the D-to-S group when either the pSMG or the VWFA was used as a seed region.

3.4. Are there differences in the intrinsic connectivity between trilinguals and bilinguals?

All multilingual participants in the current study spoke at minimum two languages. We investigated differences in intrinsic connectivity between those who spoke two languages (bilinguals) and those who spoke at least three languages (trilinguals; see Table 5). We hypothesized that stronger connectivity from the pSMG but not the VWFA seed region would differentiate groups based on the increased lexical equivalents. A 2 × 2 mixed ANCOVA revealed differences between D-to-S and S-to-D trilinguals and bilinguals, $F^{3,55} > 6.25$, $p < .001$, FDR cluster corrected at 0.05; k ≥ 142, even after controlling for sex, age, and performance IQ. Results indicated increased connectivity between the left pSMG seed region and the right precuneus (k = 142; cluster coordinates: 4 −46 42; Fig. 5). No differences were found when the VWFA, its right hemisphere homologue, or the right pSMG were used as seed regions.

To unpack the results of the interaction, follow-up analyses were run, revealing that the interaction was driven by the difference between the two groups of trilinguals, $t^{57} > 3.47$, $p <$ .001, FDR cluster corrected at 0.05; k ≥ 90. Stronger intrinsic connectivity was found for the D-to-S trilingual group compared to the S-to-D trilingual group between the left pSMG seed region and the right precuneus (k = 154; cluster coordinates: 4 −46 42), right temporal pole (k = 93; cluster coordinates: 40 16 −32), and the anterior cingulate gyrus (k = 90; cluster coordinates: 4 −4 34; Fig. 6). No differences in pSMG connectivity were found between D-to-S and S-to-D bilinguals.

4. Discussion

There is much evidence that learning another language alters the brain (see Sulpizio et al., 2020a,b and Hull and Vaid, 2007 for meta-analyses). An open question is how diverse language experiences result in neurobiological variation. While some language experience factors are well studied, such as L2 AoA (e.g., Perani et al., 2003; Berken et al., 2016) and language proficiency (e.g., Deluca et al., 2019; Li et al., 2015; Sulpizio et al., 2020), little research effort has been dedicated to understanding the role of orthographic depth in shaping the intrinsic functional connectivity of multilinguals. As such, the goal of the current study was to determine if differences in orthographic depth corresponded to differences in the intrinsic functional connectivity of multilinguals. Using seed-to-whole brain resting-state connectivity analyses, we examined three key questions. First, does the order of language acquisition with respect to orthographic depth correspond to multilinguals' intrinsic connectivity? Second, is the linguistic distance, the difference between two languages' orthographic depth, associated with multilinguals' intrinsic connectivity? Finally, does intrinsic functional connectivity differ between multilinguals who speak at least three languages (trilinguals) and those who speak two languages (bilinguals)? Below we discuss our findings in turn.

4.1. Does the order of language acquisition with respect to orthographic depth correspond to multilinguals' intrinsic connectivity?

We hypothesized that differences in the intrinsic connectivity circuits connected to the VWFA and pSMG would exist between groups of D-to-S and S-to-D multilinguals to accommodate differences in language acquisition order with respect to orthographic depth. Results showed stronger connectivity between the left pSMG seed region and two right hemisphere clusters in individuals with shallower L2 orthography (D-to-S group) compared to those with a deeper L2 orthography (S-to-D group). Stronger connectivity was found even after covarying by sex, age, performance IQ, L2 AoA, as well as L1 and L2 literacy proficiency. Specifically, stronger connectivity was found between the left pSMG seed region and the inferior parietal lobe, which includes the right pSMG and right angular gyrus as well as a cluster that included the right precuneus and cuneal cortex.

To be understood, multilinguals become proficient at language switching, adjusting their language use to accommodate another speaker's language knowledge. During fMRI language switching tasks, the left SMG has been found to bias language away from the language not in use, while the right SMG has been found to bias language towards the language in use (Abutalebi and Green, 2008; Price et al., 1999). Our finding, stronger connectivity between the left pSMG (seed region) and the right pSMG, suggests that individuals with a shallower L2 orthography (D-to-S group) may need to make greater use of language switching coordination, biasing both towards (right SMG) and away from (left pSMG) the language in use compared to individuals with deeper L2 (S-to-D group).

The right angular gyrus is involved in inhibition (Wager et al., 2005), conflict resolution (Nee et al., 2007), and, in coordination with the left angular gyrus, memory retrieval (e.g., Spaniol et al., 2009; Vilberg and Rugg, 2008). In aging populations, a negative relationship has been reported between cognitive decline and gray matter volume in the inferior parietal lobe, specifically the angular gyrus (e.g., Saykin et al., 2006; Smith et al., 2007). In contrast, Della Rosa and colleagues (2013) have found increased gray matter density in the angular gyrus, which corresponded to language competence and the ability to resolve non-verbal conflicts. Abutalebi and colleagues (2015) directly compared healthy aging bilinguals to monolinguals; they found a negative correlation between age and gray matter volume in the right inferior parietal lobe for monolinguals but not bilinguals. Further, when they divided the bilinguals into groups (Cantonese-English & Mandarin-Cantonese), their results suggested that conflict between two close and similar languages is likely greater than two dissimilar languages. Therefore, the stronger connectivity between the left pSMG (seed region) and the right angular gyrus found in the current study, may suggest that individuals with a shallower L2 orthography (D-to-S group) may need to make greater use of linguistic conflict resolution than individuals with a deeper L2 orthography (S-to-Dgroup).

When we compared individuals whose L2 orthography was shallower (D-to-S group) to those whose L2 orthography was deeper (D-to-S group), we also found increased connectivity between the left pSMG seed region and the right precuneus/cuneal cortex. This is consistent with reports of bilingual conflict monitoring. For example, during a nonlanguage conflict monitoring task, bilinguals demonstrated increased activation of the right precuneus (Abutalebi et al., 2012). This suggests that individuals with a shallower L2 orthography may need to make greater use of the connection between conflict monitoring (right precuneus) and bias away from the language in use (left pSMG).

While we also hypothesized differences between groups in intrinsic connectivity circuits connected to the VWFA, we did not find evidence of this difference. This may be attributable to the relatively small number of individuals in the D-to-S group as compared to the S-to-D group. The S-to-D group were hypothesized to rely more than the D-to-S group on lexical regions to accommodate their use of more complex mapping between orthography and phonology. Follow-up within-group analyses were run to determine if our hypothesized orthographic depth results emerged. Specifically, we hypothesized that the D-to-S group would show increased reliance on phonological regions (e.g., bilateral superior/middle temporal and precentral gyri), while S-to-D group would show increased reliance on lexical regions (e.g., left frontal cortex).

Results revealed considerable differences. When we examined only those individuals who acquired a deeper L2 compared to their L1 (S-to-D group), we found increased connectivity between the left pSMG and several left hemisphere clusters, including the left MFG, par triangularis of the IFG, angular gyrus, frontal pole, middle temporal gyrus, and anterior SMG. Negative connectivity was also observed between the left pSMG and the right precuneus. These results are consistent with the Orthographic Depth Hypotheses (Katz and Frost, 1992) and studies showing greater activation of the left frontal gyri in L2 processing when learning a deeper L2 (e.g., Liu and Cao, 2016; Liu et al., 2007; Nelson et al., 2009). Similarly, when we examined only those individuals who acquired a shallower L2 (D-to-S group), we found increased connectivity between the left pSMG and five right-hemisphere clusters, including the right pSMG and angular gyrus, MFG and frontal pole, precuneus, posterior cingulate gyrus, and precentral gyrus, superior frontal gyrus, and anterior cingulate gyrus. These within-group results are also consistent with our hypothesis and with prior results. For example, Liu and Cao (2016) reported that D-to-S bilinguals had activation in their bilateral auditory cortex and precentral gyri during L2 processing, regions consistent with phonological processing. Taken together, our results demonstrate both support for the Orthographic Depth Hypothesis and coordination of a complex system of language conflict monitoring, resolution, and switching that likely greater network coordination in those individuals with a shallower L2.

4.2. Is the distance between two languages’ orthographic depth associated with multilinguals’ intrinsic connectivity?

Green and Abutalebi’s (2013) Adaptive Control Hypothesis posits that constant management of two competing languages requires general cognitive control mechanisms, which should differ based on context. In line with their hypothesis, we aimed to determine if these mechanisms differed based on the difference in orthographic depth between two languages (i.e., linguistic distance). We found that the greater the linguistic distance between two languages, the greater the negative connectivity between our left-hemisphere seed regions (pSMG and VWFA) and clusters in both the right and left hemispheres.

When we investigated the effects of linguistic distance on intrinsic functional connectivity using the left pSMG as the seed region, greater negative connectivity was found between the left pSMG and three clusters, including the right pSMG, a cluster that included the right pars opercularis of the IFG, insular cortex, and frontal operculum cortex, and a cluster comprised of the right frontal pole and middle frontal gyrus. The increase in negative connectivity between the left pSMG and right pSMG suggests that the greater the linguistic distance, the less language use biasing that was needed.

Greater negative connectivity was also found between the left pSMG and the right IFG pars opercularis, frontal operculum cortex, and insular cortex. Increased bilateral activation of the inferior frontal gyrus has been reported in language tasks conducted in deeper orthographies (e. g., Paulesu, 2000). The right IFG, in particular, shows increased activation when bilinguals perform lexical-semantic tasks (Sulpizio et al., 2020) and tasks that require domain-general inhibitory control (Aron et al., 2004, 2014). Bilaterally, the frontal operculum plays a key role in regulating increases and decreases in activity in occipitotemporal cortical areas (Dosenbach et al., 2006, 2007). Studies have shown that the functional connectivity between the frontal operculum and specific regions of the occipitotemporal cortex become positive or negative depending upon which task stimuli need to be attended to and which stimuli need to be ignored (Higo et al., 2011). In addition, while the insular cortex is known to be involved in linguistic and non-linguistic control functions (e.g., Price, 2010), it also plays a key role in the detection of relevant stimuli (Gogolla, 2017). Taken together, the greater negative connectivity between the pSMG and the cluster including the right IFG pars opercularis, frontal operculum cortex, and insular cortex suggest a complex relation. It appears that the greater the linguistic distance between a multilingual’s first two languages, the more negative connectivity between the regions that regulate inhibitory control, activation of the occipitotemporal cortical areas, and those regions involved in the detection of relevant stimuli. Therefore, our results suggest that it may require less cortical coordination to be a multilingual with two orthographically distinct sets of language expectations, as compared to a multilingual whose first and second languages are either both orthographically shallow or orthographically deep.

Greater negative connectivity, corresponding to increased linguistic distance, was also found between the left pSMG and a second right-hemisphere frontal lobe cluster, one that included the right frontal pole and right MFG. The right MFG plays a critical role in reorienting attention from exogenous (involuntary, stimulus-driven attention) to endogenous (goal-directed attention; Japee et al., 2015). Increased activation is found in the right MFG when bilinguals’ second language phonology is compared to first language phonology but not when bilinguals’ first language phonology is compared to second language phonology (Sulpizio et al., 2020). Framed as such, bilinguals are moving attention to the goal-directed task (i.e., second language phonology) and away from their involuntary first language phonological response. Additionally, the second component of the cluster is the frontal pole, which includes the ventromedial prefrontal cortex (vmPFC) and the lateral frontopolar cortex (lFPC). The vmPFC helps promote the monitoring of outcomes expected from an ongoing course of action. Together, this indicates that less cortical coordination is needed between language biasing, goal-oriented attention, monitoring when multilinguals have two orthographically distinct sets of language expectations.

Finally, we found that increased linguistic distance corresponded to greater negative connectivity between the VWFA and the left precuneus. Prior evidence suggests that the left precuneus may be a brain region that is used to differentiate between levels of languages’ phonological-to-orthographic correspondence. The left precuneus is one of several regions that demonstrate greater activation in deeper orthographies (e.g., Halsband, 2006). It is also a region that is thought to coordinate directing selective attention (Utevsky et al., 2014). Further, coordination of activation between the VWFA and left precuneus has previously been attributed to the attunement of orthographic regularities during the acquisition of literacy, particularly when words are presented in the right visual field (Cohen et al., 2002). In the current study, greater negative connectivity between the VWFA and left precuneus, in more orthographically distinct languages, likely indicates less need to coordinate attention for word recognition in the correct language.

4.3. Does intrinsic functional connectivity differ between multilinguals who speak at least three languages (trilinguals) and those who speak two languages (bilinguals)?

Previous research suggests that the pSMG is involved in linking new words and lexical equivalents (e.g., Richardson et al., 2010). In the current study, we expand those findings, revealing that the connection between the left pSMG and the right precuneus was driven not only by the difference in bilingualism versus trilingualism, as has been previously reported, but also by the difference in relative orthographic depth between the L1 and L2. Specifically, results of the current study demonstrate that intrinsic functional connectivity can differentiate between languages' relative orthographic depth as well as between bilingualism and trilingualism. Intrinsic connectivity differences were found between the left pSMG and the right precuneus when we compared bilinguals and trilinguals whose L2 orthography was shallower than their L1 as compared to those whose L2 orthography was deeper than their L1. Follow-up analyses revealed that the interaction was the result of differences between trilinguals.

Stronger intrinsic connectivity was found for trilinguals whose L2 orthography was shallower (D-to-S trilingual group) compared to those whose L2 orthography was deeper (S-to-D trilingual Group) between the pSMG and the right precuneus, right temporal pole, and the anterior cingulate gyrus. The right temporal pole is one of several regions with greater gray matter volume in bilinguals compared to monolinguals (Abutalebi et al., 2014; Vaughn et al., 2021) and has been reported in response to viewing familiar faces and familiar buildings (Nakamura et al., 2000; Grabowski et al., 2001) and emotional recognition (Kumfor et al., 2016). The anterior cingulate gyrus is involved in tracking information about others (e.g., Apps et al., 2016) and has been found to play a role in language-switching perception rather than production (Blanco-Elorrieta and Pylkkanen, 2016). This suggests that trilinguals, with a shallower L2 orthography, may need to make greater use of the connections between conflict monitoring, others facial emotional cues, and lexical equivalents, bias away from the language in use, for language comprehension.

4.4. Limitations

A limitation of the current study is the difference in sample size between the two groups. The S-to-D group contained 53 participants while the D-to-S group contained only nine participants. To ameliorate the effects of the mismatch in sample size, subsample analyses were performed. The difference between the matched group of S-to-D participants and the D-to-S group yielded similar connectivity differences as the whole sample. Specifically, stronger functional connectivity was found between the left pSMG and the precuneus and cingulate gyrus for the subsample of D-to-S group compared to S-to-D group. In the subsample, the remainder of the significant full sample results were found but did not survive correction for multiple comparisons. Future studies may wish to collect data with trilingual orthographic depth groups of comparable size, matched on L2 AoA, sex, and performance IQ, to gain a better understanding of the group differences due to the relative orthographic depth between L1 and L2.

5. Conclusions

The findings of this study suggest that multilinguals' intrinsic functional connectivity is shaped by the orthographic depth of their L2 in relation to L1, as well as differences between bilingualism and trilingualism. The increased connectivity between the left pSMG and cognitive regions, such as the precuneus and cingulate gyrus, as well as the interhemispheric brain connections in those with a shallower L2, compared to those with a deeper L2, may reflect greater utilization of language switching coordination, conflict monitoring, and conflict resolution in transitioning from a deeper L1 to a shallower L2. Consistent with previous studies, when we focused on only those individuals with a shallower L1 and deeper L2, our results were consistent with the expectations of the orthographic depth hypothesis. Individuals with a deeper L2 had connectivity networks with greater reliance on lexical regions to accommodate the more complex mapping between phonology and orthography. Similarly, when we focused on only individuals with a deeper L1 and shallower L2, connectivity networks showed greater reliance on phonological regions. Moreover, the greater linguistic orthographic distance between a multilinguals' L1 and L2, the less cortical coordination was needed between language biasing, goal-oriented attention, and monitoring. There was also less need to coordinate attention for word recognition when multilinguals have two orthographically distinct sets of language expectations. Finally, trilinguals with a shallower L2 had stronger connectivity, compared to trilinguals with a deeper L2, between regions involved in conflict monitoring, the facial emotional cues of others, and bias away from the perception of language in use. Thus, we provide evidence of the role of relative orthographic depth between L1 and L2 in shaping multilinguals' functional neurobiology.

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Glossary

L1	first language
L2	second language
L3	third language
VWFA	visual word form area
pSMG	posterior supramarginal gyrus
MFG	middle frontal gyrus
IFG	inferior frontal gyrus
ROIs	regions of interest
AoA	age of acquisition

BOLD	blood oxygen level-dependent
vmPFC	ventromedial prefrontal cortex
lFPC	lateral frontopolar cortex.

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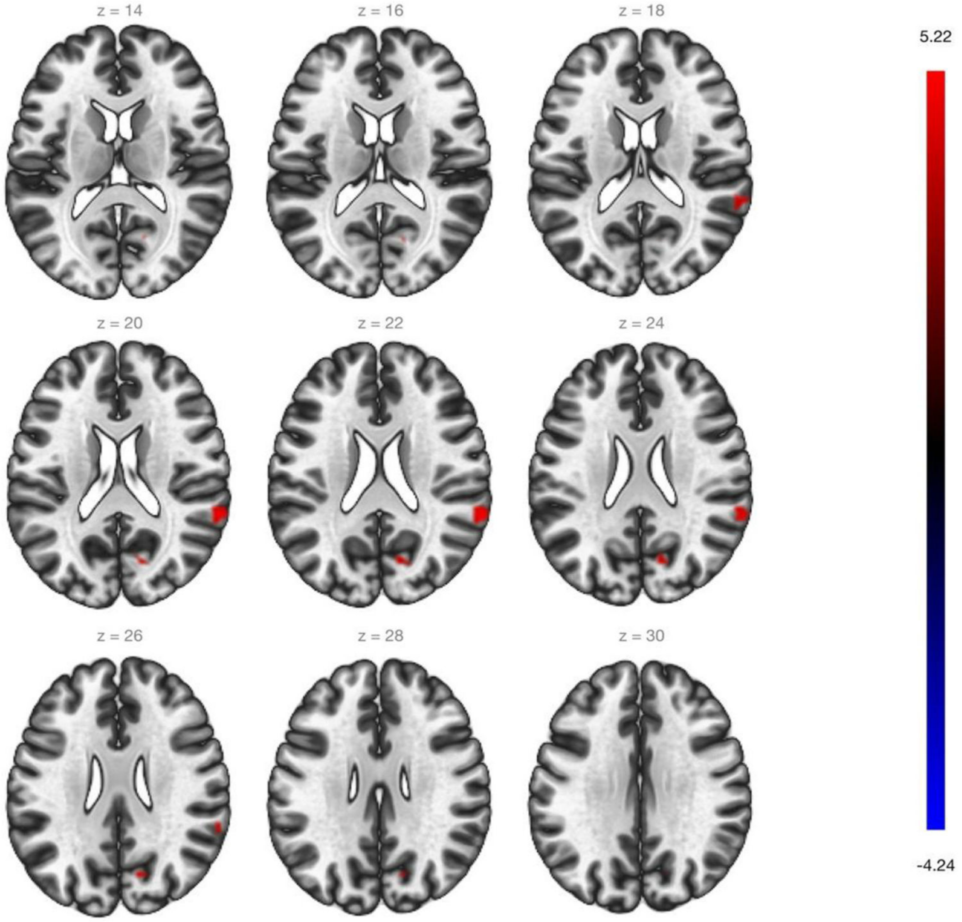

Fig. 1.

Difference in functional connectivity between the left pSMG and two right hemisphere clusters between the two groups (D-to-S > S-to-D). Increased connectivity was found between the left pSMG and a cluster that included the right SMG and right angular gyrus (z = 18 – 26) and a cluster that included the right precuneus and cuneal cortex (z = 20 – 28).

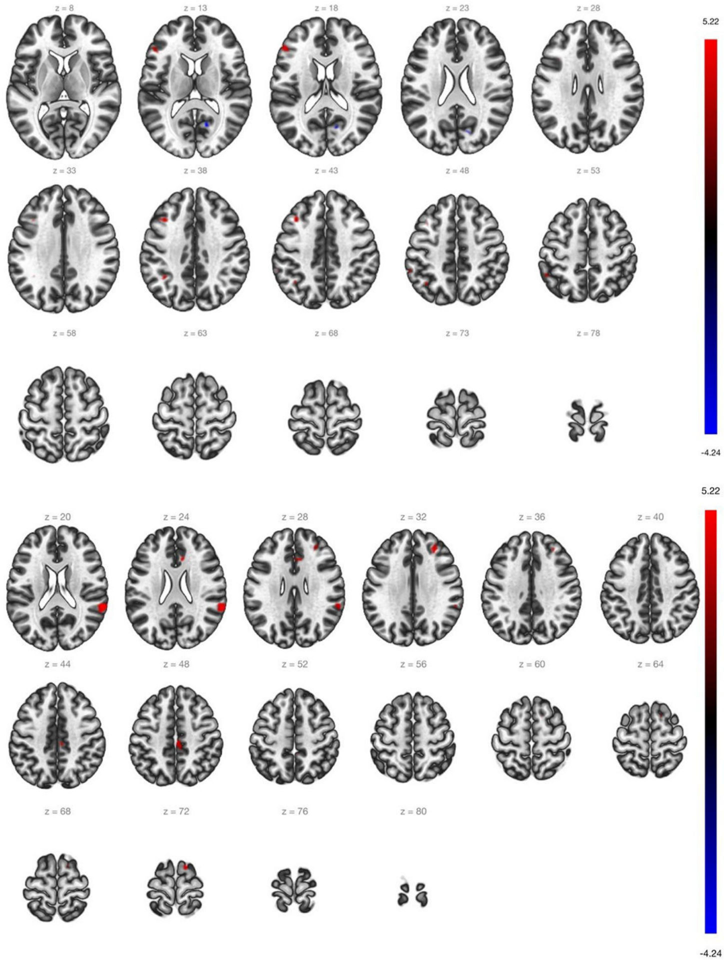

Fig. 2.

Top Panel. In the S-to-D group stronger connectivity was found between the left pSMG and the left middle frontal gyrus (z = 32 – 48), par triangularis of the IFG (z = 13 – 18), angular gyrus (z = 36), frontal pole (z = −18), posterior and temporo-occipital middle temporal gyrus (z = 4), and anterior SMG (z = 48 – 53). Negative connectivity was found between the left pSMG and the right precuneus (z = 13). Bottom Panel. In the D-to-S group stronger connectivity was found between the left pSMG and a cluster that included the right pSMG and angular gyus (z = 20 – 32), the middle frontal gyrus and frontal pole (z = 28 – 32), precuneus, posterior cingulate gyrus, and precentral gyrus (z = 44 – 48), superior frontal gyrus (z = 72), and the anterior cingulate gyrus (z = 24).

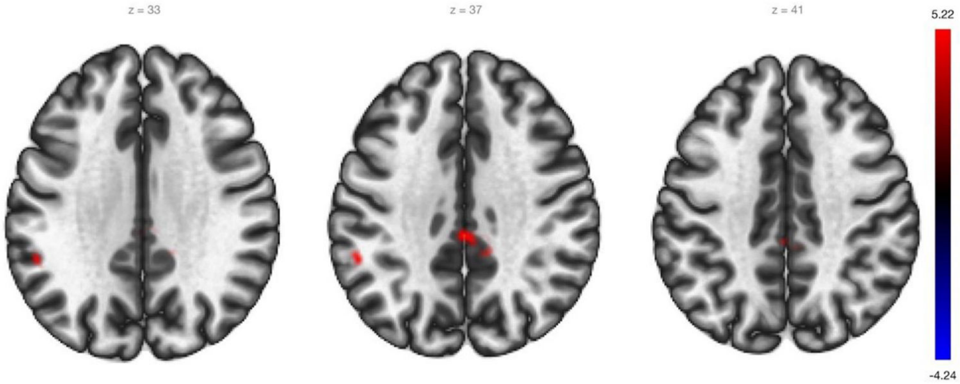

Fig. 3.

In the matched subsample analysis, stronger connectivity (D-to-S > S-to-D) was found between the left pSMG and a cluster including the precuneus and posterior cingulate gyrus (z = 33 – 41) and the left anterior SMG (z = 33 – 37).

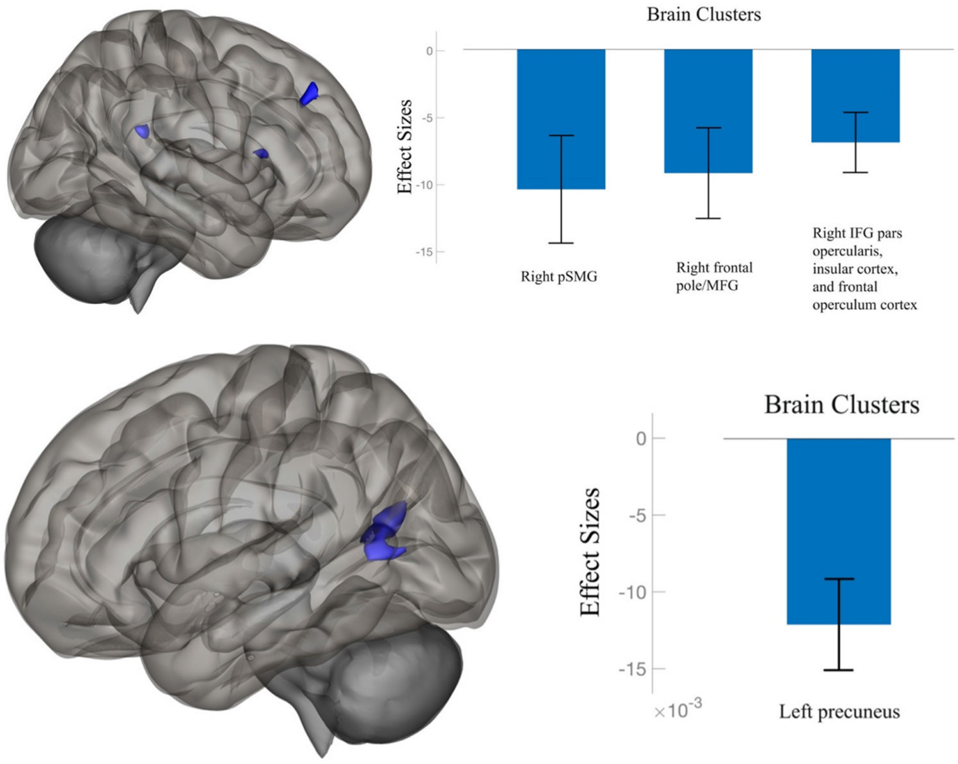

Fig. 4.

Top Panel. The greater the linguistic distance, the more negative connectivity there was between the left pSMG and three right-hemisphere clusters: (1) pSMG, (2) frontal pole and MFG, and (3) IFG pars opercularis, insular cortex, and frontal operculum cortex. Bottom Panel. The greater the linguistic distance, the more negative connectivity there was between the VWFA and the left precuneus.

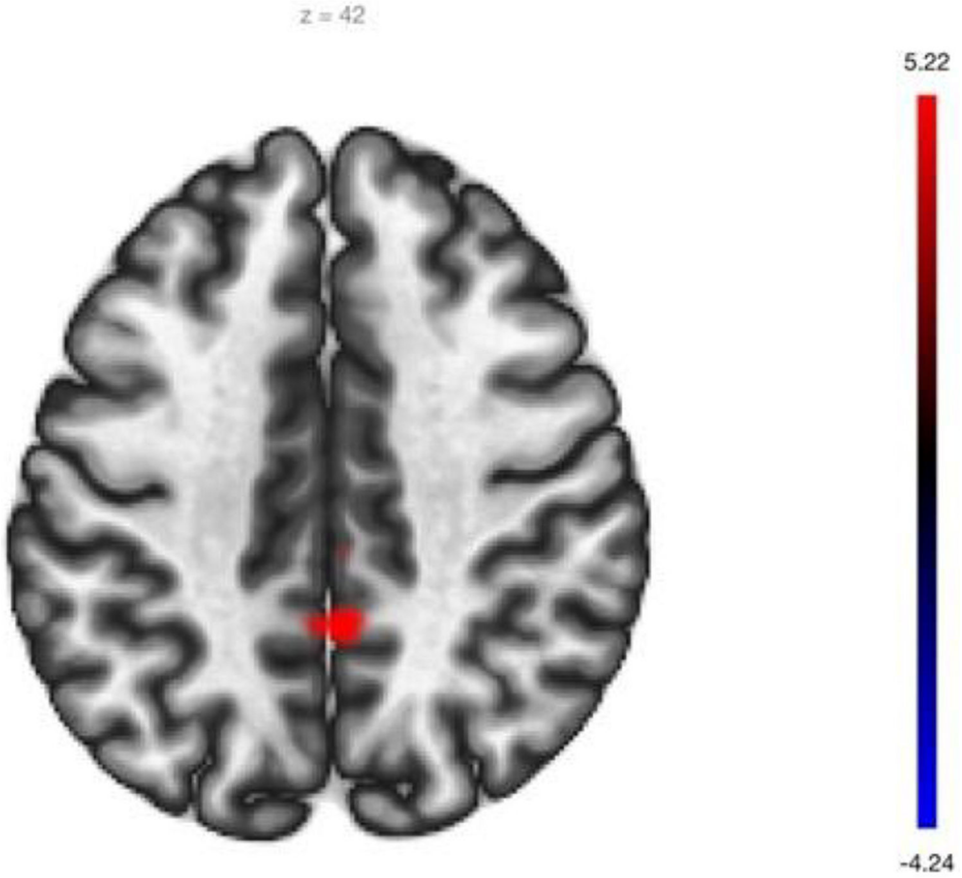

Fig. 5.

Results of the 2 × 2 mixed ANCOVA revealed stronger connectivity between the left pSMG seed region and the right precuneus.

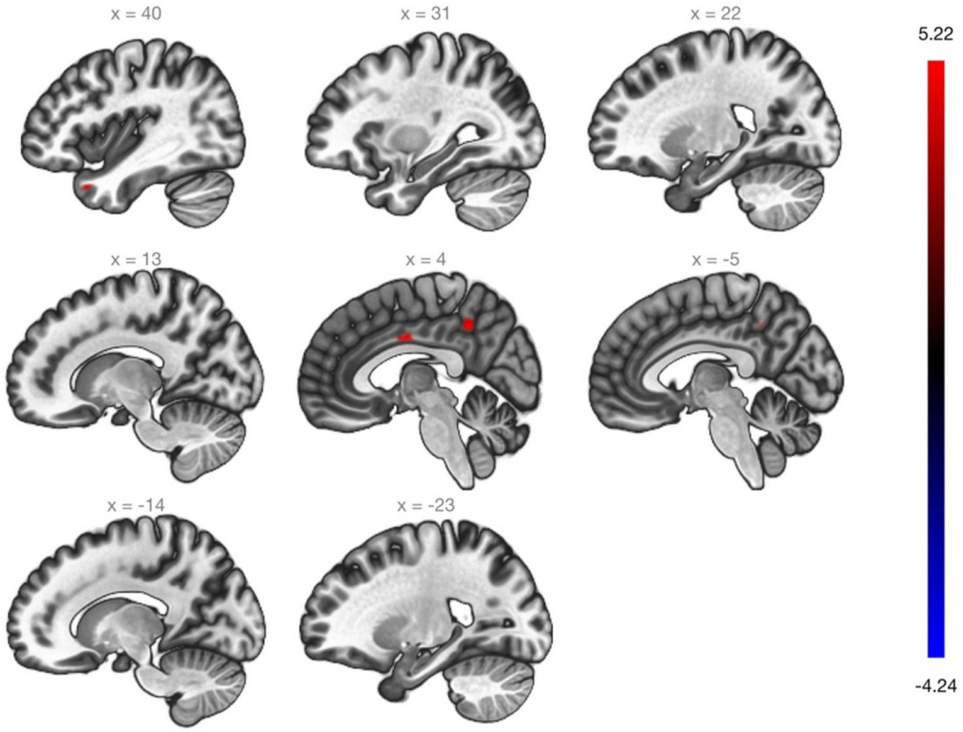

Fig. 6.

Stronger connectivity (D-to-S trilinguals > S-to-D trilinguals) between the left pSMG and the right precuneus (x = 4), right temporal pole (x = 40), and the anterior cingulate gyrus (x = 4).

Table 1

Frequency of the linguistic distance.

Distance	Frequency	Percent
1 (English & French)	2	5.1
2 (English & Chinese)	2	5.1
4 (English & Dutch)	4	10.3
6 (English & German)	12	30.8
9 (English & Portuguese)	1	2.6
11 (English & Spanish)	12	30.8
15 (English & Italian)	5	12.8
17 (English & Finnish)	1	2.6

Note. N = 39.

Table 2

Participants demographic information and descriptive statistics.

Variable	**Min.**	**Max.**	**Full sample**		**D-to-S group**		**S-to-D group**		***t***	***p***
			Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**		
Age (year)	18	52	32.05	7.67	28.22	7.89	32.69	7.52	−1.64	0.11
Raven’s Matrices IQ Score	32	54	42.26	5.10	41.44	5.98	42.40	4.98	−0.52	0.61
L2 AoA (year)	0	22	8.48	4.59	3.22	5.26	9.38	3.85	−4.20	<.001
Length of stay in the UK (month)	0.26	383.85	73.50	74.42	108.26	113.85	67.60	65.25	1.53	0.13
L1 reading proficiency	6	10	9.44	0.97	9.56	1.33	9.42	0.91	0.40	0.69
L1 writing proficiency	3	10	9.19	1.41	9.44	1.67	9.15	1.38	0.57	0.57
L2 reading proficiency	4	10	8.47	1.30	8.56	1.42	8.45	1.29	0.22	0.83
L2 writing proficiency	4	10	7.90	1.40	8.11	1.54	7.87	1.39	0.48	0.63

Note: Full sample N = 62; D-to-S group N = 9, including bilinguals whose L2 orthography was shallower than their L1; S-to-D group N = 53, including bilinguals whose L2 orthography was deeper than their L1.

Table 3

Matched subsample demographic information and descriptive statistics.

Variable	Min.	Max.	Full matched sample		D-to-S subgroup		S-to-D subgroup		*t*	*p*
			Mean	SD	Mean	SD	Mean	SD		
Age (year)	18	44	29.44	7.58	28.22	7.89	30.67	7.52	−0.67	0.51
Raven’s Matrices IQ Score	32	51	42.33	5.27	41.44	5.98	43.22	4.63	−0.71	0.49
L2 AoA (year)	0	14	5.28	4.84	3.22	5.26	7.33	3.54	−0.19	0.07
Length of stay in the UK (month)	5.53	383.85	102.15	100.49	108.26	113.85	96.03	91.72	0.25	0.81
L1 reading proficiency	6	10	9.67	1.03	9.56	1.33	9.78	0.67	−0.45	0.66
L1 writing proficiency	5	10	9.50	1.25	9.44	1.67	9.56	0.73	−0.18	0.86
L2 reading proficiency	6	10	8.78	1.26	8.56	1.42	9.00	1.12	−0.74	0.47
L2 writing proficiency	6	10	8.33	1.37	8.11	1.54	8.56	1.24	−0.68	0.51

Note: Full matched sample N = 18; D-to-S group N = 9, including bilinguals whose L2 orthography was shallower than their L1; S-to-D group N = 9, including bilinguals whose L2 orthography was deeper than their L1.

Table 4

Subsample demographic information and descriptive statistics.

Variable	**Min.**	**Max.**	**Mean**	**SD**
Age (year)	18	52	33.08	8.52
Raven's Matrices IQ Score	32	54	42.95	5.56
L2 AoA (year)	0	20	8.38	4.45
Length of stay in the UK (month)	0.69	383.85	76.96	84.93
L1 reading proficiency	8	10	9.69	0.73
L1 writing proficiency	7	10	9.62	0.88
L2 reading proficiency	4	10	8.59	1.43
L2 writing proficiency	4	10	8.13	1.49

Note. N = 39.

Table 5

Demographics and descriptive statistics by number of languages spoken.

Variable	Min.	Max.	Bilinguals		Trilinguals		Bilingual D-to-S group		Bilingual S-to-D group		Trilingual D-to-S group		Trilingual S-to-D group	
			Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Age (year)	18	52	31.74	8.11	32.25	7.33	27.33	9.00	32.80	7.70	30.00	6.24	32.61	7.49
Ravens Matrices Score (IQ)	32	54	41.94	5.05	42.58	5.20	41.83	6.68	41.96	4.76	40.67	5.51	42.79	5.23
L2 AoA (year)	0	22	8.71	5.01	8.26	4.21	4.83	5.91	9.64	4.41	0.00	0.00	9.14	3.35
Length of stay in the UK (month)	0.26	383.85	56.81	45.98	90.20	92.58	63.55	40.86	55.19	47.76	197.70	172.27	78.68	76.83
L1 reading proficiency	6	10	9.29	1.10	9.58	0.81	9.33	1.63	9.28	0.98	10.00	0.00	9.54	0.84
L1 writing proficiency	3	10	9.13	1.28	9.26	1.55	9.17	2.04	9.12	1.09	10.00	0.00	9.18	1.61
L2 reading proficiency	4	10	8.06	1.29	8.87	1.20	8.33	1.37	8.00	1.29	9.00	1.73	8.86	1.18
L2 writing proficiency	4	10	7.71	1.32	8.10	1.47	7.83	1.17	7.68	1.38	8.67	2.31	8.04	1.40

Note. Bilinguals N = 31, Trilinguals N = 31, Bilingual D-to-S group N = 6, Bilingual S-to-D group N = 25, Trilingual D-to-S group N = 3, Trilingual S-to-D group N = 28.