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Accepted Version

DeLuca, V., Rothman, J., Bialystok, E. and Pliatsikas, C. ORCID: https://orcid.org/0000-0001-7093-1773 (2019) Redefining bilingualism as a spectrum of experiences that differentially affect brain structure and function. Proceedings of the National Academy of Sciences of the United States of America, 116 (15). pp. 7565-7574. ISSN 0027-8424 doi: 10.1073/pnas.1811513116 Available at https://centaur.reading.ac.uk/82614/

To link to this article DOI: http://dx.doi.org/10.1073/pnas.1811513116

Publisher: National Academy of Sciences

AUTHOR'S ACCEPTED VERSION

To appear in the Proceedings of the National Academy of Sciences (PNAS)

Redefining bilingualism as a spectrum of experiences that differentially affect brain structure and function

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Classification:
Biological Sciences/Psychological and Cognitive Sciences, Social Sciences/Psychological and Cognitive Sciences

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Abstract

Learning and using an additional language is shown to have an impact on the structure and function of the brain, including in regions involved in cognitive control and the connections between them. However, the available evidence remains variable in terms of the localization, extent and trajectory of these effects. Variability likely stems from the fact that bilingualism has been routinely operationalized as a categorical variable (bilingual/monolingual), whereas it is a complex and dynamic experience with a number of potentially deterministic factors affecting neural plasticity. Here we present the first study investigating the combined effects of experience-based factors (EBFs) in bilingual language use on brain structure and functional connectivity. EBFs include an array of measures of everyday usage of a second language in different types of immersive settings (e.g., amount of use in social settings). Analyses reveal specific adaptations in the brain, both structural and functional, correlated to individual EBFs and their combined effects. Taken together the data show that the brain adapts to be maximally efficient in the processing and control of two languages, although modulated ultimately by individual language experience.

Significance Statement

This study sheds new light on the neuroanatomical adaptations resulting from bilingual language exposure and use, providing crucial insights into untangling the variability of findings in the existing literature. Our results demonstrate that differences in bilingual language experiences confer a range of systematic outcomes in terms of brain/mind adaptations. In doing so, our findings strongly support a shift away from traditional designs with bilingual vs. monolingual comparisons and towards an approach of modelling the experiences within bilingualism that give rise to neurocognitive adaptations. Crucially, we maintain that experience-based factors should be accounted for in all future studies investigating the effects of bilingualism on the brain and cognition.

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Introduction

Using more than one language has been found to impact both brain structure and function (1–3). Knowledge and use of an additional language creates two active representations that compete for selection at several levels of language processing and production (4, 5). Resolution is required for successful communication, yet places increased demands on both the linguistic and nonverbal executive control systems. The brain adapts both functionally and structurally to optimally handle these demands (6). Nevertheless, there is variability in specific effects of bilingualism across studies that is likely more systematic than might initially appear. A considerable portion of conflicting evidence likely stems, at least in part, from the inconsistency in how bilingualism is defined (7, 8) across studies. Reducing the dynamics of bilingualism to a discrete set of pre-defined aggregate groups collapses, and potentially obscures, factors that drive brain adaptations (9). Important differences clearly exist at the individual-to-individual level, and specific group-to-group levels, within the same and across subtypes of bilinguals. Thus, it is prudent to ponder why bilingualism is so often treated as a monolithic variable in relevant empirical studies.

Understanding the consequences of bilingualism on mind and brain requires a more nuanced examination of the predictive validity of various bilingual experiences to outcomes (language use, exposure, etc. and their relative weights) than is typically used. This study tests this general line of reasoning, sidestepping the possible comparative fallacy inherent to a monolingual versus bilingual binary designs. To do so, we focus instead on how bilingual experiences impact brain structure and functional connectivity where bilingualism is examined as a continuum. Variables that situate individuals along that continuum are modelled to better understand how the dynamic nature of bilingualism affects the brain differentially. In turn, there is potential for this approach to also shed light on the ongoing debate on the neurocognitive effects of bilingualism (10, 11).

Neural adaptations to bilingual language use are typically found in brain regions and pathways implicated in language processing and control. Discrepancies exist, however, between studies regarding where and how specific adaptations manifest in relation to bilingual language use, and the particular neuroimaging methods used (1, 12). Effects of bilingualism have been reported as differences in cortical and subcortical grey matter volume (13), subcortical shape differences (14, 15), differences in diffusivity patterns (e.g. fractional anisotropy (FA)) (16), and more. While some studies include several measures of neural adaptations, such as both structural and intrinsic functional connectivity changes (17), most examine only one type of adaptation, prompting calls for greater methodological consistency between studies (1). Perhaps more important is the acknowledgement that bilingualism itself reflects a multidimensional state of experiences, which might result in different adaptations to individuals with different language backgrounds. Indeed, Li and colleagues (2) suggested that the effects of bilingualism on the brain might rely on three main dependent factors: the *timing* of the acquisition of the second language (L2) with respect to the acquisition of the first language (L1), the L1-L2 interactions; the *nature* of L2 input, in terms of the intensity of something as complex as L2 learning; and the *extent* of L2 input, in terms of the amount of experiences and opportunities for using an L2, which might increase L2 proficiency and also cause commensurate and positively correlated neuroanatomical adaptations.[1]

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[1] They also speculate on a fourth potential factor of interest in their conclusion about which little is known. The role of L1-L2 typological distance—degree of overlap of the neurocognitive representations between the languages—might be deterministic for structural adaptations following from differential demands of control. See also (63) for a similar discussion related to how typological proximity impact multilingual grammatical development and processing for similar reasons of cognitive control differences.

Two proposals have attempted to explain observed variance with respect to bilingual language experiences, focusing primarily on the extent of the L2 input, as defined by Li and colleagues; these concepts are used to understand results from our empirical study. The Adaptive Control Hypothesis (ACH) (6, 18) states that language use context (single-language, dual-language, or dense code-switching) dictates the recruitment of the relevant networks best suited to handle the computational load. The Bilingual Anterior to Posterior and Subcortical Shift (BAPSS) model (19) states that reliance on specific networks changes from frontal regions to subcortical and posterior regions commensurate with increased L2 use. Following from these suggestions, a growing number of studies have begun to examine neuroanatomical effects of experience-based factors (EBFs) within bilingualism, for example L2 Age of Acquisition (AoA) (20, 21), length of immersion (15, 22) and L2 proficiency (23, 24). However, the factors addressed in available studies to date are limited because they were examined in (a) relatively narrow ranges, and (b) in (relative) isolation from each other. Thus, potential combined effects shared between variables are unknown. For example, L2 immersion provides an environment of intensive exposure to native input in the L2 and opportunities to use the L2 in ecologically authentic contexts, which, in turn, facilitate gating of the L1 (25). However, L2 immersion does not guarantee the same degree of L2 exposure, nor opportunity for use, across all individuals. An analysis that can model the relative weight/contribution of various EBFs across a large enough cohort— capturing, for example, relationships between duration and quantity of bilingual language use— could begin to uncover the underlying reasons for conflicting evidence in the literature.

The present study addresses this call by examining neuroanatomical impacts of two such factors and their combined effects; namely the duration and extent of bilingual language use of experienced bilinguals residing a country (UK) where their L2 (English) is the dominant language. In order to test the claim that reliance on brain regions and the structural and functional adaptations it confers depends on the amount of the bilingual experience as proposed in the BAPSS model, we examined the effects of two EBFs related to duration of L2 use: *L2 AoA*, to examine overall length of bilingual language use, and length of *L2 Immersion*, to examine length of bilingual language use in settings where exposure to the L2 is increased (25). To test the predictions of the ACH model, namely that structural and functional adaptations relate to the specific context of L2 use, we also examined measures related to the extent of engagement with the non-native language. We chose composite factor scores derived from the Language and Social Background Questionnaire (26) detailing (i) L2 engagement in *social/community settings* and (ii) L2 use in *home settings*, to further isolate potentially explanatory patterns of language use and adaptation. Specifically, although both scores give us a measure of exposure to at least a dual-language context, as defined by the ACH, L2 use at home might be a better indicator of it. Lower scores on this scale would indicate one primarily engages with L1 speakers (partner, family) at home, which make home an L1 domain, and broader social contexts a (potentially) L2 domain. Conversely, higher sores in *L2 in social settings* describe better a dense code-switching context, especially in multilingual communities where language-switching and mixing is common, as in the UK. Note that it would be particularly difficult to identify an EBF that would only measure dense-code-switching in the absence of a dual-language context, especially in our sample of people who have migrated in the UK. Finally, we also examined the effects of *active* L2 use through time, both overall (total length of exposure to English) and in their immersion timespan living in the UK.

These factors were used as predictors in models assessing adaptation across a range of neuroanatomical measures, which are complementary in describing experience-based adaptations at the structural and functional level. As such, they can provide different types of evidence that apply to different levels of the proposed models (local structure, long-distance connectivity, default functionality at rest). Measures of grey matter included cerebral and cerebellar cortical grey matter volume (GMV) and shape adaptations in subcortical structures, to measure local adaptations in regions subserving language and cognitive control. Measures of white matter integrity included FA, mean diffusivity (MD), radial diffusivity (RD), and axial diffusivity (AD) values, to measure changes in diffusivity that signify adaptations in structural connectivity commensurate with fluctuating needs for language control. Finally, resting-state functional connectivity was examined, to study potential functional equivalents of structural adaptations in connectivity, but also potential functional adaptations without structural correlates.

Several hypotheses follow regarding both duration and extent of L2 experience. With respect to duration of L2 exposure, differences in specific experience-based factors will result in measurable neuroanatomical adaptations in regions and/or structural connectivity and functional networks involved in language processing and control. Based on the suggestions of the BAPSS model, we predict that factors capturing duration of exposure and use (L2 immersion and L2 AoA) will predict adaptations related to increased efficiency in L2 processing and control in both cortical and subcortical regions. Cortical grey matter volume (GMV) will decrease in frontal regions related to top-down language control, such as the ACC and the dorsolateral prefrontal cortex (DLPFC), including the left inferior frontal gyrus (LIFG) (19). This will reflect more automatized language control due to extensive exposure, and less reliance on top-down processes. Moreover, decreases in GM are also predicted in the right hippocampus, a region involved in short-term/declarative memory procedures (27), which has been repeatedly reported to increase in volume during initial stages of L2 vocabulary acquisition (13, 28). This would indicate that long-term experienced users might rely less on the region as they might have smaller needs for learning new vocabulary. Moreover, increased duration of L2 use will result in increases in subcortical structures related to phonological monitoring and selection such as the globus pallidus and putamen (15), suggesting increased (and efficient) engagement of these nuclei with increased experience, and decreases in structures central to language control such as the caudate and thalamus (6), signifying more efficient controlling of the available languages with increased bilingual experience. Similarly, we predict white matter integrity to positively correlate to longer L2 use in tracts that provide fronto-parietal connectivity and underlie syntactic and semantic processing, such as the IFOF, and SLF (21, 29), signifying experience-dependent recruitment of long distance networks.

With respect to greater extent of engagement with the L2, we predict adaptations commensurate with increased demands on language selection and control, in cortical and subcortical regions predicted by the ACH model, as well as the white matter tracts that connect them. Specifically, we predict volume increases in cortical regions such as the bilateral IFG, inferior parietal lobule (IPL) and anterior cingulate cortex (ACC), and shape/volume increases in subcortical structures such as the thalamus and caudate (6, 30). Additionally, increased FA (and/or decreased RD/MD) were predicted in tracts connecting these regions, notably the corpus callosum (CC), which provides interhemispheric connectivity between the two homologues of the IFG and the IPL, and the anterior thalamic radiation (ATR), which provides connectivity between the thalamus and the frontal cortex (21, 29). Moreover, a context of increased dense code-switching should cause further adaptations to the cerebellum and its functional connectivity with frontal regions, as suggested by the ACH (31).

With respect to EBFs related to length of active engagement to the additional language, these have not previously been examined, thus this analysis is exploratory in nature. Based on existing proposals, however, we tentatively predict that any neuroanatomical adaptations will overlap with the duration-based predictors, specifically adaptations related to increased efficiency of language control processes (6, 19).

Methods

Ethics Statement

This research procedures in this study were approved by the University of Reading Research Ethics Committee. Prior to taking part in the experiment, participants gave written informed consent and confirmed no contraindication to MRI scanning.

Participants and materials

Sixty-five healthy, right-handed bilingual adults (49 females, *m*age: 31.7yrs, SD: 7.24, range: 18-52) participated in the study. Participants spoke a variety of first languages (L1), but all spoke English as their second language (*m*AoA: 8.51 yrs., SD: 4.87, range: 0-22). The majority were born in other countries and moved to the UK at varying ages (*m*age: 26.41yrs, SD: 7.73, range: 3.1- 50.9), apart from 3 who were indeed born in English-speaking countries (UK and Ireland) to non-UK parents, spoke their family language as their L1, moved to their parent's country of residence and then moved back to the UK at a later age. In terms of educational level, all participants reported holding at least a post-secondary degree or diploma apart from three who reported holding a high school degree; in terms of employment, all participants but one reported being either students in postgraduate education or professionals in a variety of sectors, including in business, marketing, finance, health care and education. All participants were living in the UK at time of testing (*m*length immersion: 70.94 months, SD: 73.7, range: 0.26- 383.85). Crucially, minimal exclusion criteria were applied to recruit as wide a range of linguistic experiences as possible. Several of the participants (n=33) reported knowledge of additional languages beyond their native language and English. Of these participants there was some variability between these participants regarding amount of current engagement with these languages. To control for potential effects of L3/n language experience, any current engagement with these additional languages was included as a nuisance covariate in the analyses. This was calculated as a percentage of engagement and was based on responses to four questions related to reading, writing, speaking, and listening, for each language; and then summed across all additional languages for each participant. Here, we observed an average current additional language exposure of 0.13 (SD: 0.26; range: 0-1.5).

Participants completed an English proficiency test, the paper-and-pen version of the Oxford Quick Placement test (QPT) (32). All were found to be high-intermediate to high proficiency speakers of English, based their QPT performance (*m*score 88.35%, SD 10%, range 51.7-100%).

Participants also completed a language history questionnaire, the LSBQ (7), which documents language use in the participants' known languages from early childhood to the present day in a range of settings. Participants rated themselves as proficient, frequent users of English (Table 1).

A factor score calculator developed by Anderson and colleagues provides a series of language use scores indicating extent of bilingual language engagement (26) based on responses to multiple questions regarding language exposure, proficiency and use in the LSBQ. Two of these factor scores were adapted and used as variables in the model. These detail extent of L2 use in two different settings- at home and in social/community settings- and are derived as weighted aggregate scores from measures recorded within the LSBQ (26). The first of these, L2_Home, detailed the extent of L2 proficiency and use in home settings. The other, L2_Social, detailed L2 exposure and use in societal and community settings. It should be noted that as we used an older version of the LSBQ (Version 1) than the one Anderson and colleagues used to created their factor score calculator (Version 3+), one of the questions included in the score

L2_social ("Language use with Friends") was not in our version of questionnaire, and was not included in our factor score calculation. Thus, the L2_Social factor score will not directly overlap with that of Anderson and colleagues' but is likely still a good approximation. On the other hand, the L2_Home factor score was calculated in the same way as in Anderson et al. For both factor scores, a higher score indicates more usage in the L2, a lower score indicates more engagement with the native language. We observed a mean score of 51.5 for L2_Social (SD: 11.36, range: 10.77-74.53), and a mean score of 2.38 for L2_Home (SD 5.25, range: -8.91-16.7). A summary of the participant demographics is given in Supplementary Information.

Language experience factors

Model 1 included four EBFs as predictors testing duration and degree, respectively, of L2 exposure and use. These were 1) L2 age of acquisition (years), 2) L2 length of immersion (months), 3) L2 use in social/community settings (L2_Social), and 4) L2 use in home settings (L2_Home). The predictors in Model 1 were analyzed individually in the GLM, controlling for effects of the other predictors and nuisance covariates (see below for details). This was done to test individual effects of each language experience. L2 AoA and length of L2 immersion examined length of exposure and use of the additional language. Length of immersion was calculated as the time in months that one had been continuously living in the UK prior to scanning. We log transformed both AoA and Immersion for two reasons: first, the data were not normally distributed (AoA: $W=0.95576$, $p=0.02739$; Immersion: $W=0.8142$, $p< 0.0001$) and second, we did not expect a linear rate of adaptation over time (22). The other two predictors (L2_Social, & L2_Home) examined the degree of bilingual or L2 use in various settings and were weighted factor scores derived from the LSBQ (26) as described above. Bivariate correlations showed participants' QPT scores (English proficiency) scores to correlate with all other measures (Table 2), suggesting that proficiency in itself is an outcome of bilingual language experience, and thus was not included in the model (for a discussion on the suitability of using proficiency measures as predictors of brain adaptations, see (33)).

Given that duration-based predictors do not account for the extent to which one engages with the additional language, we also sought to examine if *active* use of the additional language through time would modulate neuroanatomical adaptations. Thus, Model 2 was run to assess the effects of duration of active engagement with the additional language. This was examined in two settings: 1) the total number of years spent actively using the L2 (Yrs_Active_L2) and 2) the length of time spent actively using the L2 in immersion settings (Immers_Active_L2). The first predictor (Yrs_Active_L2) was determined by calculating the average percentage of English use in several stages, from the point the language was acquired through to the time of testing. This percentage was then multiplied by the total years spent using the L2. This calculation produced values indicating the number of years actively using the L2 (*m*length: 10.11yrs, SD: 5.11, range: 0.96-30.08). The second predictor (Immers_Active_L2) was determined by first calculating a percentage reflecting the regular use of English, including four questions related to reading, writing, speaking, and listening, respectively. This value was then multiplied by the number of months of immersion. This computation resulted in values corresponding to the amount of time actively engaged with English in immersion settings (*m*length active immersion: 58.43mo, SD: 60.85, range: 0.1-287.89). As neither of the predictor variables were normally distributed (Years_Active_L2: $W=0.89929$, $p<0.0001$; Immers_Active_L2: $W=0.8344$, $p<0.0001$), both were log-transformed.

For both Models 1 and 2, group mean, age (in years), sex, and any continued exposure to a third (or more) language were run as nuisance covariates to account for any of these effects. Finally, all variables included in the models were mean-centered.

MRI data acquisition

Neuroimaging data were acquired on a 3T Siemens MAGNETOM Prisma_fit MRI scanner, with a 32-channel Head Matrix coil and Syngo software. Whole brain resting-state functional images were acquired (300 volumes, FOV: 192 x 192, 68 transversal slices, 2.0mm slice thickness, voxel size 2.1x2.1x2.0mm, repetition time (TR)=1500ms, echo time (TE)=30ms, flip angle 66°). Participants were asked to keep their eyes open during this scan. A high resolution anatomical scan using a MPRAGE sequence was carried out for purposes of registration and structural analysis (256 sagittal slices, 0.7 mm slice thickness, in-plane resolution 250 x 250, acquisition matrix of 246 x 256 mm, TE=2.41ms, TR=2400ms, inversion time = 1140ms, flip angle = 8°). Finally, a diffusion-weighted echo planar imaging (EPI) scan was run (60 transversal slices, 2mm slice thickness, acquisition matrix 256 x 256, in-plane resolution 128 x 128, 2 averages, TE=70ms, TR=1800ms, 64 directions). MRI data will be made freely available.

MRI data preprocessing

Neuroimaging data were pre-processed and analyzed with software pipelines in FSL (34). T1-weighted images were pre-processed with the FSL_anat software pipeline (35). Due to incidental findings from scanning, one participant was removed from the cohort for analysis.

Images were reoriented to the Montreal Neurological Institute (MNI)-152 orientation, automatically cropped, bias-field corrected, and non-linearly-registered to MNI space. Grey matter volume (GMV) was assessed via the voxel-based morphometry (VBM) pipeline in FSL (36, 37). Pre-processed images were brain extracted and grey matter segmented. A study specific template was then created using the average of the GM images. Native GM images were registered to this template and modulated to correct for local expansions and contractions due to the non-linear component of registration. They were spatially smoothed with an isotropic Gaussian Kernel of 3mm.

The subcortical structures were assessed via a vertex analysis using the FIRST software pipeline (38). The following structures were automatically segmented for analyses: bilateral nucleus accumbens, hippocampus, amygdala, thalamus, globus pallidus, putamen, and caudate nucleus. These were then submitted to vertex analyses. For all participants, each structure underwent a 6 degrees of freedom rigid body transformation to study-specific template in standard space. The vertex coordinates of individuals were then projected onto the average coordinates of the template. This resulted in spatial maps signifying perpendicular displacement from the average structure including positive (outside the surface) or negative (inside the average surface) values.

DTI data were pre-processed using the topup (39), and eddy (40) pipelines within FSL. White matter integrity was assessed via several measurements including FA, MD, RD, and AD values (41, 42). These values were calculated using the FDT and DTIFIT (43) pipelines. Individual differences in WM integrity were assessed using the tract-based spatial statistics (TBSS) pipeline in FSL (44). The FA (and other diffusivity) images were non-linearly registered to a standard space FA target image and affine-transformed to MNI standard space. This resulted in a 4D image which consisted of each FA image from the participants. An FA skeletonization program was used to create an FA skeleton that included the voxels identified as white matter (WM) in each FA image, thresholded at 0.2. MD, RD and AD images were then also nonlinearly registered to standard space and then warped and registered into respective single 4D files which were projected onto the mean FA skeleton.

Resting state connectivity was analyzed using the Multivariate Exploratory Linear Optimized Decomposition into Independent Components (MELODIC) pipeline within FSL (45, 46). This data-driven approach mitigates potential biases associated with traditional seed-based analyses of resting-state fMRI data (45). The data were first pre-processed including motion corrections, corrections for field distortions, and registered first to the participant's anatomical scan, and then to MNI standard space. The processed datasets were then decomposed into spatial and temporal components using a multi-session temporal concatenation across participants. This results in a series of spatial maps containing components common across all participants. The total number of components calculated at the group level was limited to 20 (47). These components were then manually inspected and classified, per the guidelines specified by Griffanti and colleagues (48). Components classified as noise were excluded from further analysis. This included 1 component with spectra containing more than 50% power at greater than 0.1Hz frequencies, 5 components with excessive spatial distribution in white matter, ventricles and/or the brainstem, 2 components with spatial distribution indicative of motion or basal physiological activity (47–49), and 1 with excessive jumps in oscillatory patterns in their time courses. This totaled to 9 components which were removed from further analysis. The remaining 11 were visually matched to existing resting-state networks including the default mode, visual, cerebellar, executive control, sensorimotor, auditory, and left and right frontoparietal networks (47). The components were then subject to group-level analysis via the dual_regression pipeline (50). This pipeline first regresses the spatial maps of the selected components into the 4D dataset for each participant, creating time courses for each component within each participant. The time courses were subsequently regressed into a single dataset creating spatial maps for each participant. This resulted in a series of statistical maps detailing effects of each predictor on intrinsic connectivity within each component.

MRI data analysis

For each of the four types of neuroimaging data described above, language experience adaptations across participants were assessed with voxel-wise comparisons using design matrices created with the GLM tool in FSL. Demographics from the LSBQ were used as predictors, with age, sex and exposure to additional languages included as nuisance covariates, as described above. Statistical analyses on the neuroimaging data were conducted using the Randomise pipeline (51), in which a voxel-wise, non-parametric permutation analysis was performed with 5000 permutations for each factor of interest. Corrections for multiple comparisons were implemented using Threshold-Free Cluster Enhancement (TFCE) (52). This created maps of areas of adaptations significantly predicted by a given factor, thresholded at $p<0.05$. For the resting-state analysis, a further correction was required. Given that the dual_regression pipeline does not correct for multiple comparisons across components, the significance values were further Bonferroni-corrected to a threshold of $p\leq 0.0045$.

Results

Model 1: Independent effects of AoA, immersion, extent of L2 use in home settings, and L2 use in social/community settings

TBSS analysis

L2 AoA positively correlated with FA values across several portions of the head and genu of corpus callosum (Table 3) (Fig 2). None of the other factors predicted FA patterns. The analyses did not reveal any significant effects of the predictors on AD, MD, or RD values.

Vertex analysis results

Several factors relating to both duration and degree of bilingual language use were found to predict reshaping of the subcortical structures. L2 AoA was found to significantly predict expansions in the left nucleus accumbens and the bilateral thalamus. Length of L2 immersion significantly predicted significant adaptations in posterior sections of the right caudate nucleus (an expansion and contraction), an expansion in the right putamen (Fig. 2, b), and contractions in the bilateral thalamus and nucleus accumbens (Table 3). L2_Social predicted expansions in several portions of the left caudate nucleus (Fig. 2, a), left nucleus accumbens, and right thalamus (Table 4).

Resting-state connectivity

L2 AoA was found to significantly predict resting state functional connectivity at the corrected significance threshold. Specifically, a negative correlation was found between L2 AoA and connectivity within the component related to the Visual network (Table 5) (Fig. 3) (47). No other predictors predicted functional connectivity patterns.

VBM analysis

None of the language experience factors significantly predicted cortical GMV patterns when corrected for multiple comparisons.

Model 2: Duration of active L2 use

Significant effects for each language experience factor were found for subcortical adaptations. Neither language-use factor was found to significantly predict GMV, diffusivity, or resting-state connectivity patterns.

Vertex Analysis

Both factors were found to predict reshaping within several structures. An expansion in the left nucleus accumbens was predicted by Years_Active_L2. Immers_Active_L2 was found to predict both an expansion and contractions in the right caudate nucleus (Fig. 4) and a contraction in the right nucleus accumbens (Table 6).

Discussion

This study examined the effects of bilingualism on the structure and connectivity of the brain by accounting for the influence of specific language experience factors, to highlight the nuances that give rise to a continuum of neuroanatomical effects in bilingual individuals and groups. The EBFs examined in the study were found to incur specific effects on brain structure and structural and functional connectivity. In Model 1, the neural adaptations differed between overall factors related to duration (AoA and Immersion) and degree (L2_Social, and L2_Home) of L2 use respectively. Model 2, which examined the effects of the length of time one was actively engaged with the additional language, produced both similar and distinct effects to the duration-based predictors of Model 1. Considered together, the results highlight the need for further consideration of specific language experiences/individual differences in examining the neuroanatomical effects of the bilingual experience. The remainder of this discussion presents the findings in detail and links them to theoretical proposals on brain adaptations related to bilingual experience.

Independent effects of AoA, Immersion, L2 use in social/community settings, and L2 use in home settings

The first model revealed independent effects of language experience factors modulated by duration and degree of bilingual language use. This is in line with our predictions. The effects of duration of bilingual language use reflected adaptations towards increased efficiency in L2 processing and control, whereas effects of extent of use reflected adaptations towards increased cognitive cost of language selection and monitoring processes.

Adaptations for AoA indicate an increased efficiency in bilingual language processing with earlier exposure to bilingualism. The positive correlation between L2 AoA and FA in the corpus callosum (CC) potentially reflects increased efficiency associated with longer duration of L2 use, specifically a decreased reliance on frontal inter-hemispheric connectivity. This is compatible with findings from a recent longitudinal study that revealed increases in frontal diffusivity over time in immersed L2 speakers of English (33). Taken together, these patterns reflect a return to 'baseline' diffusivity with increased time using the L2, likely commensurate with increased efficiency and/or automation in language control. Similarly, expansions in the thalamus signify increased reliance in this structure which in turn reflects increased automation and efficiency in language selection at several levels of processing and production. The thalamus has been implicated in language control processes, specifically language selection, given its extensive connections to the basal ganglia and IFG (6, 53), and has been shown to expand in immersed L2 speakers (15). The increases in functional connectivity in the Visual network were not predicted, as the visual network is not routinely linked to language processing. However, Smith and colleagues have also associated the Visual Network with cognitive and language (mainly orthographic) processing (47). Based on those findings, the connectivity increases seen here may reflect transitions towards more automated or efficient grapheme-to-phoneme mapping in the L2[2]. However, this interpretation is speculative, and requires more research to assess its validity. The expansion in the left nucleus accumbens was also not predicted, as it is not typically implicated in language processing and control. The nucleus accumbens is typically implicated in processes related to reinforcement, action selection and salience in prediction-error processing (54, 55). Under such a view, we may interpret the expansions here as an optimization towards language selection processes and processing. This is corroborated by a highly similar adaptation in the accumbens to relative to the number of years of active L2 use. However, this interpretation requires more evidence to assess its validity. It is worth noting that the adaptations related to AoA are consistent with

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[2] Particularly in the case of sequentially acquired bilinguals, it may not be as surprising to see this effect. In native language acquisition where literacy—which requires the visual domain—is strapped on, this may then be ancillary. However, in typical non-native acquisition where the language is often taught through literacy in a conscious fashion, this effect might be more robust. This, however, requires further research.

predictions from the BAPSS framework (19); specifically, a decreased reliance on frontal cortical structures, and an increased reliance on the subcortical and posterior structures commensurate with prolonged L2 experience.

The adaptations related to length of L2 immersion seem to reflect an increased automation or proceduralization in language control processing with prolonged intensive exposure to the L2 (25). The contractions seen in the right caudate nucleus could suggest a return to baseline from prior expansions earlier in L2 immersion (13, 15, 56), given increased efficiency in language monitoring and selection. Such an interpretation is supported by the contractions seen in the bilateral thalamus, which indicates a decreased reliance on this structure with increased efficiency in language selection (18, 30). The left caudate nucleus is more often implicated in language and task-switching cognitive demands (6), however several studies report recruitment of the right caudate for more demanding language switching tasks (57, 58). Regarding the predictions of the ACH, we may interpret the right caudate and thalamic contractions as a marker of decreased requirements for gating the interfering language. Similarly, the contractions in the bilateral nucleus accumbens may reflect a decreased reliance on reinforcement learning strategies (54) as a result of the prolonged intensive L2 exposure and use that is associated with the immersive environment (25). Finally, the expansions in the right putamen indicate adaptations towards increased efficiency in L2 speech production (14, 15). The putamen has been implicated in phonological and articulatory monitoring demands (6, 59). As the values for immersion were log-transformed, this pattern likely indicates a gradual plateau of expansion once the monitoring system has optimized.

The effects related to degree of L2 use in social settings reflect adaptations towards increased language control demands. Following predictions of the ACH, the expansions in the left caudate suggest increased language switching and control demands, specifically gating of interference from the non-target language in processing and production (6, 18). This interpretation is supported by other studies that find caudate engagement with increased language switching and selection demands (56, 60). This interpretation is also supported by the expansions in the bilateral thalamus. The thalamus is often implicated in language selection processes, working with the caudate and IFG (6). The increases seen here likely reflect adaptations towards increased language control and selection demands commensurate with increased engagement with the L2. Finally, the expansions in the left accumbens associated with L2 use in social settings may also reflect adaptations towards increased demands for prediction-error processing, which would be stressed commensurately with an increased degree of L2 use on a regular basis.

Taken together, the results from Model 1 suggest specificity in adaptation towards duration and degree of L2 use respectively. Under interpretations of the BAPSS framework and ACH, adaptations related to duration of L2 use indicate optimizations towards efficiency and automation in L2 processing and control. Increased degree of L2 use related to adaptations towards increased language control and selection demands.

Effects of the duration of active L2 use

Model 2 revealed effects of the amount of time spent actively engaged with the additional language, both overall and in immersion settings. Some similarities in terms of neural effects were found between the predictors in this model and the EBFs from the first model, however, distinct neural adaptations were also found. The results here indicate that specific effects related to proportions of language use manifest differently through the time course of L2 use.

The adaptations in the right caudate related to length of active L2 use in immersion settings highly overlap with those found for immersion in Model 1. This is not necessarily surprising, given the high degree of similarity between the two factors. Nevertheless, the adaptations in the right caudate found here support the interpretations of the ACH for decreased reliance on right hemisphere structures in gating or suppressing the interfering language as language control processes become progressively more efficient in immersive environments. These data support an interpretation of increased intensive L2 exposure in immersion relating to changing recruitment of the affected structures, as the system optimizes through time to more efficiently handle the language control demands.

Taken together, the data from Model 2 indicate that sustained, active L2 use drives specific neural adaptations towards maximal efficacy in L2 processing/production and control.

General Discussion

Bilingualism is a multifaceted experience comprising various proportions of EBFs that present themselves differently to groups and individuals over time. If individual EBFs matter in predicting specific changes to the brain, then it stands to reason that treating bilingualism as a monolithic variable does not sufficiently account for all the potential adaptations. This is not to suggest that there is nothing to be gained from the monolingual vs. bilingual comparison from the past and moving forward. Data of the type we present here, however, suggest caution is needed with respect to what can be claimed from such comparisons alone. A bilingual-centric approach that seeks to unpack how and why EBFs in bespoke proportions confer differences in adaptations is in a privileged position to reveal the dynamicity of the bilingualism-mind/brain relationship. Such an approach should be able to deal with all data from well-designed, well-executed studies, even and especially when they are seemingly in conflict with each other. In principle, when a replication fails, factoring in and modelling EBFs can potentially resolve the apparent quandary. The effect of bilingualism on the mind/brain need not be conceived of in binary terms; rather, studies like the present provide the evidence that permits a shift away from binary answers towards: “how much” and “under what (EBF) conditions”.

Experiences are individualistic, although certain experiences cluster together in non-random ways by bilingual type, geographic location and other societal factors (61, 62). Our own bilingual cohort provides such an example: our participants moved to the UK at varying ages, and migration to the UK will delimit certain language choices, particularly depending on the reasons for which one immigrates and who is available to converse with in each language. Our participants had a fairly consistent socioeconomic status (see Methods), and the majority emigrated to the UK from another European country, minimizing variability that might emerge from very distinct backgrounds. Nevertheless, the opportunities for L2 use, and the neurocognitive adaptations they confer, cannot be viewed independently of the immersive environment per se (i.e. the UK), which would have inevitably dictated these opportunities based on factors such as societal expectations for L2 use, availability for L1 communication, perceived respective status of L2s and L1, social status of particular ethnic or religious groups and so on. This could mean that a group with similar demographics and language background might demonstrate a different pattern of adaptations even if immersed in a different English-speaking country, e.g. the United States, Canada or Australia[3]. Therefore, given the pervasiveness of language use across all aspects of life, when studying bilinguals it is necessary to account not only for the self-reported proficiency and age of L2 acquisition, but also for the more in depth reported language use patterns and social interactions, as well as the extent to which the particular environment provides opportunities for such interactions. Research of this type underscores the potential indispensability of such contextualizing data that cannot be overlooked in future research.

Consider a scenario in which for the same languages (e.g., English and Spanish), relative proficiency and age at time of testing are held constant yet apply to different individual bilinguals. Notwithstanding crucial commonalities, some EBFs will necessarily be different at the group level (e.g. AoA). Other EBFs will tend to cluster differently depending on various external factors. In our view, one should not be surprised if for example Hispanic-American simultaneous bilinguals who grew up in Hispanic-majority areas of California are different from those raised in English-dominant Iowa. It is not necessarily reasonable to expect that either group would be the same as compared to successful adult English-native second language learners of Spanish residing in Madrid. Should we anticipate that the same results of the previous groups would apply to native Spanish speakers who moved to California as teenagers and have resided there for decades and/or in successful English-native acquirers of L2 Spanish who have never left the US? Moreover, should we expect that all individuals of each or any of the juxtaposed groups will, should or could be the same? We submit that the answer is “no”. EBFs will distribute differently across all five groups and somewhat differently across individuals within groups. Opportunities to use the language, factors affecting language choice, differences in code-switching proportions, and more will affect how EBFs distribute. In line with what we have shown for EBF effects in neuroanatomical differences across bilinguals, we expect differences in all bilingual neurocognitive adaptations. Denying the veracity of existing data simply because it cannot be replicated under different conditions is discordant with scientific prudence (62). It is more likely that differences relate to tendencies of how EBFs distribute in certain cohorts of bilinguals as compared to others and across idiosyncratic tendencies of individuals within discernible groups. Minimally, the suggestion constitutes a strong and relatively easily testable hypothesis that should be exhaustively pursued.

Modelling the general weighting of EBFs not only has a good chance of explaining variable outcomes across studies, but it also embodies a major step towards uncovering the dynamic nature of how bilingualism translates into mind/brain adaptations. In this same vein, it is important to keep in mind that proxies such as ‘bilingual type’ (e.g. early vs. late), while useful especially when they reduce the likelihood for vast differences in individual EBFs across members, can also conflate too many variables, as alluded to above. Taking again the example of ethnic Hispanic-American simultaneous bilinguals, AoA is ubiquitously early. Nevertheless, factors related to exposure to both languages, use/preference of both languages (likely changing dynamically over time), and more will differentiate individuals. Unless we are sure none of these matter, we need to move towards models that take these factors seriously and can place

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[3] Such has been documented even for linguistic competence in heritage language Spanish bilingualism in distinct English-speaking environments—Canada versus the United States (see (64))—where more favourable attitudes towards Spanish in one place over the other gave rise to distinctly measurable competence differences despite the languages being held constant and other key factors differentiating the groups.

individuals on a discernible continuum. Doing so will increase ecological validity in our field and move us closer to understanding variability in findings.

The goal of this study was to test the hypothesis that specific experience-based factors related to bilingualism predict specific adaptations in the brain. We found specificity in neuroanatomical adaptations in regions responsible for language and cognitive control to respective EBFs. This suggests that the brain optimizes to be maximally efficient in handling cognitive demands of the communicative environment. In relation to bilingual language use, this neurocognitive optimization is a dynamic process which is modulated by both duration and extent of language use, and their combined effects. Taken together, the data support the notion that specific language experiences should be considered in detail in future research examining bilingualism and related neurocognitive adaptations. The EBFs we examined do not comprise an exhaustive list. These data point to a promising program where an increasingly comprehensive cohort of individual EBFs and their combined effects will add to unraveling the complexity of language experience with its ensuing bilingual cognitive and neurological consequences as well as explaining the dynamic interaction that bilingualism has in mind/brain adaptations.

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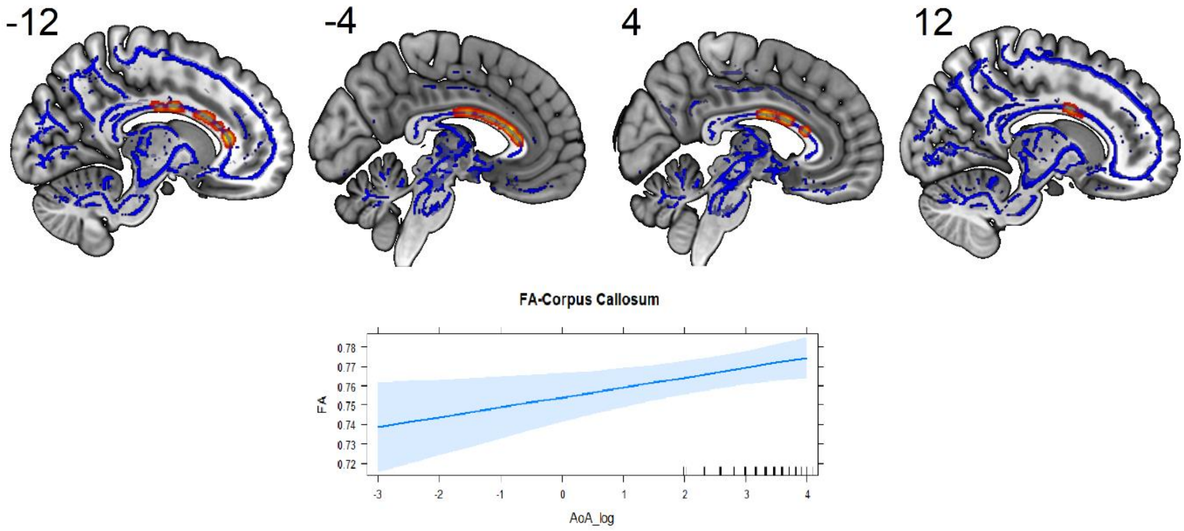

Figure 1: Results of TBSS analysis. (Above) Significant effects of AoA (red/yellow) within FA skeleton (blue). (Below) plot of correlation between AoA and extracted significant FA values in the corpus callosum Coordinates listed are in MNI-space.

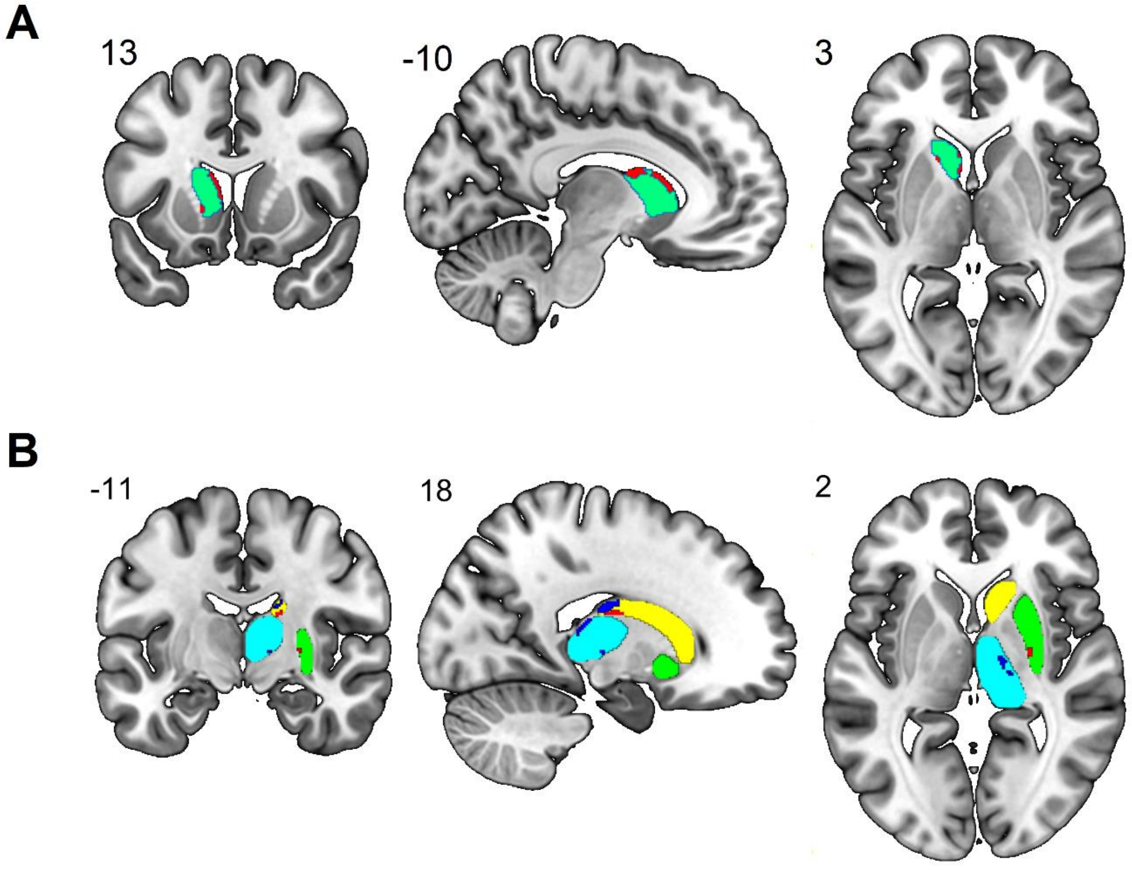

Figure 2: Results from vertex analysis: A: Significant expansions (red) on the left caudate nucleus (green) predicted by L2_Social. B: Significant expansions (red) and contractions (blue) on the right caudate (yellow), putamen (green), and thalamus (cyan) predicted by immersion.

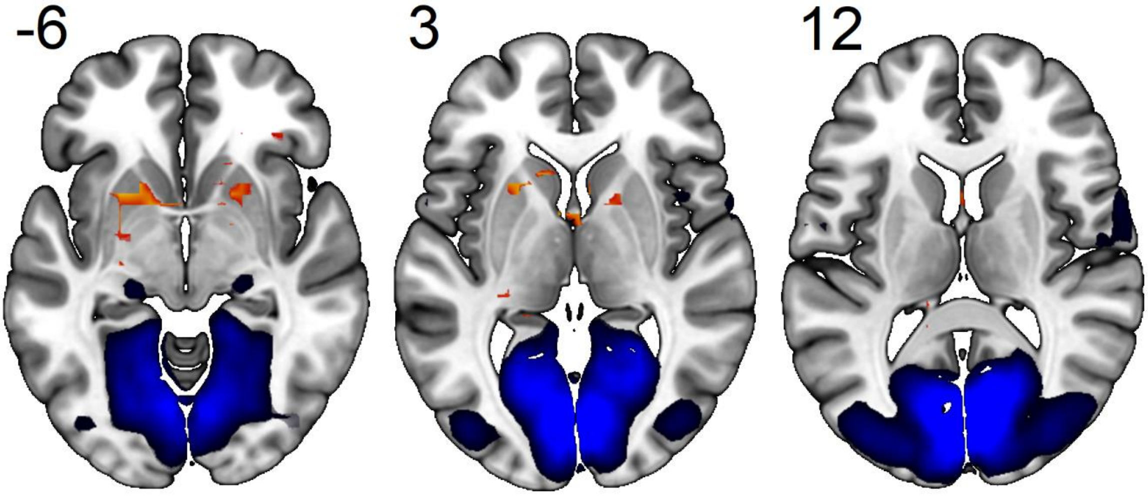

Figure 3: Results from resting-state connectivity analysis. Modulations in connectivity (red) in the Visual network (blue) predicted by AoA.

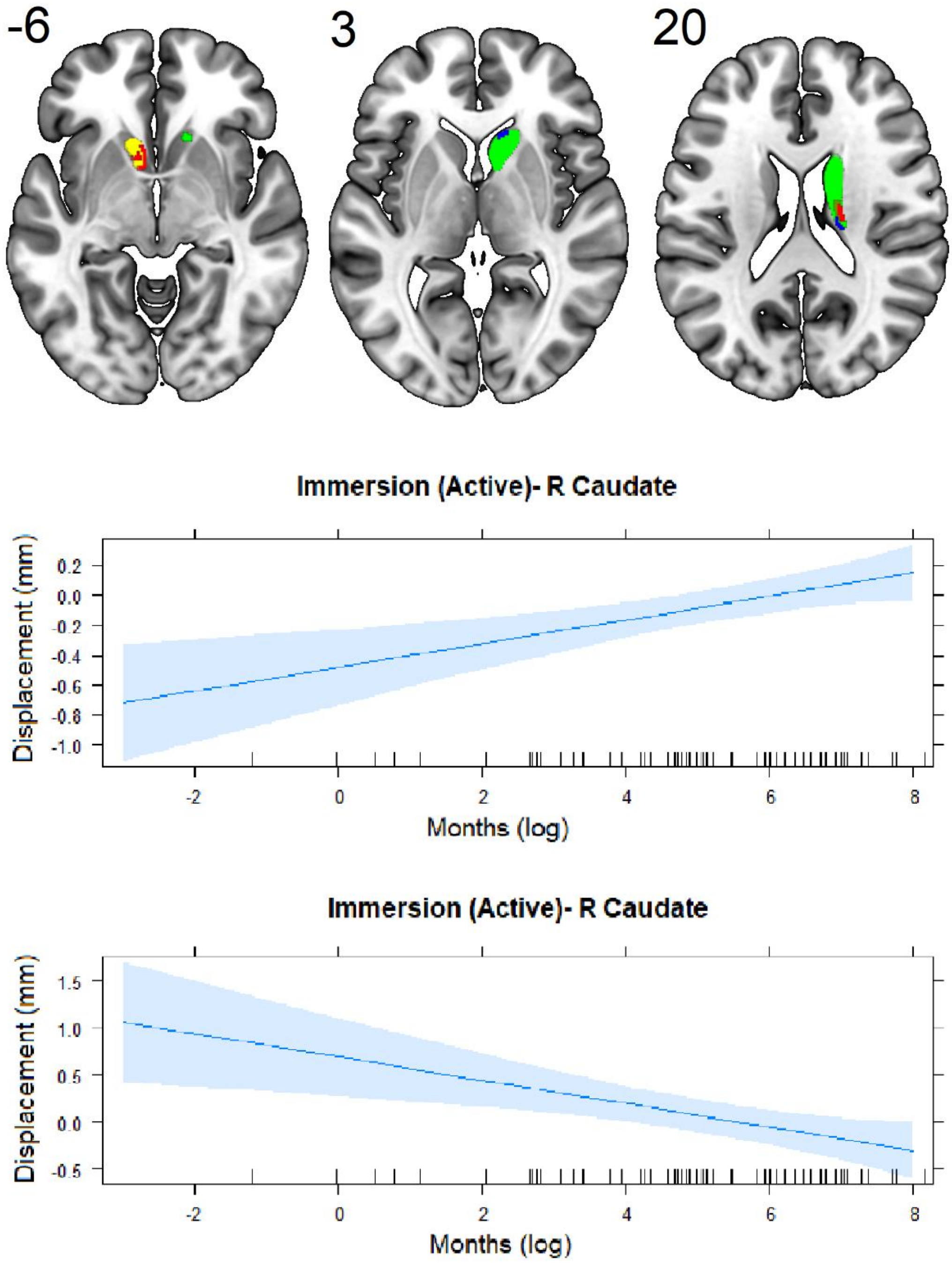

Figure 4: Results of Vertex analysis for Model 2. (Top) expansions (red) on the left nucleus accumbens predicted by Years_Active_L2. Expansions (red) and contractions (blue) on the right caudate nucleus predicted by Immers_Active_L2. (Middle) Plot of correlations between Immers_Active_L2 and area of significant expansion on the right caudate nucleus. (Bottom) Plot of correlation between Immers_Active_L2 and area of significant contraction the right caudate nucleus.

Table 1: Participants self-reported English ability and use.

	Proficiency [Speaking]	**Proficiency [Understanding]**	**Proficiency [Reading]**	**Proficiency [Writing]**
Avg. score (out of 10)	7.95	8.43	8.54	8.03
Standard Deviation	1.71	1.42	1.33	1.46
	Frequency [Speaking]	**Frequency [Listening]**	**Frequency [Reading]**	**Frequency [Writing]**
Avg. score (out of 4)	3.03	3.17	3.18	3.19
Standard Deviation	0.71	0.63	0.61	0.68

Table 2: Correlations between the language experience factors.

	QPT	**Immersion**	**AoA**	**L2_ Home**	**L2_ Social**	**Years_ Active_L2**	**Immers_ Active_L2**
QPT	1						
Immersion	0.31	1					
AoA	-0.29	-0.08	1				
L2_Home	0.53	0.29	-0.66	1			
L2_Social	0.29	0.46	-0.1	0.46	1		
Years_Active_L2	0.49	0.51	-0.31	0.64	0.41	1	
Immers_Active_L2	0.33	0.99	-0.1	0.33	0.49	0.53	1

Table 3: Results of TBSS analysis for Model 1. Coordinates are in MNI-space.

EBF	**Tract**	**Direction**	**Voxels**	**p**	**X**	**Y**	**Z**
AoA	Corpus Callosum	+	568	0.044	-10	31	7
		+	200	0.047	8	6	25
		+	2	0.05	10	27	12

Table 4: Results of vertex analysis for Model 1. Coordinates are in MNI space.

EBF	Hemisphere	Structure	Direction	Voxels	p	X	Y	Z
AoA	L	Accumbens	-	224	0.001	-10	11	-6
		Thalamus	-	960	0.017	-9	-29	10
	R	Thalamus	-	173	0.029	15	-32	9
Immersion	L	Accumbens	-	2	0.047	-11	18	-9
		Thalamus	-	78	0.04	-8	-4	0
	R	Accumbens	-	52	0.024	9	8	-6
			-	31	0.015	12	19	-8
			-	9	0.031	10	11	-11
		Caudate	+	38	0.028	17	-14	19
			-	81	0.022	19	-19	22
		Putamen	+	12	0.032	27	-9	1
		Thalamus	-	155	0.038	12	-30	11
			-	29	0.048	16	-19	0
L2_Social	L	Accumbens	+	327	<0.001	-10	14	-11
		Caudate	+	342	0.019	-10	2	15
			+	59	0.013	-16	15	-2
			+	16	0.034	-18	-3	19
		Thalamus	+	7	0.049	-6	-24	13
	R	Thalamus	+	7	0.05	8	-24	13

Table 5: Results of resting-state connectivity analysis for Model 1.

EBF	Network	Direction	Voxels	p	X	Y	Z
AoA	Visual	-	186	0.001	-26	10	-4
		-	88	0.001	-2	-42	-24
		-	28	0.002	-14	-18	24
		-	13	0.003	38	30	-4
		-	8	0.002	-18	-38	0
		-	6	0.003	-6	-58	-28
		-	6	0.003	-26	-30	4
		-	6	0.003	6	-34	48
		-	5	0.003	26	-30	-8
		-	3	0.004	58	-54	-4
		-	2	0.003	26	-6	-16
		-	2	0.004	58	-46	-12
		-	2	0.003	54	-10	-12
		-	1	0.004	-10	-50	-36
		-	1	0.004	-22	-10	-24
		-	1	0.004	18	-38	40

Table 6: Results of vertex analysis for Model 2. Coordinates are in MNI space.

EBF	**Hemisphere**	**Structure**	**Direction**	**Voxels**	**p**	**X**	**Y**	**Z**
Years_Active_L2	L	Accumbens	+	334	0.002	-6	15	-5
Immers_Active_L2	R	Accumbens	-	17	0.032	12	19	-9
	R	Caudate	+	47	0.022	17	-11	19
	R		-	107	0.015	13	23	1
	R		-	91	0.014	19	-20	21

Supplementary Information for

Redefining bilingualism: a spectrum of experiences that differentially affect brain structure and function

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This PDF file includes:
Table S1

Table S1: Demographic information per participant

Subject	**Age**	**Sex**	**Native Language**	**Country of birth**	**QPT (%)**	**Addtl Lang**	**Current Addtl Lang use**	**AoA English**	**Immersion (Mo)**	**Age at Immersion**	**L2 Home**	**L2 Social**	**Years Active L2**	**Immersion Active L2**
1	33	F	Portuguese	Portugal	90.0	French	0	10	0.26	33.50	-7.15	10.77	0.96	0.10
2	33	F	Italian	Italy	91.7	Spanish, Norwegian, French	0.75	5	1.32	33.68	3.54	44.25	11.67	0.99
3	35	F	German	Germany	91.7	French, Spanish	0.06	11	11.38	.59 34.28	2.90	49.91	12.00	8.54
4	28	F	Polish	Poland	83.3		0	5	105.86	19.41	6.83	61.36	12.46	105.86
5	29	M	Greek	Greek	96.7	German, Russian	0.19	0	44.01	26.29	10.29	56.03	13.37	33.01
6	25	M	Japanese	Japan	86.7		0	21	7.17	24.83	-8.91	41.23	2.00	3.59

7	34	M	Turkish	Turkey	93.3		0	12	18.49	33.39	3.55	65.79	13.06	13.87
8	29	F	Turkish	Turkey	91.7		0	17	38.72	26.44	-3.20	48.27	4.88	31.46
9	22	F	Romanian	Romania	68.3	French	0	7	28.65	19.64	2.43	46.16	5.25	28.65
10	18	F	Italian	Italy	95.0		0	0	36.15	15.50	16.70	53.47	14.32	33.89
11	30	F	Italian	Italy	71.7		0	14	47.17	26.56	-0.85	61.85	7.50	35.38
12	23	M	Swiss-German	Switzerland	96.7	German	0.25	0	43.88	19.93	13.19	59.11	14.31	32.91
13	38	F	German	Germany	96.7	Spanish	0.13	10	165.13	24.59	4.04	60.94	7.58	165.13
14	39	F	Dutch	Netherlands	95.0		0	6	85.16	32.85	3.58	59.54	14.44	74.52
15	39	F	German	Germany	96.7	Russian	0	11	240.33	19.51	6.54	53.95	14.00	210.29
16	32	F	Italian	UK*	95.0	French	0.19	0	165.36	19.12	3.25	43.31	11.96	165.36
17	26	F	Latvian	Latvia	78.3	Russian	0.13	6	2.93	26.70	-3.50	32.91	5.00	2.20
18	38	F	French	France	100.0	German, Spanish	1.0	12	172.11	23.93	1.12	57.07	13.00	129.08
19	35	F	Spanish	UK**	100.0	French, Italian	0.13	0	383.85	3.09	11.47	45.33	21.81	287.89
20	26	M	Spanish	Spain	96.7	French, Italian	0.5	6	68.29	20.72	-2.20	50.94	6.25	68.29
21	26	F	Spanish	Spain	91.7		0	4	11.22	25.34	-2.46	58.93	5.50	7.01
22	34	F	Polish	Poland	91.7	Portuguese, Spanish, Italian	0.5	6	118.68	24.80	6.22	63.53	9.92	89.01
23	22	F	Bulgarian	Bulgaria	95.0	Macedonian	0.13	7	36.91	19.92	3.29	59.55	8.75	36.91

24	44	F	Mandarin	China	90.0		0	13	91.25	37.42	-1.61	39.88	11.63	68.44
25	28	F	French	France	91.7	Spanish	0.25	7	85.76	21.73	1.13	53.84	8.31	64.32
26	34	F	Polish	Poland	95.0	German	0.06	10	127.37	24.25	4.99	68.73	11.00	103.49
27	23	M	Czech	Prague	93.3		0	0	34.84	20.37	12.74	51.85	8.59	34.84
28	47	F	Dutch	Netherlands	91.7		0	8	8.98	47.17	7.59	48.88	26.00	6.74
29	27	F	Urdu	Pakistan	98.3		0	5	134.67	16.57	11.74	74.53	11.55	134.67
30	23	F	Swedish	Ireland***	95.0		0	0	46.22	19.67	12.77	66.31	14.31	34.66
31	26	M	Dutch	Netherlands	95.0		0	4	5.53	26.09	8.05	67.59	9.97	4.14
32	37	F	Greek	Cyprus	98.3		0	6	36.28	34.39	6.17	46.69	12.92	27.21
33	52	F	German	Germany	98.3		0	10	21.12	50.89	-2.66	32.25	10.50	10.56
34	26	F	Polish	Poland	93.3	French, German	0	11	59.64	21.06	5.55	53.40	5.86	44.73
35	30	F	Spanish	Poland	66.7	Spanish	0.13	22	87.50	22.85	-2.96	59.15	4.00	82.03
36	43	M	German	Germany	96.7		0	5	74.44	37.03	8.07	43.01	30.08	74.44
37	41	F	Spanish	Spain	83.3		0	14	52.53	37.16	0.89	38.38	11.81	32.83
38	21	F	Portuguese	Portugal	95.0		0	5	31.81	18.55	1.35	70.18	6.67	31.81
39	38	F	Russian	Russia	98.3		0	11	180.56	23.16	0.76	48.31	11.81	135.42
40	50	F	Spanish	Venezuela	80.0	French	0.13	7	23.65	48.78	-0.67	37.78	8.36	19.22
41	43	F	Finnish	Finland	93.3	Swedish, French	0.19	9	289.90	19.52	3.17	58.00	16.06	217.43

42	25	M	Dutch	Netherlands	95.0	Swedish, French	0.13	5	11.84	24.11	4.34	49.38	7.50	9.62
43	27	M	Italian	Italy	83.3		0	8	12.53	26.45	-3.11	62.59	7.52	8.62
44	27	F	Spanish	Spain	55.0		0	9	12.70	26.86	-2.22	49.25	7.50	6.35
45	38	F	Greek	Greece	86.7	German, Spanish, Italian	0.56	7	38.42	35.11	-4.16	51.85	10.33	24.01
46	29	F	German	Germany	95.0	Chinese, Latin	0	10	34.28	26.44	4.88	59.25	7.28	25.71
47	23	M	Spanish	Spain	65.0	German	0.25	7	0.69	23.05	-3.12	30.89	4.33	0.43
48	39	M	Greek	Greece	93.3		0	6	131.78	28.81	1.39	60.57	11.86	131.78
49	29	F	Spanish	Spain	75.0		0	10	58.52	24.24	-2.43	38.65	6.86	43.89
50	32	M	Greek	Greece	90.0	French	0.44	8	61.61	27.23	6.95	69.80	16.50	61.61
51	29	M	Spanish	Spain	63.3		0	10	24.64	27.28	-5.81	40.40	5.94	15.40
52	31	F	Spanish	Spain	80.0		0	6	84.93	24.28	0.40	63.99	11.46	63.70
53	24	F	German	Germany	86.7	French	0	8	9.51	24.02	2.53	52.63	5.00	6.54
54	22	F	Greek	Greece	81.7	German, Spanish	1.5	7	2.27	22.76	-1.76	33.79	4.38	1.70
55	38	F	German	Germany	93.3	French, Spanish, Hungarian	0.44	12	146.32	26.45	2.25	45.02	10.56	109.74
56	35	F	German	Germany	88.3	French	0	11	125.43	25.18	2.22	38.03	8.00	94.07
57	30	F	Norwegian	Norway	83.3	German	0.06	7	1.91	30.46	4.88	49.03	11.50	1.43

58	29	M	Mandarin	China	88.3		0	11	38.16	26.07	-2.21	49.98	8.44	26.23
59	28	F	Turkish	Turkey	78.3		0	9	26.74	26.25	-2.75	47.47	6.86	18.39
60	40	F	German	Germany	95.0	Spanish, Italian	0.25	11	98.98	31.82	2.89	49.95	13.29	74.24
61	39	F	Polish	Poland	91.7		0	15	162.83	26.36	0.45	54.26	9.00	122.12
62	25	F	Spanish	Colombia			0	20	32.24	22.64	-0.13	57.96	5.00	20.15
63	46	F	German	Germany	100.0	French	0.13	12	154.93	33.94	3.78	59.25	17.00	154.93
64	26	F	Spanish	Spain	51.7		0	16	39.51	23.05	-4.43	41.19	3.44	29.63
65	29	M	Romanian	Romania	88.3		0	11	75.46	23.13	1.82	49.43	8.25	56.60
Avg	31.8				88.4		0.13	8.51	70.94	26.41	2.38	51.5	10.11	58.43
SD:	7.59				10.8		0.26	4.87	73.7	7.73	5.25	11.36	5.11	60.85

*Born in UK, moved to Italy

**Born in UK, moved to Venezuela

***Born in Ireland, moved to Sweden