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

Vincent DeLuca[a,b,1], Jason Rothman[c,d], Ellen Bialystok[e], and Christos Pliatsikas[a,d]

[a]School of Psychology and Clinical Language Sciences, University of Reading, Reading RG6 6AL, United Kingdom; [b]Department of Psychology, University of Birmingham, Birmingham B15 2TT, United Kingdom; [c]Department of Language and Culture, University of Tromsø, 9019 Tromsø, Norway; [d]Facultad de Lenguas y Educación, Universidad Nebrija, 28015 Madrid, Spain; and [e]Department of Psychology, York University, Toronto, ON M3J 1P3, Canada

Edited by Patricia K. Kuhl, University of Washington, Seattle, WA, and approved March 5, 2019 (received for review July 6, 2018)

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 a 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.

bilingualism | neuroplasticity | gray matter | white matter | resting-state functionality

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 predefined 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, and so forth, 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 modeled 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 concerning 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 gray 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 acknowledgment that bilingualism itself reflects a multidimensional state of experiences, which might result in different adaptations to individuals with different language backgrounds. Indeed, Li et al. (2) suggested that the effects of bilingualism on the brain might rely on three main dependent factors: (*i*) the timing of the acquisition of the second language (L2) with respect to the acquisition of the first language (L1), the L1–L2 interactions; (*ii*) the nature of L2 input, in terms of the intensity of something as complex as L2 learning; and (*iii*) 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. [They also speculate on a

Significance

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 toward an approach of modeling 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.

Author contributions: V.D., J.R., E.B., and C.P. designed research; V.D. and C.P. performed research; V.D. and C.P. analyzed data; and V.D., J.R., E.B., and C.P. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: Data has been deposited in the OpenNeuro Repository, https://openneuro.org/ (accession no. ds001796).

[1]To whom correspondence should be addressed. Email: v.deluca@bham.ac.uk.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1811513116/-/DCSupplemental.

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 ref. 18 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 et al. (2); these concepts are used to understand results from our empirical study. The adaptive control hypothesis (ACH) (6, 19) 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 (20) 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) (21, 22), length of immersion (15, 23), and L2 proficiency (24, 25). However, the factors addressed in available studies to date are limited because they were examined: (*i*) in relatively narrow ranges and (*ii*) 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 (26). 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 (United Kingdom) where their L2 (English) is the dominant language. 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 (26). 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 nonnative language. We chose composite factor scores derived from the Language and Social Background Questionnaire (LSBQ) (27) 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 that 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 United Kingdom. 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 United Kingdom. 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 United Kingdom.

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 gray matter (GM) included cerebral and cerebellar cortical GM volume (GMV) and shape adaptations in subcortical structures, to measure local adaptations in regions subserving language and cognitive control. Measures of white matter (WM) 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 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 GMV will decrease in frontal regions related to top-down language control, such as the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC), including the left inferior frontal gyrus (IFG) (20). 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 (28), which has been repeatedly reported to increase in volume during initial stages of L2 vocabulary acquisition (13, 29). 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 WM integrity to positively correlate to longer L2 use in tracts that provide fronto-parietal connectivity and underlie syntactic and semantic processing, such as the inferior fronto-occipital fasciculus and superior longitudinal fasciculus (22, 30), 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 WM tracts that connect them. Specifically, we predict volume increases in cortical regions, such as the bilateral IFG, inferior parietal lobule (IPL) and ACC, and shape/volume increases in subcortical structures, such as the thalamus and caudate (6, 31). 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 homologs of the IFG and the IPL, and the anterior thalamic radiation (ATR), which provides connectivity between the thalamus and the frontal cortex (22, 30). 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 (32).

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, 20).

Methods

Ethics Statement. The research procedures in this study were approved by the University of Reading Research Ethics Committee. Before 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, mean age: 31.7 y, 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 (mean AoA: 8.51 y, SD: 4.87, range: 0–22). The majority were born in other countries and moved to the United Kingdom at varying ages (mean age: 26.41 y, SD: 7.73, range: 3.1–50.9), apart from three who were indeed born in English-speaking countries (United Kingdom and Ireland) to non-United Kingdom parents, spoke their family language as their L1, moved to their parent's country of residence, and then moved back to the United Kingdom at a later age. In terms of educational level, all participants reported holding at least a postsecondary 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 United Kingdom at time of testing (mean length immersion: 70.94 mo, 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) (33). All were found to be high-intermediate to high-proficiency speakers of English, based their QPT performance (mean 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 (Tables 1 and 2).

A factor score calculator developed by Anderson et al. (27) provides a series of language use scores indicating extent of bilingual language engagement 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 (27). 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 because we used an older version of the LSBQ (version 1) than the one Anderson et al. (27) used to create 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 the questionnaire, and was not included in our factor score calculation. Thus, the L2_Social factor score will not directly overlap with that of Anderson et al.'s 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 and 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). The participant demographics are provided in *SI Appendix*, Table S1.

Language Experience Factors. Model 1 included four EBFs as predictors testing duration and degree, respectively, of L2 exposure and use. These were: (*i*) L2 age of acquisition (years), (*ii*) L2 length of immersion (months), (*iii*) L2 use in social/community settings (L2_Social), and (*iv*) L2 use in home settings (L2_Home). The predictors in model 1 were analyzed individually in the generalized linear model (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 United Kingdom before scanning. We log-transformed both AoA and immersion for two reasons: first, the data were not normally distributed (Shapiro–Wilk test: AoA: W = 0.9521, P = 0.013; immersion: W = 0.81147, $P < 0.0001$) and second, we did not expect a linear rate of adaptation over time (23). The other two predictors (L2_Social and L2_Home) examined the degree of bilingual or L2 use in various settings and were weighted factor scores derived from the LSBQ (27), as described above. Bivariate correlations showed participants' QPT scores (English proficiency) to correlate with all other measures (Table 3), 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 ref. 34).

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: (*i*) the total number of years spent actively using the L2 (Yrs_Active_L2) and (*ii*) 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 (mean length: 10.11 y, 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 (mean length active immersion: 58.43 mo, SD: 60.85, range: 0.1–287.89). As neither of the predictor variables were normally distributed (Years_Active_L2: W = 0.907, $P < 0.001$; Immers_Active_L2: W = 0.8313, $P < 0.0001$), 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.

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

Average and SD	Proficiency (speaking)	Proficiency (understanding)	Proficiency (reading)	Proficiency (writing)
Average score (of 10)	7.95	8.43	8.54	8.03
SD	1.71	1.42	1.33	1.46

Table 2. Participants self-reported English ability and use: Frequency

Average and SD	Frequency (speaking)	Frequency (listening)	Frequency (reading)	Frequency (writing)
Average score (of 4)	3.03	3.17	3.18	3.19
SD	0.71	0.63	0.61	0.68

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, field-of-view (FOV): 192 × 192, 68 transversal slices, 2.0-mm slice thickness, voxel size 2.1 × 2.1 × 2.0 mm, repetition time (TR) = 1,500 ms, echo time (TE) = 30 ms, 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 × 250, acquisition matrix of 246 × 256 mm, TE = 2.41 ms, TR = 2,400 ms, inversion time = 1,140 ms, flip angle = 8°). Finally, a diffusion-weighted echo planar imaging (EPI) scan was run (60 transversal slices, 2-mm slice thickness, acquisition matrix 256 × 256, in-plane resolution 128 × 128, two averages, TE = 70 ms, TR = 1,800 ms, 64 directions). The data are publicly available (35).

MRI Data Preprocessing. Neuroimaging data were preprocessed and analyzed with software pipelines in FSL (36). T1-weighted images were preprocessed with the FSL_anat software pipeline (37). 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 nonlinearly registered to MNI space. GMV was assessed via the voxel-based morphometry pipeline in FSL (38, 39). Preprocessed images were brain-extracted and GM 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 nonlinear component of registration. They were spatially smoothed with an isotropic Gaussian kernel of 3 mm.

The subcortical structures were assessed via a vertex analysis using the first software pipeline (40). The following structures were automatically segmented for analyses: the 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.

Diffusion tensor imaging (DTI) data were preprocessed using the top-up (41), and eddy (42) pipelines within FSL. WM integrity was assessed via several measurements, including FA, MD, RD, and AD values (43, 44). These values were calculated using the FDT and DTIFIT (45) pipelines. Individual differences in WM integrity were assessed using the tract-based spatial statistics (TBSS) pipeline in FSL (46). The FA (and other diffusivity) images were nonlinearly registered to a standard space FA target image and affine-transformed to MNI standard space. This resulted in a 4D image that 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 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 pipeline within FSL (47, 48). This data-driven approach mitigates potential biases associated with traditional seed-based analyses of resting-state fMRI data (47). The data were first preprocessed, including motion corrections, corrections for field distortions, and registered 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 multisession 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 (49). These components were then manually inspected and classified, per the guidelines specified by Griffanti et al. (50). Components classified as noise were excluded from further analysis. This included one component with spectra containing more than 50% power at greater than 0.1-Hz frequencies; five components with excessive spatial distribution in WM, ventricles, and the brainstem; two components with spatial distribution indicative of motion or basal physiological activity (49–51); and one with excessive jumps in oscillatory patterns in their time courses. This totaled to nine 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 (49). The components were then subject to group-level analysis via the dual_regression pipeline (52). 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 Randomize pipeline (53), in which a voxel-wise, nonparametric permutation analysis was performed with 5,000 permutations for each factor of interest. Corrections for multiple comparisons were implemented using threshold-free cluster enhancement (54). 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 the CC (Fig. 1 and

Table 3. Correlations between the language experience factors

Factor	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

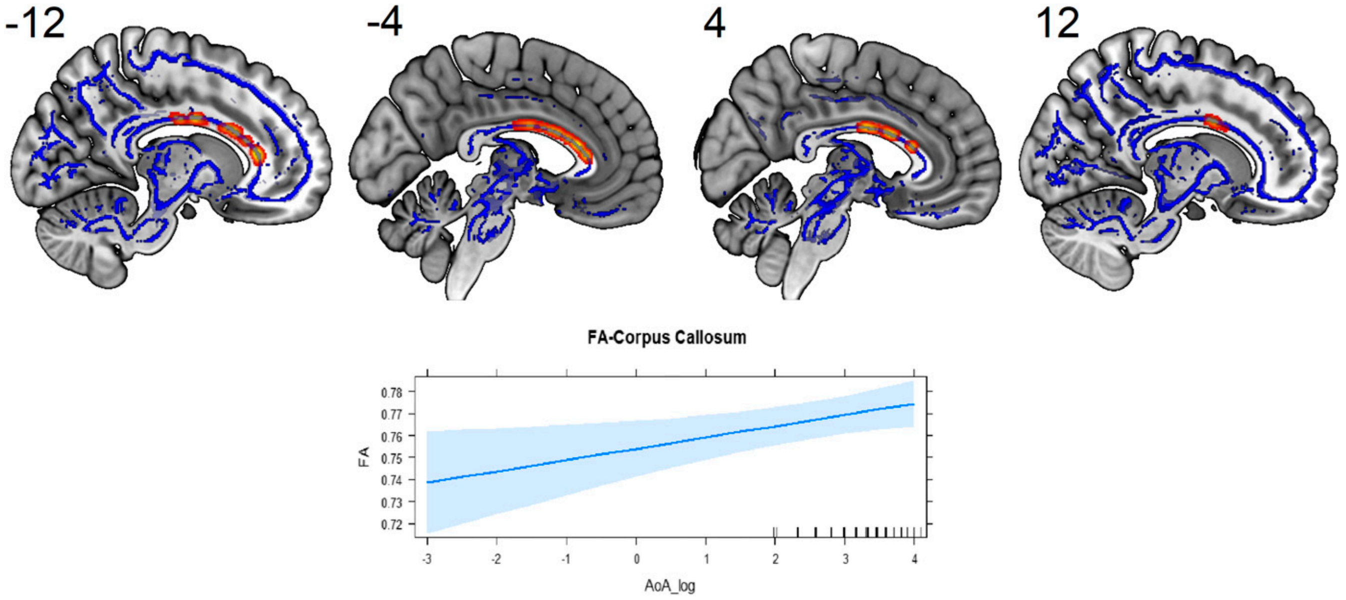

Fig. 1. Results of TBSS analysis. (*Upper*) Significant effects of AoA (red/yellow) within FA skeleton (blue). (*Lower*) Plot of correlation between AoA and extracted significant FA values in the CC coordinates listed are in MNI space.

Table 4). 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 4). L2_Social predicted expansions in several portions of the left caudate nucleus (Fig. 2*A*), left nucleus accumbens, and right thalamus (Table 5).

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 (Fig. 3 and Table 6) (49). No other predictors predicted functional connectivity patterns.

Voxel-based morphometry analysis. None of the language experience factors significantly predicted cortical GMV patterns when corrected for multiple comparisons.

Model 2: Duration of Active L2 Use. Both language experience factors were found to predict subcortical adaptations. Specifically, 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 7). Neither language-use factor was found to significantly predict GMV, diffusivity, or resting-state connectivity patterns.

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.

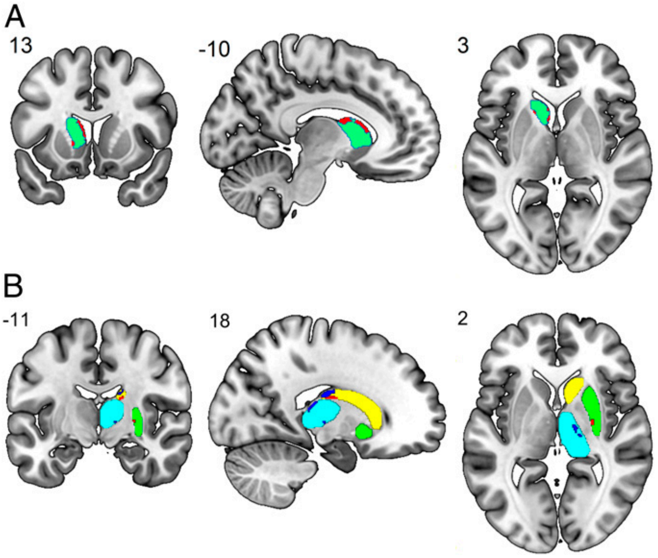

Fig. 2. Results from vertex analysis. (*A*) Significant expansions (red) on the left caudate nucleus (green) predicted by L2_Social. (*B*) Significant expansions (red) and contractions (blue) on the right caudate (yellow), putamen (green), and thalamus (cyan) predicted by immersion.

Table 4. Results of TBSS analysis for model 1

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

Coordinates are in MNI-space.

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 toward increased efficiency in L2 processing and control, whereas effects of extent of use reflected adaptations toward 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 CC potentially reflects increased efficiency associated with longer duration of L2 use, specifically a decreased reliance on frontal interhemispheric 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 (34). Taken together, these patterns reflect a return to "baseline" diffusivity with increased time using the L2, likely commensurate with increased efficiency and 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, 55), 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 et al. (49) have also associated the visual network with cognitive and language (mainly orthographic) processing. Based on those findings, the connectivity increases seen here may reflect transitions toward more automated or efficient grapheme-to-phoneme mapping in the L2. (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 nonnative acquisition where the language is often taught through literacy in a conscious fashion, this effect might be more robust. This, however, requires further research.) 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 (56, 57). Under such a view, we may interpret the expansions here as an optimization toward 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 predictions from the BAPSS framework (20): 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 (26). The contractions seen in the right caudate nucleus could suggest a return to baseline from prior expansions earlier in L2 immersion (13, 15, 58), 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 (19, 31). 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 (59, 60). 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 (56) as a result of the

Table 5. Results of vertex analysis for model 1

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

Coordinates are in MNI-space.

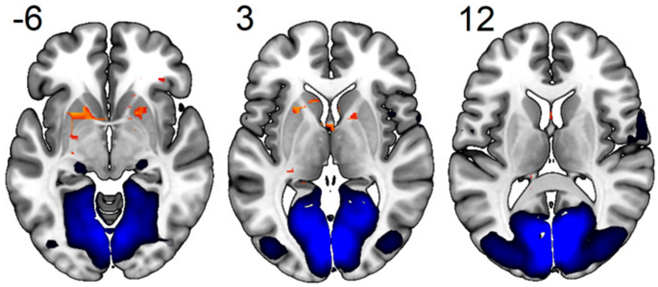

Fig. 3. Results from resting-state connectivity analysis. Modulations in connectivity (red) in the visual network (blue) predicted by AoA.

prolonged intensive L2 exposure and use that is associated with the immersive environment (26). Finally, the expansions in the right putamen indicate adaptations toward increased efficiency in L2 speech production (14, 15). The putamen has been implicated in phonological and articulatory monitoring demands (6, 61). Because 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 toward 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 nontarget language in processing and production (6, 19). This interpretation is supported by other studies that find caudate engagement with increased language switching and selection demands (58, 62). 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 toward 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 toward 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 toward duration and degree of L2 use, respectively. Under interpretations of the BAPSS framework and ACH, adaptations related to duration of L2 use indicate optimizations toward efficiency and automation in L2 processing and control. Increased degree of L2 use related to adaptations toward 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 toward 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 of 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 modeling 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 toward “how much” and “under what (EBF) conditions.”

Experiences are individualistic, although certain experiences cluster together in nonrandom ways by bilingual type, geographic location, and other societal factors (63, 64). Our own bilingual cohort provides such an example: our participants moved to the United Kingdom at varying ages, and migration to the United Kingdom 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 (*Methods*), and the majority emigrated from another European country to the United Kingdom, 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 United Kingdom), which would have inevitably dictated these opportunities based on factors, such as societal expectations for L2 use,

Table 6. 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

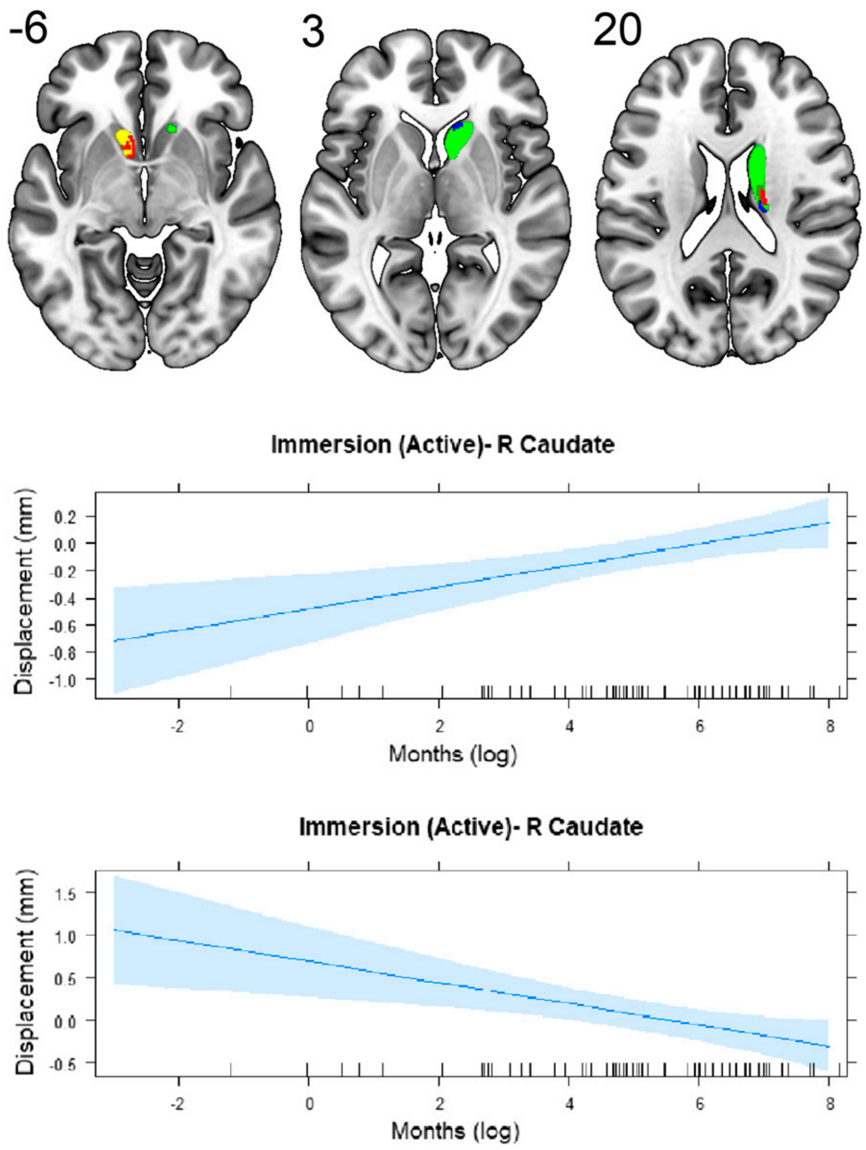

Fig. 4. Results of vertex analysis for model 2. (*Top*) Expansions (red) on the left nucleus accumbens predicted by Years_Active_L2. Expansions (red) and contractions (blue) on the right caudate nucleus predicted by Immers_Active_L2. (*Middle*) Plot of correlations between Immers_Active_L2 and area of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

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: for example, the United States, Canada, or Australia. [Such has been documented even for linguistic competence in heritage language Spanish bilingualism in distinct English-speaking environments—Canada versus the United States (see ref. 65)—where more favourable attitudes toward 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.] 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

Table 7. Results of vertex analysis for model 2

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

Coordinates are in MNI space.

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 compared with 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 or in successful English-native acquirers of L2 Spanish who have never left the United States? 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 (64). It is more likely that differences relate to tendencies of how EBFs distribute in certain cohorts of bilinguals compared with 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.

Modeling the general weighting of EBFs not only has a good chance of explaining variable outcomes across studies, but it also embodies a major step toward 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 toward models that take these factors seriously and can place 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 that 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.

ACKNOWLEDGMENTS. We would like to thank David Green, Gerit Pfuhl, and John Anderson, as well as our anonymous reviewers, for their helpful comments and suggestions. This research was supported by a University of Reading International Studentship (to V.D.), and by the Centre for Literacy and Multiligualism, University of Reading and the Centre for Integrative Neuroscience and Neurodynamics, University of Reading.

1. García-Pentón L, Fernández García Y, Costello B, Duñabeitia JA, Carreiras M (2016) The neuroanatomy of bilingualism: How to turn a hazy view into the full picture. *Lang Cogn Neurosci* 31:303–327.
2. Li P, Legault J, Litcofsky KA (2014) Neuroplasticity as a function of second language learning: Anatomical changes in the human brain. *Cortex* 58:301–324.
3. Pliatsikas C (2019) Multilingualism and brain plasticity. *The Handbook of the Neuroscience of Multilingualism*, ed Schweiter JW (Wiley Blackwell, Hoboken, NJ), pp 230–251.
4. Bialystok E, Craik FI, Luk G (2012) Bilingualism: Consequences for mind and brain. *Trends Cogn Sci* 16:240–250.
5. Kroll JF, Dussias PE, Bogulski CA, Valdes-Kroff JR (2012) Juggling two languages in one mind. What bilinguals tell us about language processing and its consequences for cognition. *Psychology of Learning and Motivation*, ed Ross B (Academic, San Diego), pp 229–262.
6. Abutalebi J, Green DW (2016) Neuroimaging of language control in bilinguals: Neural adaptation and reserve. *Biling Lang Cogn* 19:689–698.
7. Luk G, Bialystok E (2013) Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *J Cogn Psychol (Hove)* 25:605–621.
8. Surrain S, Luk G (2019) Describing bilinguals: A systematic review of labels and descriptions used in the literature between 2005–2015. *Biling Lang Cogn* 22:401–415.
9. Bialystok E (2016) The signal and the noise: Finding the pattern in human behavior. *Linguist Approaches Biling* 6:517–534.
10. Klein RM (2016) What cognitive processes are likely to be exercised by bilingualism and does this exercise lead to extra-linguistic cognitive benefits? *Linguist Approaches Biling* 5:549–564.
11. Paap KR, Johnson HA, Sawi O (2015) Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex* 69:265–278.
12. Luk G, Pliatsikas C (2016) Converging diversity to unity: Commentary on The neuroanatomy of bilingualism. *Lang Cogn Neurosci* 31:349–352.
13. Mårtensson J, et al. (2012) Growth of language-related brain areas after foreign language learning. *Neuroimage* 63:240–244.
14. Burgaleta M, Sanjuán A, Ventura-Campos N, Sebastián-Gallés N, Ávila C (2016) Bilingualism at the core of the brain. Structural differences between bilinguals and monolinguals revealed by subcortical shape analysis. *Neuroimage* 125:437–445.
15. Pliatsikas C, DeLuca V, Moschopoulou E, Saddy JD (2017) Immersive bilingualism reshapes the core of the brain. *Brain Struct Funct* 222:1785–1795.
16. Schlegel AA, Rudelson JJ, Tse PU (2012) White matter structure changes as adults learn a second language. *J Cogn Neurosci* 24:1664–1670.
17. Luk G, Bialystok E, Craik FIM, Grady CL (2011) Lifelong bilingualism maintains white matter integrity in older adults. *J Neurosci* 31:16808–16813.
18. Rothman J (2015) Linguistic and cognitive motivations for the Typological Primacy Model (TPM) of third language (L3) transfer: Timing of acquisition and proficiency considered. *Biling Lang Cogn* 18:179–190.
19. Green DW, Abutalebi J (2013) Language control in bilinguals: The adaptive control hypothesis. *J Cogn Psychol (Hove)* 25:515–530.
20. Grundy JG, Anderson JAE, Bialystok E (2017) Neural correlates of cognitive processing in monolinguals and bilinguals. *Ann N Y Acad Sci* 1396:183–201.
21. Nichols ES, Joanisse MF (2016) Functional activity and white matter microstructure reveal the independent effects of age of acquisition and proficiency on second-language learning. *Neuroimage* 143:15–25.
22. Rossi E, Cheng H, Kroll JF, Diaz MT, Newman SD (2017) Changes in white-matter connectivity in late second language learners: Evidence from diffusion tensor imaging. *Front Psychol* 8:2040.
23. Kuhl PK, et al. (2016) Neuroimaging of the bilingual brain: Structural brain correlates of listening and speaking in a second language. *Brain Lang* 162:1–9.
24. Abutalebi J, et al. (2013) Language proficiency modulates the engagement of cognitive control areas in multilinguals. *Cortex* 49:905–911.
25. Mamiya PC, Richards TL, Coe BP, Eichler EE, Kuhl PK (2016) Brain white matter structure and COMT gene are linked to second-language learning in adults. *Proc Natl Acad Sci USA* 113:7249–7254.

26. Linck JA, Kroll JF, Sunderman G (2009) Losing access to the native language while immersed in a second language: Evidence for the role of inhibition in second-language learning. *Psychol Sci* 20:1507–1515.
27. Anderson JAE, Mak L, Keyvani Chahi A, Bialystok E (2018) The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behav Res Methods* 50:250–263.
28. Ullman MT (2004) Contributions of memory circuits to language: The declarative/procedural model. *Cognition* 92:231–270.
29. Bellander M, et al. (2016) Behavioral correlates of changes in hippocampal gray matter structure during acquisition of foreign vocabulary. *Neuroimage* 131:205–213.
30. Pliatsikas C, Moschopoulou E, Saddy JD (2015) The effects of bilingualism on the white matter structure of the brain. *Proc Natl Acad Sci USA* 112:1334–1337.
31. Llano DA (2013) Functional imaging of the thalamus in language. *Brain Lang* 126:62–72.
32. Pliatsikas C, Johnstone T, Marinis T (2014) Grey matter volume in the cerebellum is related to the processing of grammatical rules in a second language: A structural voxel-based morphometry study. *Cerebellum* 13:55–63.
33. Geranpayeh A (2003) A quick review of the English Quick Placement Test. *UCLES Res Notes* 12:8–10.
34. DeLuca VF, Rothman J, Pliatsikas C (2018) Linguistic immersion and structural effects on the bilingual brain: A longitudinal study. *Biling Lang Cogn* 1:1–16.
35. DeLuca V (2019) Bilingualism and the brain. OpenNeuro. Available at https://openneuro.org/datasets/ds001796/share/. Deposited March 14, 2019.
36. Smith SM, et al. (2004) Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage* 23:S208–S219.
37. Jenkinson M, Beckmann CF, Behrens TEJ, Woolrich MW, Smith SM (2012) FSL. *Neuroimage* 62:782–790.
38. Ashburner J, Friston KJ (2000) Voxel-based morphometry–The methods. *Neuroimage* 11:805–821.
39. Good CD, et al. (2001) Cerebral asymmetry and the effects of sex and handedness on brain structure: A voxel-based morphometric analysis of 465 normal adult human brains. *Neuroimage* 14:685–700.
40. Patenaude B, Smith SM, Kennedy DN, Jenkinson M (2011) A Bayesian model of shape and appearance for subcortical brain segmentation. *Neuroimage* 56:907–922.
41. Andersson JLR, Skare S, Ashburner J (2003) How to correct susceptibility distortions in spin-echo echo-planar images: Application to diffusion tensor imaging. *Neuroimage* 20:870–888.
42. Andersson JLR, Sotiropoulos SN (2016) An integrated approach to correction for off-resonance effects and subject movement in diffusion MR imaging. *Neuroimage* 125:1063–1078.
43. Singh NC, et al. (2018) Microstructural anatomical differences between bilinguals and monolinguals. *Biling Lang Cogn* 21:995–1008.
44. Anderson JAE, et al. (2018) Effects of bilingualism on white matter integrity in older adults. *Neuroimage* 167:143–150.
45. Behrens TEJ, et al. (2003) Characterization and propagation of uncertainty in diffusion-weighted MR imaging. *Magn Reson Med* 50:1077–1088.
46. Smith SM, et al. (2006) Tract-based spatial statistics: Voxelwise analysis of multi-subject diffusion data. *Neuroimage* 31:1487–1505.
47. Beckmann CF, Smith SM (2004) Probabilistic independent component analysis for functional magnetic resonance imaging. *IEEE Trans Med Imaging* 23:137–152.
48. Beckmann CF, Smith SM (2005) Tensorial extensions of independent component analysis for multisubject FMRI analysis. *Neuroimage* 25:294–311.
49. Smith SM, et al. (2009) Correspondence of the brain's functional architecture during activation and rest. *Proc Natl Acad Sci USA* 106:13040–13045.
50. Griffanti L, et al. (2017) Hand classification of fMRI ICA noise components. *Neuroimage* 154:188–205.
51. Seeley WW, et al. (2007) Dissociable intrinsic connectivity networks for salience processing and executive control. *J Neurosci* 27:2349–2356.
52. Beckmann CF, Mackay CE, Filippini N, Smith SM (2009) Group comparison of resting-state FMRI data using multi-subject ICA and dual regression. *Neuroimage* 47(Suppl 1):S148.
53. Winkler AM, Ridgway GR, Webster MA, Smith SM, Nichols TE (2014) Permutation inference for the general linear model. *Neuroimage* 92:381–397.
54. Smith SM, Nichols TE (2009) Threshold-free cluster enhancement: Addressing problems of smoothing, threshold dependence and localisation in cluster inference. *Neuroimage* 44:83–98.
55. Ford AA, et al. (2013) Broca's area and its striatal and thalamic connections: A diffusion-MRI tractography study. *Front Neuroanat* 7:8.
56. Botvinick M, Braver T (2015) Motivation and cognitive control: From behavior to neural mechanism. *Annu Rev Psychol* 66:83–113.
57. Chase HW, Kumar P, Eickhoff SB, Dombrovski AY (2015) Reinforcement learning models and their neural correlates: An activation likelihood estimation meta-analysis. *Cogn Affect Behav Neurosci* 15:435–459.
58. Hosoda C, Tanaka K, Nariai T, Honda M, Hanakawa T (2013) Dynamic neural network reorganization associated with second language vocabulary acquisition: A multimodal imaging study. *J Neurosci* 33:13663–13672.
59. Luk G, Green DW, Abutalebi J, Grady C (2011) Cognitive control for language switching in bilinguals: A quantitative meta-analysis of functional neuroimaging studies. *Lang Cogn Process* 27:1479–1488.
60. Ma H, et al. (2014) Bilingual cognitive control in language switching: An fMRI study of English-Chinese late bilinguals. *PLoS One* 9:e106468.
61. Viñas-Guasch N, Wu YJ (2017) The role of the putamen in language: A meta-analytic connectivity modeling study. *Brain Struct Funct* 222:3991–4004.
62. Zou L, Ding G, Abutalebi J, Shu H, Peng D (2012) Structural plasticity of the left caudate in bimodal bilinguals. *Cortex* 48:1197–1206.
63. Bak TH (2016) The impact of bilingualism on cognitive aging and dementia: Finding a path through a forest of confounding variables. *Linguist Approaches Biling* 6:205–226.
64. Bak TH (2016) Cooking pasta in La Paz. *Linguist Approaches Biling* 6:699–717.
65. Valenzuela E, et al. (2015) Eventive and stative passives and copula selection in Canadian and American Heritage Speaker Spanish. *New Perspectives on the Study of Ser and Estar*, eds Pérez-Jiménez I, Leonetti M, Gumiel-Molina S (John Benjamins, Amsterdam), pp 267–292.