Sequential language learning versus language immersion in bilingualism: Diffusion MRI connectometry reveals microstructural evidence

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Background: Bilingualism is a universal phenomenon. Study of bilingual brain has provided evidence to probable advantageous outcomes of early second language learning and brain structural correlates to these outcomes. Preservation of cognitive function with aging and executive dexterity are amongst proposed benefits. *Method:* Using the data deposited by Pliatsikas we analyzed through diffusion MRI connectometry structural difference in white matter tracts in 20 healthy sequential bilingual adults, who used English as a second language on a daily basis, and 25 controls in fiber differentiation analyses. Significant tracts were extracted with and without regression against language immersion period. *Results:* Connectometry results revealed increased connectivity in corpus callosum (CC), bilateral cingulum, arcuate fasciculus (AF), and left Inferior fronto occipital fasciculus (IFOF), of sequential bilingual adults. Also bilateral IFOF, AF as well as body and genu of corpus callosum were positively correlated with language immersion time. *Conclusion*: Mentioned white matter tracts with diffusion structural significance in young adults with long immersion into the second language, confirm results of previous results. These are also in consort with known pathways involved in neurophysiological processes in speech stream and in cognitive performance. Insertion of immersion time as a variable in the model, yielded the same results with higher FDR values, except for arcuate fasciculus. Future studies are warranted to address structural differences with larger samples, investigating the effects of early language immersion on white matter tracts versus individual and social variables that interfere with white matter maturation and integrity.

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Abstract

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Method: Using the data deposited by Pliatsikas we analyzed through diffusion MRI connectometry structural difference in white matter tracts in 20 healthy sequential bilingual adults, who used English as a second language on a daily basis, and 25 controls in fiber differentiation analyses. Significant tracts were extracted with and without regression against language immersion period.

Results: Connectometry results revealed increased connectivity in corpus callosum (CC), bilateral cingulum, arcuate fasciculus (AF), and left Inferior fronto occipital fasciculus (IFOF), of sequential bilingual adults. Also bilateral IFOF, AF as well as body and genu of corpus callosum were positively correlated with language immersion time.

Conclusion: Mentioned white matter tracts with diffusion structural significance in young adults with long immersion into the second language, confirm results of previous results. These are also in consort with known pathways involved in neurophysiological processes in speech stream and in cognitive performance. Insertion of immersion time as a variable in the model, yielded the same results with higher FDR values, except for arcuate fasciculus. Future studies are warranted to address structural differences with larger samples, investigating the effects of early language immersion on white matter tracts

versus individual and social variables that interfere with white matter maturation and integrity.

Keywords: *Bilingualism; Immersion; Connectometry; Diffusion MRI*

Introduction

Active use of two or more languages in daily life, or bilingualism is a global phenomenon, which has a known role in "cognitive reserve" or preservation of cognitive function. Bilinguals are more successful in resolving nonlinguistic cognitive conflicts (1), are less prone to degenerative brain processes with aging (2), and have better executive control (3). Neuroimaging studies have opened a window into the underlying structural changes in "bilingual brain", especially structural changes affecting integrity of the white matter.

One unresolved question is whether critical periods exist for the developing brain to make microstructural adaptations while learning a new language? It appears that white matter microstructural changes associated with beneficial cognitive characteristics and increased white matter integrity in terms of significantly increased fractional anisotropy (FA), occur in both early and simultaneous learning of a second language (L2) (4). Increased FA in the inferior fronto occipital fasciculus (IFOF), and decreased FA in genu and anterior corpus callosum (CC), are amongst reported changes in early L2 learners among school aged children (5). Pliatsikasa and his colleagues provided insights into white matter structural differences in young bilingual adults, who were are sequential learners of English as second language and were highly immersed, meaning that they had been using L2 on a daily basis for a long period (6). Through tract based spatial statistics, they reported increased white matter integrity, in bilateral IFOF, uncinated fasciculi

(UF), and superior longitudinal fasciculus. They failed however to demonstrate a correlation between the degree of immersion in months and white matter changes.

Grey matter change in volume has been also proposed in bilinguals. While no statistically meaningful difference was apparent in point analyses by voxel based morphometry, longitudinal data supported grey matter increase in size and volume in bilateral hippocampal areas (7), left inferior parietal lobule (8), left anterior temporal gyrus (8), and bilateral anterior cingulate cortices (1). Grey matter volume in these areas positively correlated with lexial efficiency and negatively correlated with the age at which bilinguals had started learning a new language (7).

Using the data deposited at https://central.xnat.org/ the by Pliatsikas (9), we analyzed through diffusion MRI connectometry structural difference in white matter tracts in 20 healthy sequential bilingual adults, and further investigated the probable correlation of diffusion metrics against immersion period of the second language.

2. Materials and methods

2.1 Participants

Twenty healthy young adults who all used English as second proficient language and had lived in the United Kingdom for at least 13 months, with various ethnic and mother languages backgrounds formed the study group. Control group consisted of 25 age, sex and education matched native speakers of English. All the subjects were taken the Quick Placement Test (QPT) for assessment of their proficiency in English. Both groups scored at least 80 %. Detailed demographics of both groups can be reached at the http://xnat.org depository (9).

2.2 Data Acquisition

A 3.0-Tesla Siemens MAGNETOM Trio MRI scanner was used with Syngo software and 36-channel Head Matrix coil to acquire a whole-brain diffusion-weighted Echo-Plannar Imaging image (Two averages, 30 directions, 60 axial slices; slice thickness, 2 mm, no interslice gap; field of view, 256×256 mm; acquisition matrix, 128×128; voxel size, 2 mm isotropic; echo time, 93 ms; repetition time, 8,200 ms; b-value, 1,000 s/mm2).

2.3 Diffusion MRI Data Processing

Diffusion MRI data were corrected for subject motion, eddy current distortions, and susceptibility artefacts due to the magnetic field inhomogeneity using ExploreDTI toolbox.

2.4 Comparison Analysis

The diffusion data were reconstructed in the MNI space using q-space diffeomorphic reconstruction to obtain the spin distribution function. A diffusion sampling length ratio of 1.25 was used, and the output resolution was 1 mm.

Diffusion MRI connectometry was conducted to compare group differences in a total of 44 subjects. The group difference was quantified using percentage measurement. A threshold of 25% difference was used to select local connectomes that had substantial difference. A deterministic fiber tracking algorithm was conducted to connect the selected local connectomes. A length threshold of 50 mm was used to select tracks. The seeding density was 20 seeds per mm^3. The analysis was conducted using DSI Studio (http://dsi-studio.labsolver.org).

2.5 Correlation Analysis with Immersion

In this part, Diffusion MRI connectometry was conducted in a total of 17 subjects using a multiple regression model considering immersion. A percentage threshold of 50% was used to select local connectomes correlated with immersion. A deterministic fiber tracking algorithm was conducted to connect the selected local connectomes. A length threshold of 65 mm were used to select tracks. The seeding density was 20 seeds per mm^3. To estimate the false discovery rate, a total of 500 randomized permutations were applied to the group label to obtain the null distribution of the track length.

3. Results

Our case-control study was carried out on 20 healthy "sequential" bilinguals, who spoke English as their second language (original language varied across the participants). The case group consisted of 7 (55%) male and 13 (65%) female bilinguals living part of their lifetime in United Kingdom (with a mean of 91 months of UK residency).The mean age of bilinguals was 31.85 ± 8.07 (ranging from 20 to 47), and the age of L2 learning differed from 4 to 18 years among bilingual adults.

Imaging data was analysed for 11 (44%) males and 14 (56%) females, who were matched with respect to age, sex and English proficiency (measured through QTP criteria, scoring a minimum of 80%), as control group.

3.1 Comparison Analysis

The connectometry analysis results showed tracks with increased quantitative anisotropy in bilingual group with an FDR of 0.043. These tracks include corpus callosum (CC), bilateral cingulum, arcuate fasciculus (AF) and left IFOF. Significant tracks are showed in Figure 1.

3.2 Correlation Analysis

Analysis of diffusion parameters against immersion period revealed that anisotropy values of IFOF bilaterally, AF bilaterally, genu and body of CC, are positively associated with immersion with FDR of 0.075, showing a trend toward significance (Figure 2). Higher FDR values mean higher probability of variation in brain connection patterns, and the observed FDR value is predictable due to low case numbers of this study.

4. Discussion

Bilingualism has been linked to a variety of cognitive benefits, including delayed brain aging, in terms of better executive performance in childhood, higher ability to resolve verbal and non-verbal conflicts and cognitive preservation of cognitive function with aging (10). The beneficial effects of bilingualism in cognition is still under debate, while measurements of executive function can give inconsistent reports even in a single population based on their current social, and educational status. The wide range of executive functions and the wide range of the tasks measuring one or two of the executive functions, along with different mechanisms by which an individual might have learned second language, further complicates an answer to this question (11).

There are different conditions through which someone might be exposed to a new language. This ranges from individuals being exposed to both languages since or early after birth, and thus are naturally immersed in the context of both languages, to those learning a second language in a sequential, not parallel, manner e.g. through classroom instruction etc. These cognitive benefits and aging preservation of bilinguals appear to be more prominent in the former, long immersed, natural/simultaneous learners (3). Finally, while executive and cognitive measurements are inaccurate, brain structural changes certify significant developmental or structural differences in bilingual versus monolingual individuals at least.

Also, apart from many factors that have been noticed apart from age, brain plasticity and perhaps social and ethnic background that might affect white matter integrity in bilinguals, is the ‘’immersion’’, or the time interval individual has been exposed to both languages

Luk and colleagues (12) performed one of the first DTI studies on bilingual subjects to extract WM microstructural features and compare brain architecture in bilingual individuals. Their sample consisted of lifelong bilingual individuals with English as first language and age-matched English monolinguals. TBSS analysis revealed higher values of FA in bilingual group particularly in CC, bilateral superior longitudinal fasciculi, right ILOF and uncinate fasciculus (UF). Pliasticas and his colleagues (6) reported almost the same correlations on DTI scan in 20 young ‘’sequential’’ proficient English learners.

These fibers are parts of brain semantic processing as ventral and dorsal speech streams (13). Gold (2), Cummine (5) and their colleagues, reported FA decrease in CC, Inferior longitudinal fasciculi (ILF), IFOF and fornix in English sequential bilinguals, and in the right ILF and anterior thalamic radiation in young Chinese–English late bilinguals respectively. IFOF and ILF share mutual projections to and from the occipital and temporal lobes. Integrity of the ILF correlates well with object recognition with lexical labels in children and increases sequentially with elaboration of the skill.

These results were enough to propose the hypothesis that not necessarily bilingualism relies on critical periods in life, but particular conditions are warranted to strongly induce it and that weather by increase or decrease of anisotropy, white matter major associational fibers undergo structural adaptations in response to new language learning.

Mohades et al. used ROI FA measurements assessed fractional anisotropic values in a sample including 3 subgroups: 15 simultaneous bilingual children, 15 age-matched sequential bilingual participants and 10 monolinguals. They obtained FA values for the left IFOF and four other language related projections, and the right IFOF as control. In a longitudinal assessment, sequential learners' depicted highest degree of change in FA values in the IFOF, and the mean FA value in this region was able to distinguish simultaneous bilinguals from monolinguals (14). The left inferior fronto-occipital fasciculus is primarily involved in semantic processing and integrative functions of the ventral stream of speech formation, connecting the frontal and dorsolateral prefrontal cortices to occipital and temporal gyri (15). Further from semantic processing, IFOF actively participates in verbal-visual incongruence recognition and also in word recognition (14). In a maturation point of view, these results confirm a temporal significance for critical changes in microstructure of the IFOF as previously reported, and suggest that the degree of structural maturity in fibers is determined by the duration of being bilingual (16). In another study Mohades et al. revealed that maximal anisotropic values changes in the left IFOF occur with simultaneous bilinguals or those using a merging of both languages (14).

There are also longitudinal reports studying the process of brain structural and functional changes during L2 acquisition. One striking result was obtained from a cohort study by Schlegel et al (17), who followed two groups of English monolinguals with the experiment group receiving intensive Chinese language acquisition. Even as early as nine months of learning, higher FA values in “late" new language learners was obvious, especially in the genu of CC and left frontal language associative areas. This is in consort with advantageous effects of second language (L2) learning in brain microstructural changes and improvements in connectivity, emerging even after short term intervals in sequential bilinguals. More interesting was that with expansion of vocabulary domain i.e. the ability to remember and use new words in new learners of a foreign language, FA values of the mentioned fibers changed respectively.

Hosoda and his colleagues (18) report results of a cross-sectional study followed by their longitudinal follow up on bilinguals after they had received 4 months of intensive language training. Not only the baseline FA of Japanese-English proficient individuals was higher in the arcuate fasciculus, inferior frontal gyrus (IFG), caudate nucleus and superior temporal gyrus, but also these values tended to increase proportionately with L2 learning. Finally, when L2 training was halted for one year, DTI findings certified a regression to start point values, the same as their matched counterpart monolinguals. This brings us to realize the immense potential of brain plasticity in language learning, compatible with constant active use of the second language in daily life (19).

Arcuate fasciculus is part of the dorsal speech stream, mapping the heard language onto motor areas for speech. This area is a network of three distinct cortical areas, the left inferior frontal gyrus, left middle temporal gyrus, and left inferior parietal lobe (20). Together these results underscore the bilingual advantage theory (3), connecting the neuroanatomical changes in fibers to physiological function in bilingual brain.

Through Diffusion MRI connectometry, we identified white matter areas with increased quantitative anisotropy in bilingual adults with long immersion period, compared to healthy age-sex matched individuals. According to Yeh et al. (21) quantitative anisotropy (qa), is a measure water density in a voxel or tract, rather than diffusivity, as measured by other diffusion variables such as fractional anisotropy or mean diffusivity. Indeed, qa gives more accurate information about normal/healthy distribution of water along the length of a fiber or within a voxel, and thus is a diffusivity marker of a healthy fiber. QA is less sensitive to axonal degeneration than FA and is hence a marker of choice in comparing the two groups of healthy adults in our population.

Our results on significant increased qa in bilateral cingulum, inferior front occipital fasciculi, arcuate fasciculi, and corpus callsoum, are in consort with previously reported areas. Apart from Aboutaleb et al. who suggested a role for ACC cortex in language switching and ability in non-verbal conflict, nothing was previously reported on cingulum structural adaptations in learning a new language. The cingulum is critical for emotion formation, executive function, visuospatial skills and attention. As a whole, cingulum is suggested to play a multimodal role in cognitive function and is highly active while performing cognitive tasks, especially those demanding a complex of executive and intellectual function (22). On the contrary, posterior cingulate areas are in a relative deactive state during cognitive tasks and accordingly regulate "internally directed cognition" or default mode self-awareness function of the brain (23).

Immersion period analysis revealed almost the same results of differentiation analysis, except for the AF, that did not show significant difference in qa value when regressed against immersion period, even with an FDR of 0.075. This might suggest that the aforementioned white matter changes in our sample of young healthy bilingual individuals, who had commenced their language learning no earlier than 4 years old, are mostly results of brain plasticity and active use of a second language rather than a developmental phenomenon of early L2 learning.

Structural connectivity in developing brain and brain structural maturation occurs in consort with normal developmental stages, aging process, and learning new skills. One major limitation of this study was the small number of cases in both groups, yielding to high FDR values. It is justifiable to repeat this study with larger sample group while taking into account the individual and social variables, most importantly language proficiency, use of language, and immersion period as probable confounding developmental factors.

5. References

1. Abutalebi J, Della Rosa PA, Green DW, Hernandez M, Scifo P, Keim R, et al. Bilingualism tunes the anterior cingulate cortex for conflict monitoring. Cerebral cortex (New York, NY : 1991). 2012;22(9):2076-86.
2. Gold BT, Johnson NF, Powell DK. Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. Neuropsychologia. 2013;51(13):2841-6.
3. Olulade OA, Jamal NI, Koo DS, Perfetti CA, LaSasso C, Eden GF. Neuroanatomical Evidence in Support of the Bilingual Advantage Theory. Cerebral cortex (New York, NY : 1991). 2016;26(7):3196-204.
4. Mohades SG, Struys E, Van Schuerbeek P, Mondt K, Van De Craen P, Luypaert R. DTI reveals structural differences in white matter tracts between bilingual and monolingual children. Brain Res. 2012;1435:72-80.
5. Cummine J, Boliek CA. Understanding white matter integrity stability for bilinguals on language status and reading performance. Brain structure & function. 2013;218(2):595-601.
6. Pliatsikas C, Moschopoulou E, Saddy JD. The effects of bilingualism on the white matter structure of the brain. Proc Natl Acad Sci U S A. 2015;112(5):1334-7.
7. Grogan A, Parker Jones O, Ali N, Crinion J, Orabona S, Mechias ML, et al. Structural correlates for lexical efficiency and number of languages in non-native speakers of English. Neuropsychologia. 2012;50(7):1347-52.
8. Olsen RK, Pangelinan MM, Bogulski C, Chakravarty MM, Luk G, Grady CL, et al. The effect of lifelong bilingualism on regional grey and white matter volume. Brain Res. 2015;1612:128-39.
9. Effects of bilingualism on brain structure and function [Internet]. 2015. Available from: https://central.xnat.org/app/template/XDATScreen_report_xnat_projectData.vm/search_element/xnat:projectData/search_field/xnat:projectData.ID/search_value/L2struc.
10. Valian V. Bilingualism and cognition. Bilingualism: Language and Cognition. 2015;18(1):3-24.
11. García-Pentón L, Fernández García Y, Costello B, Duñabeitia JA, Carreiras M. The neuroanatomy of bilingualism: how to turn a hazy view into the full picture. Language, Cognition and Neuroscience. 2016;31(3):303-27.
12. Luk G, Bialystok E, Craik FI, Grady CL. Lifelong bilingualism maintains white matter integrity in older adults. The Journal of neuroscience : the official journal of the Society for Neuroscience. 2011;31(46):16808-13.
13. Rauschecker JP. Ventral and dorsal streams in the evolution of speech and language. Frontiers in evolutionary neuroscience. 2012;4:7.
14. Mohades SG, Van Schuerbeek P, Rosseel Y, Van De Craen P, Luypaert R, Baeken C. White-matter development is different in bilingual and monolingual children: a longitudinal DTI study. PloS one. 2015;10(2):e0117968.
15. Chang EF, Raygor KP, Berger MS. Contemporary model of language organization: an overview for neurosurgeons. Journal of neurosurgery. 2015;122(2):250-61.

16. Lebel C, Walker L, Leemans A, Phillips L, Beaulieu C. Microstructural maturation of the human brain from childhood to adulthood. NeuroImage. 2008;40(3):1044-55.

17. Schlegel AA, Rudelson JJ, Tse PU. White matter structure changes as adults learn a second language. Journal of cognitive neuroscience. 2012;24(8):1664-70.

18. Hosoda C, Tanaka K, Nariai T, Honda M, Hanakawa T. Dynamic neural network reorganization associated with second language vocabulary acquisition: a multimodal imaging study. The Journal of neuroscience : the official journal of the Society for Neuroscience. 2013;33(34):13663-72.

19. Mechelli A, Crinion JT, Noppeney U, O'Doherty J, Ashburner J, Frackowiak RS, et al. Neurolinguistics: structural plasticity in the bilingual brain. Nature. 2004;431(7010):757.

20. Benetti S, Pettersson-Yeo W, Allen P, Catani M, Williams S, Barsaglini A, et al. Auditory verbal hallucinations and brain dysconnectivity in the perisylvian language network: a multimodal investigation. Schizophrenia bulletin. 2015;41(1):192-200.

21. Yeh F-C, Verstynen TD, Wang Y, Fernández-Miranda JC, Tseng W-YI. Deterministic Diffusion Fiber Tracking Improved by Quantitative Anisotropy. PloS one. 2013;8(11):e80713.

22. Marques P, Soares J, Alves V, Sousa N. BrainCAT - a tool for automated and combined functional Magnetic Resonance Imaging and Diffusion Tensor Imaging brain connectivity analysis. Frontiers in human neuroscience. 2013;7(794).

23. Leech R, Sharp DJ. The role of the posterior cingulate cortex in cognition and disease. Brain : a journal of neurology. 2014;137(1):12-32.

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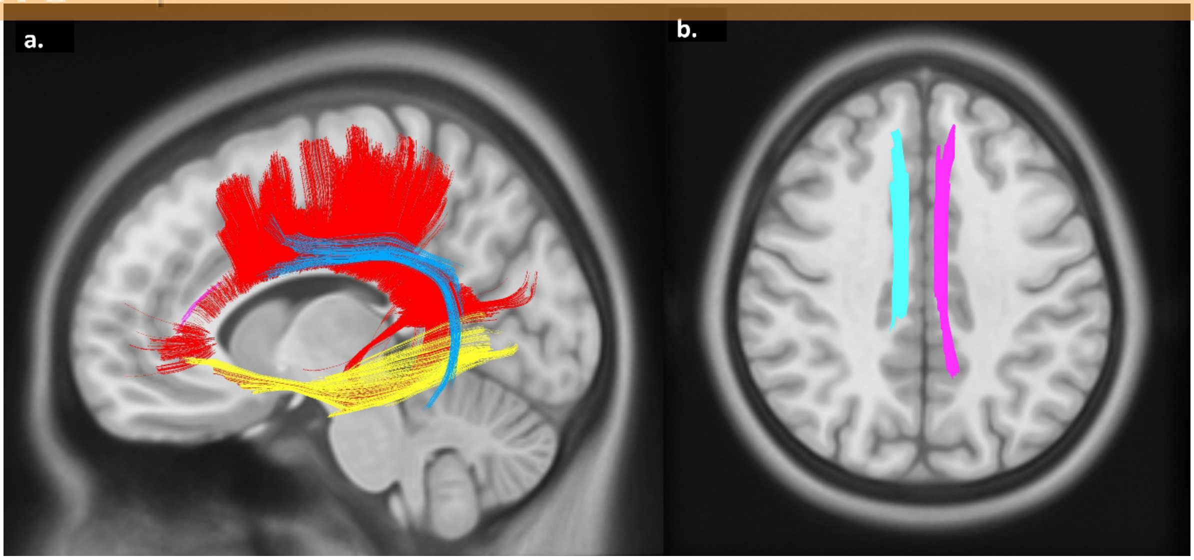

Figure 1. Brain pathways with increased QA in sequential bilingual adults compared to healthy monolingual controls a) corpus callosum, bilateral arcuate fasciculi and left inferior fronto occipital fasciculus, b) bilateral cingulum

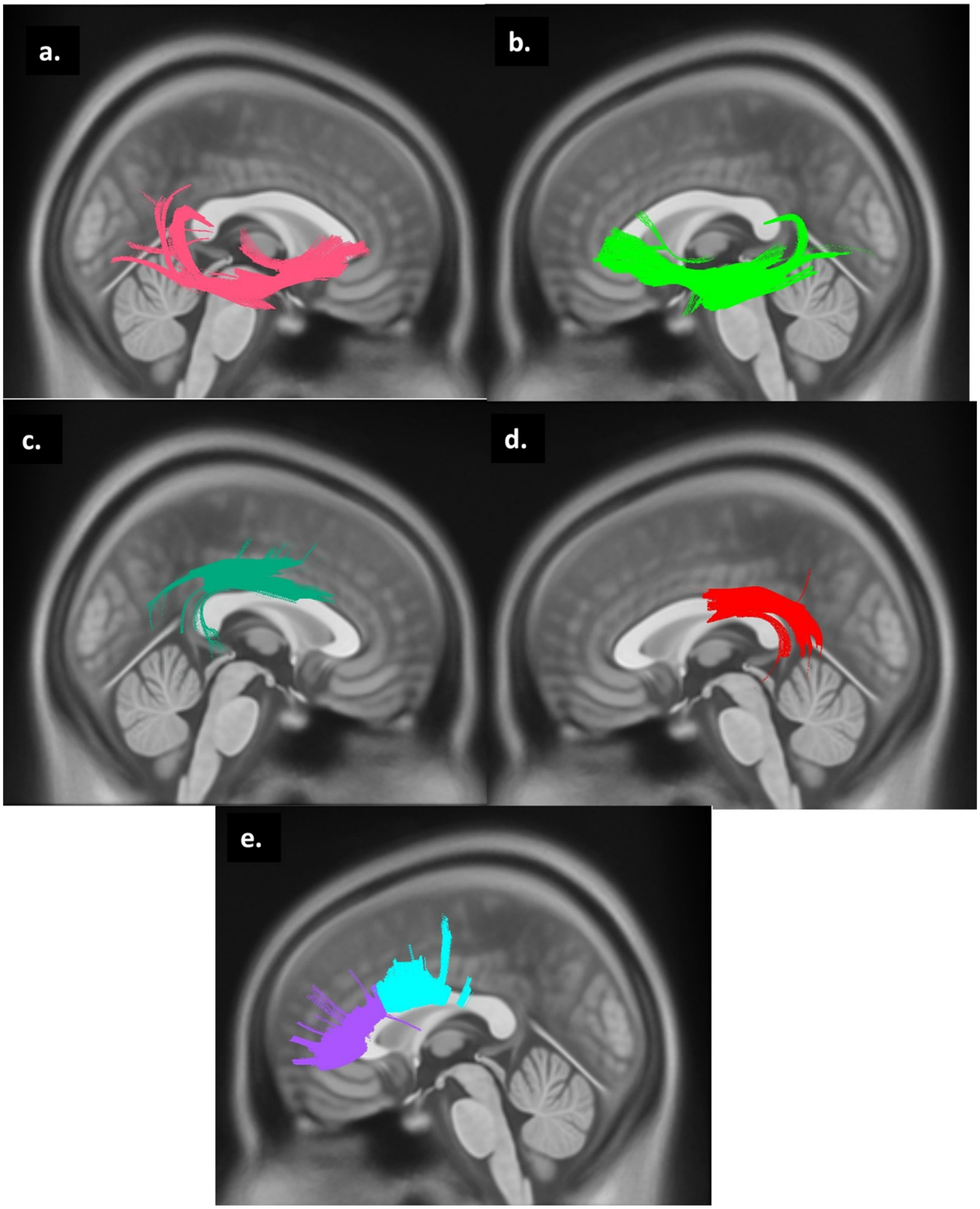

Figure 2. Brain pathways with positive correlation with immersion period in a group of sequential bilingual adults a & b) right and left inferior fronto occipital fasciculi, c & d) right and left arcuate fasciculi and e) genu and body of corpus callosum