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Research Article

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DTI Analysis of White Matter Integrity and Cognitive Brain Reserve in Lifelong Musicians and Controls

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Abstract

Previous research has focused on structural and functional changes to the human brain by training and experience in both linguistic (esp. bilingualism) and musical domains. While normal aging produces trends of decreasing WM integrity, research on cognitive brain reserve suggests that complex sensory-motor activities across the life span may slow down or reverse these trends. The current study incorporates findings from our recent DTI study of lifelong musicianship and building cognitive brain reserve [1] and expands that analysis to include age and education matched non-musician controls. Reinforcing previous results, we show that non-musician controls in aging do not show the increases in WM integrity found in the subcortical tracts in lifelong musicians and that the difference between the groups was significant (p = 0.0065).

Keywords: Cognitive reserve; Musicianship; Diffusion tensor imaging; Fractional anisotropy; White matter integrity

Introduction

Neuroimaging studies of musicians and musicianship is an important focus of inquiry that began to emerge robustly in the early 2000s [2, 3, 4, 5, 6]. Recent work on musicians, especially diffusion tensor imaging (DTI) analysis of white matter tracts, has contextualized imaging analysis within the framework of aging and building cognitive reserve [e.g. 7, 8, 9, 1].

Neuroimaging research focusing on professional musicians can be categorized into the following main topics: (1) the relationship of musicianship and neuroplasticity [5, 3], (2) neuroanatomical correlates of musicianship [2,10], (3) enhanced encoding of vowels and speech in professional musicians [11], (4) timbre-specific auditory cortical representations in musicians [12], (5) shared networks for auditory and motor processing in professional musicians [4], and (6) brainstem recordings of speech sounds in musicians [10]. The above studies have been investigated using various functional and structural magnetic resonance imaging techniques (MRI). Resting-state functional MRI (rfMRI) focusing on musicians began to emerge more recently and have been limited to studies of improvisation [13, 14, 15, 16, 17 for some examples), different types of musical training [18] and more general musical creativity [19]. These studies apply regions of interest (ROI) seed-based analysis approaches.

Cognitive brain reserve

There are a range of terms used in the published literature to characterize different types of brain reserve. Neurological (brain) reserve, one of the earliest terms proposed [20] is generally considered to be more biologically

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and genetically based, and includes different definitions, including:

(1) “The neurological brain reserve hypothesis proposes that individuals generally differ in the numbers of neurons and synapses available to be lost before clinical symptoms emerge” [21].

(2) “Brain reserve refers to ‘passive’ factors (e.g., brain volume, synapse count) that confer a particular capacity to endure neuropathological processes until a critical threshold is reached, after which cognitive and functional impairments are expressed” [22].

In contrast, cognitive reserve, also called behavioral brain reserve, is acquired through specific sensory–motor activities that span across the life cycle (including but not restricted to musicianship and bilingualism). This type of cognitive brain reserve is considered “resilience to neural insult” and strategies that strengthen alternative FNs across the life cycle can improve tolerance of atrophy [23]. Moreover, higher cognitive reserve should require more structural decline in order for symptoms to manifest [24]. For more discussion on cognitive reserve, see [25, 26, 27, 28, 9,1].

In the current work, we will examine white matter (WM) integrity and in particular fractional anisotropy (FA) values in healthy subjects who are high proficiency musicians and in age and educational matched non-musician controls. This is a direct extension of our original analysis [1] where only high proficiency, lifelong musicians were analyzed. The mechanisms for the different types of brain and cognitive reserve are poorly understood, but may include enhanced generation of neuronal, dendritic and synaptic connections and functional reorganization of neural networks across multimodalities. For example, [29] argue in favor of a shift to subcortical/posterior region-based networks in bilinguals, as opposed to more frontal regions in monolinguals [30]. focuses on increased gray matter (GM) in bilingualism as an example of cognitive reserve and potential protective effects in aging.

Thus, while cognitive brain reserve may play an important role in delaying the appearance of symptoms of certain pathologies, it also may play a role in healthy subjects. And that is the focus of our current study – lifelong musicians and potential effects of musicianship on subcortical WM matter fiber tracts. While we do not consider GM in this paper, we do not exclude the importance of cognitive reserve in GM volume changes [31].

Research question and hypotheses

The published research on cognitive reserve, the potential interactions between bilingualism and musicianship, and studies specifically focusing on musicianship provide the foundation for our research question and hypotheses. It has been shown in multiple studies that WM integrity decreases in normal aging [32, 33, 34, 35, 36].

Research focusing on cognitive reserve has noted that the process of WM integrity loss can be slowed down or changed by lifelong bilingualism and musicianship. Our first paper published on DTI study of lifelong musicianship [1] hypothesized that there will be an increase in WM integrity in certain subcortical fiber tracts in lifelong musicians, and that this increase will be reflected bilaterally in FA values for the bilateral superior longitudinal fasciculus (SLF) and the uncinate fasciculus (UF) – 2 specific WM tracts shown to be relevant in musicianship. We also hypothesized that the bilateral SS, which includes the IFOF (a tract important in bilingualism), may not show the same effects. The current study considers specifically lifelong musicianship with age-matched non-musician controls and the age span included is from 20 to 67 years and hypothesizes that the age-matched non-musician controls will not show the increases in WM integrity across the age span found in lifelong musicians for bilateral SLF and bilateral UF.

Materials and Methods

Participants

Sixteens subjects (eight musicians and eight non-musician controls) gave written consent in accord with the guidelines of Duke Health Institutional Review Board and were scanned in 2019-2021 at Duke University Hospital at the Duke Brain Imaging and Analysis Center: Eight musicians (five females and three males between the ages of 20 and 67 years, with a mean age of 44.1 years) and eight non-musician healthy controls (five females and three males between the ages of 20 and 63 years, with a mean age of 43 years). Both groups (musicians and controls) have college degrees that span the baccalaureate (completed or in progress) through the MA/MS and PhD, and 1 Associate’s degree.

All eight musicians began musical training between the ages of three and twelve years, at an average of 6.4 years. The number of years the subjects had been musicians was a correlate of chronological age since all were currently active musicians, performing regularly with a mean of 38 years of active musicianship. Musicians reported an average of three hours per day rehearsing/practicing and an average of nine hours per day in peak times (i.e. during periods of performance). Additional credentials included college degrees in music (including undergraduate minor, master’s and doctorate) and multiple affiliations with orchestra, symphony or operatic theatre in the United States and abroad. Five of the professional musicians have extensive experience in the United States and abroad. All subjects played at least the piano or violin. The eight non-musicians control subjects do not play any instruments and do not sing in any groups. Four of the eight have never played a musical instrument, three played in high school between 14 to 18 years of age, and one played for six months at the age of 14. This yields a

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mean of 35 years since any of the controls were involved in musical activity.

Data

Behavioral data

All 16 participants (8 musicians and 8 non-musicians) completed an extensive background questionnaire on their education, musicianship and knowledge of languages.

Image acquisition

All subjects were scanned in the same scanner at Duke University Hospital, using a GE 3T Discovery 750 MRI (General Electric, Milwaukee, WI) with an 8-channel head coil. Diffusion weighed images (DWIs) were collected using an oblique single-shot spin-echo echo-planar imaging (EPI) sequence with a repetition time (TR) = 9,000 ms, echo time (TE) = 93 ms, having a 256 × 256 image matrix over a 25.0 cm2 FOV, covering 69 interleaved axial slices each 2 mm thick. 25 diffusion directions were uniformly distributed in 3D space with a b = 1000 s/mm2, together with an acquisition with b = 0 s/mm2. A T2 and proton density weighted sequence (FRFSE-XL) with a TR = 3,000 ms, TE = 90 ms, 256x256 matrix, 24.0 cm2 FOV and 5 mm slice thickness was used to acquire 28 interleaved axial slices.

DTI processing

All images were processed using Tortoise 3.1.4 [37, 38] and FMRIB Software Library [39, 40, 41]. The raw DTI were corrected for distortion, eddy currents and motion, using the DIFFPREP command in Tortoise and subject specific T2 weighted image. A brain mask was then generated from the distortion corrected B0 using ExtractImage and bet2. All Tortoise quality control outputs were inspected for signal dropouts, excessive motion, and B0 and T2 registration accuracy. Then, the Tortoise commands EstimateTensorNLLSRESTORE, with the RESTORE option and ComputeFAMap generated the fractional anisotropy maps. Next, FSL was used to normalize the individual FA maps to MNI space, using the FLIRT and FNIRT commands. Finally, the FA for each ROI in each subject were averaged, using the commands fslmaths and fslstats. Using the ICBM-81 atlas [42] FA values in the following regions of interests were computed: left and right superior longitudinal fasciculus (LSLF and RSLF), left and right sagittal striatum (LSS and RSS), and left and right uncinate fasciculus (LUF and RUF).

Statistical methods

In order to test our hypotheses concerning changes in WM integrity in aging musicians in the original 2021 study, we present linear regression calculations of the six regions of interest (LSLF, RSLF, LUF, RUF, LSS, RSS). Additionally, we present linear regression calculations of the same six regions of interest for both musicians and non-musician controls (Figure 2), and all slope regression analysis was conducted in SAS (SAS Institute Inc., Cary, NC, USA). We compare the slope difference between the two groups for each white matter tract of interest using a test for parallelism [43], followed by application of the Fisher's method for pooling p-values, a statistical method for combining results from multiple tests into one test statistic.

$$-2\sum_{i=1}^{k}\ln(p_i)$$

Fisher (1025) showed that the test statistic has the chi-squared distribution with 2k degrees of freedom, where k is the number of p-values being pooled. The intuition is that if one has several independent experiments, each of which modestly supports the alternative hypothesis, then by combining the weak signals one can increase power for rejecting the null. Previous studies of lifelong musicianship showed that relevant subcortical white matter fiber tracts show an increase in FA values. According to our research hypothesis, WM integrity may increase over the life span in musicians in bilateral SLF and UF, but not in others.

Results

Table 1: Mean fractional anisotropy (FA) values for each subject (controls in blue, musicians in red) in specific ICBM-81 brain regions *****.

Control subjects

Subject	LSLF	RSLF	LUF	RUF	LSS	RSS
1	0.440	0.439	0.411	0.466	0.511	0.507
2	0.453	0.455	0.421	0.491	0.531	0.539
3	0.480	0.470	0.455	0.481	0.559	0.584
4	0.470	0.485	0.469	0.482	0.521	0.570
5	0.474	0.462	0.490	0.486	0.557	0.600
6	0.463	0.471	0.422	0.444	0.539	0.578
7	0.475	0.477	0.439	0.426	0.521	0.564
8	0.469	0.467	0.454	0.531	0.565	0.603

Musicians

Subject	LSLF	RSLF	LUF	RUF	LSS	RSS
1	0.471	0.471	0.472	0.472	0.531	0.528
2	0.512	0.503	0.505	0.530	0.560	0.580
3	0.472	0.488	0.456	0.493	0.540	0.544
4	0.462	0.457	0.426	0.470	0.580	0.562
5	0.465	0.482	0.411	0.465	0.571	0.581
6	0.481	0.490	0.441	0.480	0.593	0.615
7	0.475	0.488	0.467	0.468	0.569	0.586
8	0.483	0.475	0.436	0.476	0.563	0.599

*LSLF – left superior longitudinal fasciculus, RSLF - right superior longitudinal fasciculus, LUF – left uncinate fasciculus, RUF – right uncinate fasciculus, LSS – left sagittal striatum and RSS – right sagittal striatum. Regions were defined according to the ICBM-81 DTI atlas.

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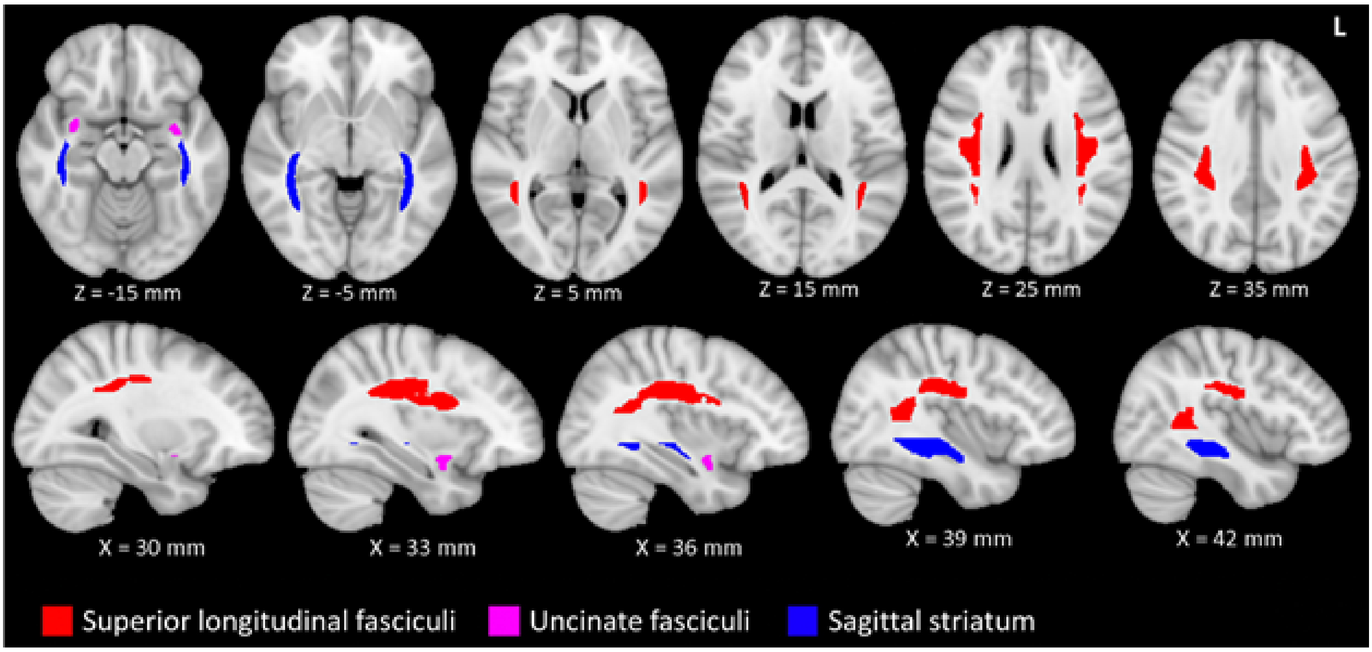

Figure 1: The superior longitudinal fasciculi (SLF) and uncinate fasciculi (UF) are related to musical proficiency and age. The sagittal striata (SS) are also related with age, but not musical proficiency. The SLF (red), UF (magenta) and SS (blue) are depicted in accordance with the ICBM-81 atlas [42]. The tracts are superimposed on a T1 weighted image in the Montreal Neurological Institute 152 space. The figure uses the left-posterior-inferior convention. Legend: L, left.

A simple linear regression shows the following FA values for bilateral SLF and UF in musicians. As shown below, there is greater WM integrity in aging musicians in the bilateral SLF and bilateral UF.

Figure 2 shows the linear regression of the following FA values for bilateral SLF, UF and SS in musicians and age and education matched non-musician controls. First, we used the test for parallelism [43] to calculate the significance of how much higher the musicians' slopes were than the controls' slopes for each of the four white matter tracts (LSLF, RSLF, LUF and RUF). Then we pooled the tracts, using Fisher's method, resulting in a chi-squared distribution with 8 degrees of freedom (-2Σ ki=1,4 ln(pi) = 21.255), the resulting pooled p-value is 0.0065.

Based on previous research on cognitive brain reserve using DTI, we hypothesized that we would find increased WM integrity in FA values of two important tracts, SLF and UF, in lifelong musicians, but not in non-musician controls. We also hypothesized that the bilateral SS, a tract important for bilingualism, would not be impacted by musicianship and show loss as seen in healthy aging. Following our hypothesis, the superior longitudinal fasciculus (SLF) and uncinate fasciculus (UF) tracts show a positive correlation between FA and age in subjects with high musical proficiency, while FA decreases with age in the sagittal strata (SS) in the same subjects and, thus, the SS may be unrelated to musical proficiency. Therefore, we focus on the 4 WM tracts from our original hypothesis (bilateral SLF and UF). Using Fisher's method, resulting in a chi-squared distribution with 8 degrees of freedom (-2Σ ki=1,4 ln(pi) = 21.255), the resulting pooled p-value is 0.0065. The results are in keeping with our hypothesis. In future analysis, we will explore the WM integrity and FA values of bilateral SS and IFOF in bilinguals and multilinguals, as well as possible cross-modality benefits between musicianship and multilingualism.

Discussion

The bilateral SLF and bilateral UF have been noted in the literature on cognitive reserve and bilingualism [44, 45, 46, 301]while only the FA values of the bilateral SLF has been noted in the literature on cognitive reserve in musicianship, specifically with regard to relative and absolute pitch [8]. Halwani et al. [7] focuses primarily on increased FA values in bilateral AF in musicians, including instrumentalists and singers. In terms of the function of these white matter tracts in processing language, the dorsal-ventral pathway is often mentioned, but without further differentiation or explanation [31]. In studies of cognitive reserve and healthy aging in musicians, there are no studies that focus specifically on the UF. The lesion-deficit DTI literature includes research involving musicians and music-based treatments identify the UF as important in pitch perception in healthy subjects, and also important in music therapy. There is a larger body of lesion-deficit studies that consider the bilateral UF and FA values, that address visual memory delay [47, 48, 49] naming impairment [50, 51, 52] and psychopathy [53]. One possible point of interest emerges from the work of [54] on

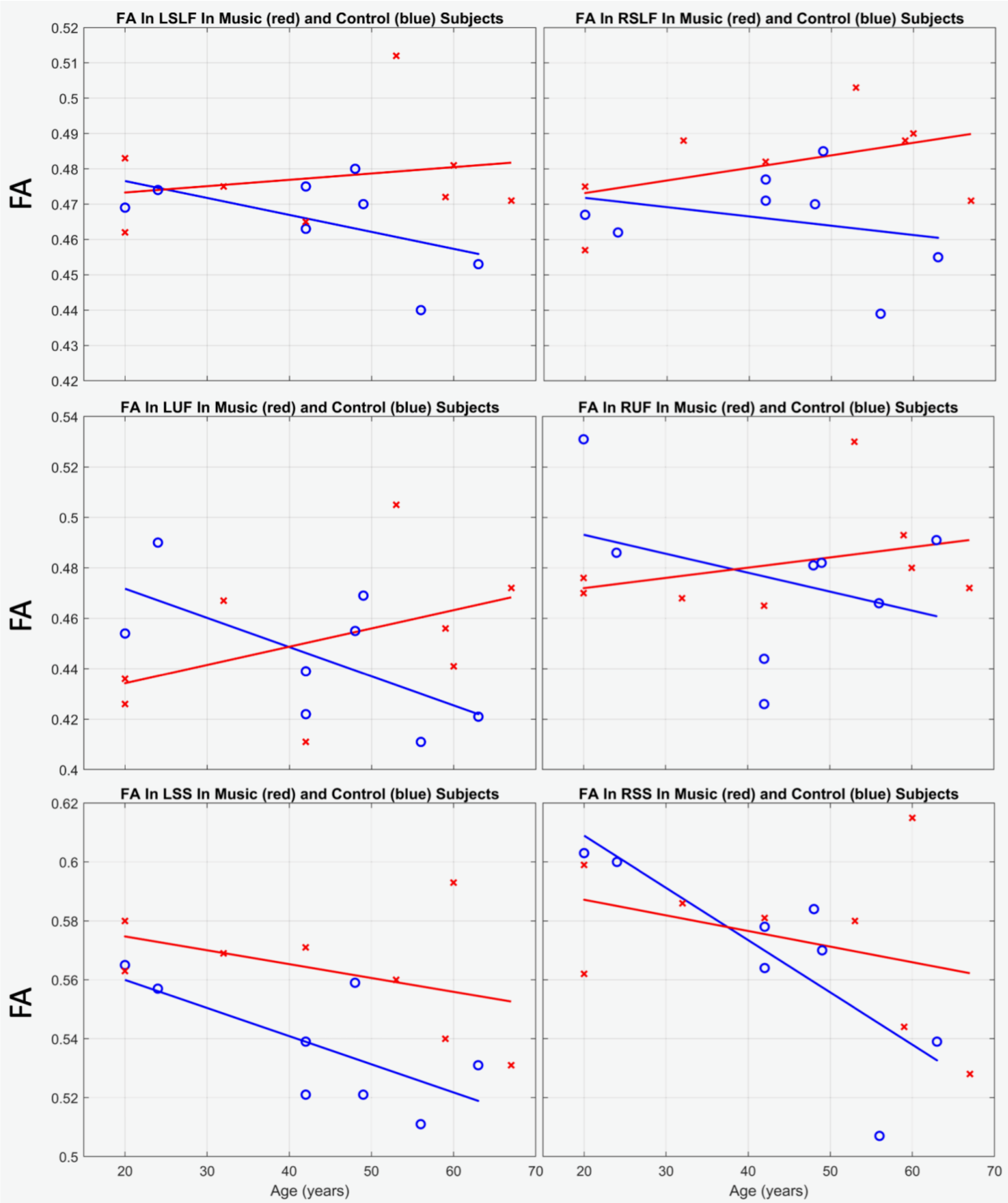

Figure 2: Scatter plots and linear fits between FA values and subjects' ages for musicians (in red) and controls (in blue). The difference between the musician and non-musicians' slopes by region have the following p-values: LSLF 0.094, RSLF 0.101, LUF 0.023, RUF 0.111, LSS 0.212, RSS 0.034. The superior longitudinal fasciculus (SLF) and uncinate fasciculus (UF) tracts (top two rows) show a positive correlation between FA and age in musicians, but a negative correlation between FA and age in non-musicians.

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the possible role of the IFOF and UF in language processing with patients undergoing surgery (left anterior temporal lobe or orbito-frontal region). They were not able to confirm or reject that the UF is essential in language processing. While our scans did not show any systematic scanner-related errors, there is some research suggesting that all diffusion imaging may require additional correction [55, 56]. Duke University BIAC is part of the Biomedical Informatics Research Network (BIRN) that examined potential system biases across the vendors, and have taken measures to address any concerns about systematic errors in DTI acquisition in DUHS scanners [57]. The present study focuses on how musicianship may affect changes to WM integrity across the life cycle, and change the trend of reduction in FA structures that are relevant in musicianship, specifically the SLF and UF. Previous research has shown that FA values in the SLF and UF show a significant decrease in FA values with age [32, 58, 59, 60, 33, 33, 34, 35, 36].

Westlye et al. [34] examined age changes in WM integrity in 430 healthy subjects between the ages of 8 and 85 years. The SLF and UF are included bilaterally in their analysis of 7 major WM tracts. Their findings show a significant ($p < 0.0001$) decrease in FA values across whole brain WM fiber tracts and the maximum FA values were found at 29.1 years of age (2010: 2058-60). The age of maxima for SLF and UF were 28.8 and 28.6 respectively (2010: 2061). Rathee et al. [36] also examined FA values for 177 healthy subjects and divided the subjects into three age groups: 20-40, 41-60, 61-85. Whole brain values show a consistent decrease in FA values across each of the three age groups, and voxel-wise FA values include a significant decrease in 22 regions (mid to oldest group), 26 regions (youngest to oldest group), and 4 regions (youngest to mid group). Furthermore, all FA values were lower in all regions between the oldest and youngest groups, and explicit reference to the SLF and SS showed significantly lower FA values in the oldest to youngest groups (2016: 14-15). As mentioned earlier, the research focusing on cognitive reserve has shown that the process of WM integrity loss in normal aging may be slowed or changed by lifelong bilingualism and musicianship. Our study is unique in its requirement for active musicianship across the life cycle. Our hypotheses looked specifically at the bilateral SLF and the bilateral UF in lifelong musicians and age-matched/education-matched non-musician controls. While previous studies on musicianship did not focus on the UF, given that it is one of the tracts with a later period of maturation and connects temporal and frontal lobe structures, it was included in our analysis. Our results support the research on cognitive reserve and show that the FA values for bilateral SLF and bilateral UF were greater in older musicians, but not in age-matched non-musician controls. As shown in the application of Fisher's method, the resulting chi-squared distribution yields a pooled p-value = 0.0065. These findings suggest that musicianship across the life cycle may change the expected decrease in FA values in these two subcortical tracts. A third tract, the bilateral SS, which includes the IFOF – a tract important in bi- and multilingualism, did not show the same effects. However, the decrease in FA values in bilateral SS was less in lifelong musicians than that found in the non-musician controls.

Limitations and Future Directions

Future directions include replication of results across a larger data set, investigation of the functional activations and connectivity through fMRI, and other direct comparisons of musicians and bi/multilinguals.

Conclusion

The present study has focused on lifelong professional musicians and age and education-matched non-musician controls. Our findings suggest that lifelong musicianship may contribute to WM integrity in the bilateral SLF and bilateral UF in aging. While earlier research identified higher FA values in the right SLF [64], our findings show increases in bilateral SLF. The identification of higher FA values in bilateral UF is also interesting and expands the examination of subcortical WM tracts that may be affected by lifelong musicianship. This study is an additional contribution to the growing body of research on behavioral cognitive reserve and suggests additional evidence that highly proficient musicianship may produce similar effects of higher FA values in certain WM tracts, while differing in others.

Author Contributions

Conceptualization: E.A., C.E., D.B., T.H., A.M., and C.R.; methodology: E.A., C.E., D.B., T.H., A.M., and C.R.; software: C.E., T.H., and A.M.; validation: E.A., C.E., D.B., and A.M.; formal analysis: E.A., C.E., and A.M.; investigation: E.A., C.E., D.B., T.H., A.M., and C.R.; resources: E.A., C.E., D.B., T.H., A.M., and C.R.; data curation: E.A., C.E., and C.R.; writing—original draft preparation: E.A., C.E., D.B., T.H., A.M., and C.R.; writing—review and editing: E.A., C.E., D.B., and A.M.; supervision: E.A., C.E., and A.M.; project administration: E.A. and C.E.; funding acquisition: E.A. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Duke University Health System Institutional Review Board (protocol code Pro00014272).

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. Andrews E, Eierud C, Banks D, et al. Effects of Lifelong Musicianship on White Matter Integrity and Cognitive Brain Reserve. Brain Sci 11/1 (2021): 67.
2. Pantev C, Roberts LE, Schulz M, et al. Timbre-specific enhancement of auditory cortical representations in musicians. Neuroreport 12 (2001): 169-174.
3. Munte TF, Altenmuller E, Jäncke L. The musician's brain as a model of neuroplasticity. Nature Reviews Neuroscience 3 (2007): 473-478.
4. Bangert M, Peschel T, Schlaug G, et al. Shared networks for auditory and motor processing in professional pianists: Evidence from fMRI conjunction. Neuroimage 30 (2006): 917-926.
5. Jäncke L. The plastic human brain. Restorative Neurology and Neuroscience 27 (2009): 521-538.
6. Elmer S, Jäncke L. Relationships between music training, speech processing, and word learning: a network perspective. Annals of the New York Academy of Sciences 1423 (2018): 10-18.
7. Halwani GF, Loui P, Ruber T, et al. Effects of practice and experience on the arcuate fasciculus: comparing singers, instrumentalists, and non-musicians. Frontiers in Psychology 2 (2011).
8. Oechslin MS, Imfeld A, Loenneker T, et al. The plasticity of the superior longitudinal fasciculus as a function of musical expertise: a diffusion tensor imaging study. Frontiers in Human Neuroscience 4 (2010).
9. Pliatsikas C. Bilingualism and brain structure: insights from healthy ageing and progressive neurodegenerative diseases. In Luk G, et al. (Eds.): Understanding Language and Cognition through Bilingualism: In honor of Ellen Bialystok¸ John Benjamins (2023): 301-317
10. Bermudez P, Lerch JP, Evans AC, et al. Neuroanatomical Correlates of Musicianship as Revealed by Cortical Thickness and Voxel-Based Morphometry. Cerebral Cortex 19 (2009): 1583-1596,
11. Weiss MW, Bidelman GM. Listening to the Brainstem: Musicianship Enhances Intelligibility of Subcortical Representations for Speech. Journal of Neuroscience 35 (2015): 1687-1691.
12. Kuhnis J, Elmer S, Meyer M, et al. The encoding of vowels and temporal speech cues in the auditory cortex of professional musicians: An EEG study. Neuropsychologia 51 (2013): 1608-1618,
13. Bengtsson S L, Csíkszentmihályi M, Ullén F. Cortical Regions Involved in the Generation of Musical Structures during Improvisation in Pianists. Journal of Cognitive Neuroscience 19 (2007): 830–842.
14. Lopata J A, Nowicki EA, Joanisse MF. Creativity as a distinct trainable mental state: An EEG study of musical improvisation. Neuropsychologia 99 (2017): 246–258.
15. Rosen D S, Erickson B, Kim Y E, et al. Anodal tDCS to Right Dorsolateral Prefrontal Cortex Facilitates Performance for Novice Jazz Improvisers but Hinders Experts. Frontiers in Human Neuroscience 10 (2016).
16. Berkowitz, A. L.; Ansari, D. Generation of novel motor sequences: The neural correlates of musical improvisation. NeuroImage 2008, 41, 535–543.
17. Ansari, D. Effects of development and enculturation on number representation in the brain. Nature Reviews Neuroscience 2008, 9, 278–291.
18. Belden A, Zeng T, Przysinda E, et al. Improvising at rest: Differentiating jazz and classical music training with resting state functional connectivity. NeuroImage 207 (2020): 116384.
19. Bashwiner DM, Bacon DK, Wertz CJ, et al. Resting state functional connectivity underlying musical creativity. NeuroImage 218 (2020): 116940.
20. Valenzuela MJ, Sachdev P. Brain reserve and dementia: a systematic review. Psychological Medicine 36 (2006): 441-454.
21. Stern Y. Cognitive reserve in ageing and Alzheimer's disease. Lancet Neurology 11(2012): 1006-1012.
22. Guzmán-Vélez E, Tranel D. Does bilingualism contribute to cognitive reserve? Cognitive and neural perspectives. Neuropsychology 29 (2015): 139-150.
23. Bialystok E, Craik FIM, Freedman M. Bilingualism as a protection against the onset of symptoms of dementia. Neuropsychologia 45 (2007): 459-464.
24. Gold BT, Johnson NF, Powell DK. Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. Neuropsychologia 51 (2013): 2841-2846.

Andrews E, et al., J Psychiatry Psychiatric Disord 2023
DOI:10.26502/jppd.2572-519X0187

25. Craik FIM, Bialystok E, Freedman M. Delaying the onset of Alzheimer disease Bilingualism as a form of cognitive reserve. Neurology 75 (2010): 1726-1729.

26. Andrews E, Frigau L, Voyvodic-Casabo C, et al. Multilingualism and fMRI: Longitudinal Study of Second Language Acquisition. Brain Sci 3 (2013): 849-876.

27. Andrews E. Neuroscience and multilingualism; Cambridge University Press: Cambridge (2014).

28. de Bot K. Multilingualism and aging. In T.K. Bhatia & W.C. Ritchie, eds., The new handbook of second language acquisition, Emerald Group Publishing: Bingley, UK, 425-442 (2009).

29. Grundy JG, Anderson JA, Bialystok E. Neural correlates of cognitive processing in monolinguals and bilinguals. Annals of the New York Academy of Sciences 1396 (2017): 183-201.

30. Abutalebi J, Guidi L, Borsa V, et al. Bilingualism provides a neural reserve for aging populations. Neuropsychologia 69 (2015): 201-210.

31. Pliatsikas C, Moschopoulou E, Saddy JD. The effects of bilingualism on the white matter structure of the brain. Proceedings of the National Academy of Sciences of the United States of America 112 (2015): 1334-1337.

32. Tang Y, Nyengaard JR, Pakkenberg B, et al. Age-induced white matter changes in the human brain: A stereological investigation. Neurobiology of Aging 18 (1997): 609-615.

33. Giorgio A, Santelli L, Tomassini V, et al. Age-related changes in grey and white matter structure throughout adulthood. Neuroimage 51 (2010): 943-951.

34. Westlye LT, Walhovd KB, Dale AM, et al. Life-Span Changes of the Human Brain White Matter: Diffusion Tensor Imaging (DTI) and Volumetry. Cerebral Cortex 20 (2010): 2055-2068.

35. Billiet T, Vandenbulcke M, Madler B, et al. Age-related microstructural differences quantified using myelin water imaging and advanced diffusion MRI. Neurobiology of Aging 36 (2015): 2107-2121.

36. Rathee R, Rallabandi VPS, Roy PK. Age-Related Differences in White Matter Integrity in Healthy Human Brain: Evidence from Structural MRI and Diffusion Tensor Imaging. Magnetic Resonance Insights 9 (2016): 9- 20.

37. Pierpaoli C, Walker L, Irfanoglu M O, et al. TORTOISE: an integrated software package for processing of diffusion MRI data, ISMRM 18th annual meeting (2010).

38. Irfanoglu M O, Nayak A, Jenkins J, et al. TORTOISE v3: Improvements and New Features of the NIH Diffusion MRI Processing Pipeline, ISMRM 25th annual meeting 2017, Honolulu (2018).

39. Woolrich MW, Jbabdin S, Patenaude B, et al. Bayesian analysis of neuroimaging data in FSL. Neuroimage 45 (2009): 173-186.

40. Smith SM, Jenkinson M, Woolrich MW, Beckmann, et al. Advances in functional and structural MR image analysis and implementation as FSL. Neuroimage 23 (2004): 208-219.

41. Jenkinson M, Beckmann CF, Behrens TE, et al. Fsl. Neuroimage 62 (2012): 782-790.

42. Mori S, Oishi K, Jiang H, et al. Stereotaxic white matter atlas based on diffusion tensor imaging in an ICBM template. Neuroimage 40 (2008): 570-582.

43. Kleinbaum DG, Kupper LL, Muller KE, et al. Applied Regression Analysis and Other Multivariable Methods, Duxbury Press, Pacific Grove, CA (1998).

44. Friederici AD. Pathways to language: fiber tracts in the human brain. Trends Cogn Sci 13 (2009): 175-181.

45. Luk G, Bialystok E, Craik FLM, et al. Lifelong Bilingualism Maintains White Matter Integrity in Older Adults. Journal of Neuroscience 31 (2011): 16808-16813.

46. Madhavan KM, McQueeny T, Howe SR, et al. Superior longitudinal fasciculus and language functioning in healthy aging. Brain Research 1562 (2014): 11-22.

47. Riley JD, Franklin DL, Choi V, et al. Altered white matter integrity in temporal lobe epilepsy: association with cognitive and clinical profiles. Epilepsia 51 (2010): 536-545.

48. Diehl B, Busch RM, Duncan JS, et al. Abnormalities in diffusion tensor imaging of the uncinate fasciculus relate to reduced memory in temporal lobe epilepsy. Epilepsia 49 (2008): 1409-1418.

49. McDonald CR, Ahmadi ME, Hagler DJ, et al. Diffusion tensor imaging correlates of memory and language impairments in temporal lobe epilepsy. Neurology 71(2008): 1869-1876.

50. Lu LH, Crosson B, Nadeau SE, et al. Category-specific naming deficits for objects and actions: semantic attribute and grammatical role hypotheses. Neuropsychologia 40 (2002): 1608-1621.

51. Hamberger MJ, Drake EB. Cognitive functioning following epilepsy surgery. Curr Neurol Neurosci Rep 6 (2006): 319-326.

52. Grabowski TJ, Damasio H, Tranel D, et al. A role for left temporal pole in the retrieval of words for unique entities. Hum Brain Mapp 13 (2001):199-212.

Andrews E, et al., J Psychiatry Psychiatric Disord 2023
DOI:10.26502/jppd.2572-519X0187

53. Craig MC, Catani M, Deeley Q, et al. Altered connections on the road to psychopathy. Mol Psychiatry 14 (2009): 946-953.

54. Duffau H, Gatignol P, Moritz-Gasser S, et al. Is the left uncinate fasciculus essential for language? A cerebral stimulation study. J Neurol 256 (2009): 382-389.

55. Krzyżak AT, Olejniczak Z. Improving the accuracy of PGSE DTI experiments using the spatial distribution of b matrix. Magn Reson Imaging 33 (2015): 286-95.

56. Borkowski K, Krzyżak AT. Analysis and correction of errors in DTI-based tractography due to diffusion gradient inhomogeneity. J. Magn. Reson 296 (2018): 5–11.

57. Helmer KG, Chou MC, Preciado RI, et al. Proceedings Volume 9788, Medical Imaging 2016: Biomedical Applications in Molecular, Structural, and Functional Imaging 97881 (2016).

58. Kochunov P, Thompson PM, Lancaster JL, et al. Relationship between white matter fractional anisotropy and other indices of cerebral health in normal aging: tract-based spatial statistics study of aging. NeuroImage 35 (2007): 478-487.

59. Kochunov P, Glahn DC, Lancaster J, et al. Fractional anisotropy of cerebral white matter and thickness of cortical gray matter across the lifespan. Neuroimage 58 (2011): 41-49.

60. Bennett IJ, Motes MA, Rao NK, et al. White matter tract integrity predicts visual search performance in young and older adults. Neurobiol Aging 33 (2012): 421-431.

61. Ansari D. Effects of development and enculturation on number representation in the brain. Nature Reviews Neuroscience 9 (2008): 278–291.

62. Fisher RA. Statistical Methods for Research Workers; Oliver and Boyd: Edinburgh, UK (1925).

63. Wan CY, Schlaug G. Neural pathways for language in autism: the potential for music-based treatments. Future Neurol 5 (2010): 797-805.

64. Yuskaitis CJ, Parviz M, Loui P, et al. Neural Mechanisms Underlying Musical Pitch Perception and Clinical Applications Including Developmental Dyslexia. Curr Neurol Neurosci Rep 15 (2015): 51.

65. Li JF, Luo C, Peng YH, et al. Probabilistic Diffusion Tractography Reveals Improvement of Structural Network in Musicians. Plos One 9 (2014).