Music literacy shapes the specialization of a right hemispheric word reading area

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ARTICLE INFO

ABSTRACT

This study aimed to examine differences in the brain activity of professional musicians and non-musicians, particularly in relation to neuroplastic changes that may be associated with musical training. Specifically, we investigated whether the ability to read complex musical notation might be linked to neurofunctional adaptations that could influence word reading mechanisms. The study involved 80 participants (half of which were musicians). High-density EEG recordings and swLORETA inverse solutions were employed to analyze brain activity related to word processing and orthographic analysis. The electromagnetic signals were analyzed in the temporal window corresponding to the latency of N170 component (150–190 ms). Musicians and musically naïve people (controls) were matched based on native language, sociocultural and educational status, age, and laterality preference. Behavioural data and reading proficiency tests demonstrated higher reading skills (for words, non-words and text), and faster RTs to target letters embedded in words, in musicians. Source reconstruction showed fundamental differences in word reading mechanisms between musicians and non-musicians, including a larger involvement of the right occipitotemporal cortex, in the former than the latter. In particular, musicians showed a bilateral activation of the middle occipital gyrus (BA19, *Visual Word Form Area*), which was strongly lateralized to the left hemisphere in controls, during word orthographic analysis. A relationship is proposed between music literacy, enhanced reading skills and the development of a right-sided reading area for notation recognition in musicians, which could serve as a potential protective factor for 'surface' dyslexia.

1. Introduction

The understanding of individual differences in reading abilities and the acquisition of literacy skills are crucial aspects of comprehending human cognition (Fischer-Baum et al., 2018). While the creation of written language is a recent development in human history, literacy skills are acquired through long years of training, which results in the development of a specialized reading area (Dehaene-Lambertz et al., 2018). The pursuit of unraveling the neural mechanisms involved in word reading has been ongoing, dating back to the standard model articulated by Dejerine (1892). Central to this model is the left-lateralized word identification process and the role of the callosal splenium in processing stimuli in the left visual field (Cohen et al., 2000). The so-called *Visual Word Form Area* (VWFA, McCandliss et al., 2003) has been localized in the left midfusiform cortex and its role in word recognition has been supported by a large literature (Dehaene and Cohen, 2011; Dehaene et al., 2015; Polk et al., 2002; Petersen et al., 1990). Additionally, Debska et al. (2023) highlighted the diverse cognitive functions of the language-specific VOT area, extending beyond visual word processing. Interestingly, Vin et al. (2024) revealed significant regions engaged in word processing in both the left and right hemispheres, emphasizing interhemispheric connectivity and the potential functional role of the right hemisphere in visual word processing.

On the other hand, the N170 response of event-related potentials (ERPs) is believed to reflect the electromagnetic manifestation of VWFA activity during the orthographic processing of letters and words. It notoriously shows larger amplitudes to orthographic characters than objects, icons or faces (Bentin et al., 1999; Proverbio et al., 2008, 2013; Rossion et al., 2003; Maurer et al., 2005). N170 would also show a sensitivity to word features such as visual familiarity (Yum and Law, 2021), frequency of use (Andria et al., 2022), orthographic regularity, orientation (Rossion et al., 2003; Proverbio et al., 2007), and lexicality

(Proverbio et al., 2008). Moreover, clinical studies have demonstrated that the N170 amplitude is reduced in individuals diagnosed with visual or "surface" dyslexia, indicating a lack of or atypical activation in response to letters/words compared to nonlinguistic stimuli (Salmelin et al., 1996, González et al., 2016; Araújo et al., 2012; Kronbichler and Kronbichler, 2018).

As for reading mechanisms in musicians, Proverbio et al. (2013), and more recently Pantaleo et al. (2024), observed that N170 response recorded to visually presented words during an orthographic detection task exhibited larger amplitude and bilateral distribution in the brains of professional musicians compared to musically naïve individuals. Additionally, the former demonstrated faster and more proficient reading abilities than the latter. Furthermore, the researchers observed a correlation between reading proficiency in good vs. poor readers and the degree of right-hemispheric lateralization of their VWFA. The authors postulated that musicians might develop an extra right-sided orthographic area for mastering complex musical notation; this right lateralized mid-fusiform area might become automatically active during word reading, leading to a more proficient reading ability. In those studies, also the neural mechanism of note reading was investigated; however, in order to avoid setting-induced response persistence, the music reading task (note selection) and the word reading task (letter selection) were performed in different experimental sessions. According to the available literature, professional musicians would indeed develop a specialized right midfusiform area for reading pentagram signs and notation; the areas variously reported by available studies range from: the right transverse occipital sulcus, right occipital gyrus, right inferior occipital gyrus, right occipitotemporal junction, right fusiform gyrus, right superior parietal cortex, and supramarginal cortices (Mongelli et al., 2017; Nakada et al., 1998; Sergent et al., 1992; Schön et al., 2002; Proverbio et al., 2024).

It is common knowledge that musical training induces neuroanatomical and functional adaptations in brain regions associated with auditory perception and motor functions. These alterations correlate with improvements in cognitive domains and sensorimotor integration, including audio/visuomotor representation of musical gestures (Proverbio and Bellini, 2018; Proverbio et al., 2017).

Studies confirm enhanced gray and white matter volumes in musicians than controls (Gaser & Schlaug, 2003; Zatorre et al., 2007; Elmer et al., 2013; Sato et al., 2015; Karpati et al., 2017; Olszewska et al., 2021; Steele et al., 2013; Abdul-Kareem et al., 2011), along with altered neurofunctional activation patterns in various brain regions (Brown and Penhune, 2018). Diffusion Tensor Imaging reveals more developed white-matter pathways in musicians, facilitating motor and sensory integration (Giacosa et al., 2016). Additionally, musicians demonstrate enhanced functional connectivity during word learning tasks, suggesting a reshaping of the brain's functional organization (Dittinger et al., 2018).

While there is a vast amount of data on these issues, currently, the neuroplastic changes of visual cortex in musicians are poorly comprehended, with a few exceptions. An interesting fMRI investigation examined how musical expertise influences visual cortex activations during the processing of musical notation, written words, and other objects (Mongelli et al., 2017). The data showed that, regardless of expertise, activations for music were located posteriorly and laterally to those for words in the left occipitotemporal cortex. Furthermore, musical expertise was associated with increased activation volume for music and a shift of word-related activations toward the anterolateral direction. Musicians exhibited a notable expansion of brain-scale networks connected to music-selective visual areas. These findings suggest that acquiring expertise in two symbolic systems involves the expansion of category-selective areas, the development of new long-distance functional connectivity, and potential competition for cortical space.

In a series of electrophysiological studies (Proverbio et al., 2013, 2024; Pantaleo et al., 2024) it was demonstrated that professional musicians exhibited bilateral N170 responses, and bilateral brain activation

in the fusiform and inferior occipital gyri, during both word and music processing. This suggests that musical expertise, following prolonged and intensive music-reading training, may alter the way the brain processes letters and words. Again, Wong and Gauthier (2010), in an fMRI study, found higher neural responses in the bilateral fusiform gyrus and the bilateral early visual areas (V1/V2) in musicians, compared to non-musicians, as observed in a gap detection task with musical notes presented. Li and Hsiao (2015) showed that while non-musicians exhibited a typical RVF/LH advantage in naming English words, musicians showed an LVF/RH advantage and responded significantly faster than non-musicians when words were presented in either the LVF or in the center position (Li and Hsiao, 2015). This effect suggested a facilitation of RH English word processing due to music reading experiences. Consistently, exploring how music reading proficiency affected the visual processing of English words in Chinese readers, Li et al. (2017) found that musicians exhibited reduced N170 amplitudes in the right hemisphere when processing English non-words vs. words, indicating a shared visual processing resource for musical notation and non-words. Finally, Bouhali et al. (2017) investigated how musical literacy affected the processing of written words finding that musical literacy was associated with a shift in hemispheric asymmetry for word processing. In particular, they discovered that in individuals with high musical literacy, the left hemisphere's dominance in language processing (i.e., word processing) was reduced, whereas in those with low musical literacy, the left hemisphere still dominated. Conversely, individuals with high musical literacy showed increased involvement of the right hemisphere in language processing, whereas those with low musical literacy did not.

In conclusion, these findings suggest that musical literacy may reorganize brain function to promote more bilateral processing of language, particularly in the ventral visual cortex. This could be due to the shared neural mechanisms between music and language processing, which may be enhanced by musical training. It is worth noting that in the Bouhali et al.'s (2017) study, the musicians varied in their level of music practice, but they all started learning to read words and music at the same age (~5/6 years). Therefore, they were proficient in reading music and started to specialize their visual cortex for music and word literacy at the same time. Conversely, in the present study, all participants started learning to read words at ~5/6 years of age, but musicians started learning *solfeggio* about 4/5 years later (the average age of acquisition - AOA - was 9.7 years). Music learning began after the VFWA was presumably well formed in the left hemisphere. By comparing the degree of laterality with the AoA we were able to observe the effect of neuroplasticity at different ages, disentangling the effect of musical literacy from that of AoA in promoting a bilateral reading mechanism.

Overall, despite extensive research on musicians' visuomotor skills, there remains a gap in understanding their reading abilities and the consequent development of brain areas associated with notation reading skills. Addressing this void, the present experimental research aimed to explore potential developmental changes in the brains of musicians resulting from their music training. Particularly we aimed to assess whether musical literacy (the mastered ability to read notation), among professional musicians, is associated with neuroplastic changes that directly affect the mechanisms of reading written language, even if acquired later in childhood, as compared to word literacy. We conjectured that musicians and non-musicians would demonstrate fundamentally different processing mechanisms in word reading, stemming from additional neural processes associated with the skill of notation reading in musicians.

The primary objective of this EEG study was to investigate the neurofunctional correlates of word reading mechanisms in a heterogeneous sample of readers, distinguished by their proficiency in professional music performance. Notably, this study diverges from the prevailing paradigm in the existing literature by integrating individual-level neuroimaging data analysis with examinations of individual brain laterality patterns, individual lateral preference, and individual word reading

proficiency. To this aim, we employed source reconstruction techniques on previously collected scalp-recorded ERP data (Proverbio et al., 2013; Pantaleo et al., 2024). Furthermore, this research closely scrutinizes the neural circuits activated during orthographic processing across different individuals, within a specific time frame, and as a function of musicianship expertise.

In order to ensure that participants were indeed processing orthographic features and not merely engaging in visual processing, graphene-to-phoneme processing, or semantic processing, our analysis focused on a specific time window between 150 and 190 ms post-stimulus. This precise temporal range has been consistently linked to orthographic processing in prior MEG studies, providing a reliable indicator of the neural activity related to this specific linguistic stage (Salmelin et al., 1996; Tarkiainen et al., 1999; Gwilliams et al., 2016), as opposed to generic visual processing.

2. Materials and methods

2.1. Participants

EEG signals were recorded in eighty healthy young adults, as described in Proverbio et al. (2013, 2024) and Pantaleo et al. (2024) where their ERP waveforms and attentional effects were analyzed. Due to excessive artifacts and noise, data from four participants were discarded. The final sample consisted of 76 graduate students of Milan universities. They were 31 males and 45 females with a mean age of 24.1 years (SD = 7.3). Half of them (38 individuals) were professional musicians, while the other half (38 individuals) were musically naïve (see Table 1 for all biographical data), having had only some basic choir, theater and music schooling during childhood, not including *solfeggio* or score reading).The participants in the study were matched for socio-cultural status, as they all possessed a diploma or bachelor's degree and were all native Italian speakers. They also shared a similar economic status, being able to live and graduate in the same metropolitan area, and did not differ for age (t = 0.42, p = 0.68). The mean age of acquisition of musical ability (AoA) for the musicians was 9.71 years (SD = 4.24) while the mean duration of music study was 15.7 years (SD = 9.1).

Musicians were majored in the following instruments: violin, trumpet, piano, clarinet, composition, orchestra conducting, cello, flute, organ, guitar, opera singing, saxophone, oboe, electric bass, bassoon, double bass, euphonium. Non-musicians were majors in psychology or other humanities and STEM fields. All participants were right-handed as preliminarily assessed by administration of the Edinburgh Inventory of Lateral Preference (Oldfield, 1971), whose scale ranges from −1 (indicating left-handedness) to +1 (indicating right-handedness). The mean laterality score for musicians was 0.72 (SD = 0.184) and for controls was 0.82 (SD = 0.159), indicating that all participants were strongly right-handed (mean score = 0.77), with no statistical difference between groups (t = 1.36, p = 0.348). Inclusion criteria ensured that participants had never suffered from psychiatric or neurological disorders, were not currently taking drugs or narcoleptics, or were predisposed to epilepsy.

All participants had normal or corrected-to-normal vision and hearing. No participant had a history of or was diagnosed with a learning, cognitive, or reading disorder (e.g., developmental dyslexia, alexia, autism spectrum disorder, attention deficit hyperactivity disorder, etc.).

A large majority of participants (N = 60, i.e. those recently tested between 2022 and 2023) were administered reading tests taken from the Battery for the Assessment of Developmental Dyslexia and Dysorthographia (Sartori et al., 1995) and the VALS-Assessment of Reading and Writing Difficulties in Adulthood (George and Pech-Georgel, 2017); see Proverbio et al. (2024) for details. The musician group exhibited superior reading abilities compared to non-musicians, as indicated by significantly faster reading speeds for words, non-words, and text (see performance data in Table 2). They also outperformed non-musicians in the orthographic detection task (N = 80), with equal accuracy but faster reaction times. In contrast, non-musicians displayed typical reading skills, with reading abilities slightly better (5.53) than those of normative data (5.14 syllables per second for single words, corresponding to the average reading speed for Italian first-year university students, as reported by Re et al., 2011).

All participants provided written informed consent and were unaware of the research purpose. The study lasted approximately 3 h, with breaks, training, and questionnaire administration factored in. Participants voluntarily offered their participation or received academic credits for it. The Ethics Committee of the local University (protocol number RM-2021-370) approved the project.

Table 2

Behavioral performance on reading and orthographic tasks in the two groups of participants. Letter recognition task data were pooled across studies (Pantaleo et al., 2024; Proverbio et al., 2013). Syl/sec = syllables per second.

Task	Musicians	Controls	Musicians (Min-Max)	Controls (Min-Max)
Accuracy in letter detection task % (N = 80) during word reading. Group difference: N.S.	**98.82%** SD= 1.009	**98.74%** SD= 1.01	Min = 98.35 Max = 99.3	Min = 98. 25 Max = 99.20
RTs in letter detection task (ms) (N = 80) during word reading. Group: [F 1, 79 = 4.61, p < 0.0348]	**543.82** SD= 71.79	**566.47** SD=66.46	Min = 527.81 Max = 559.84	Min = 551.68 Max = 581.26
Reading speed (syl/sec) for words (N = 60) Group: t(59) = 2.051, p = 0 0.02	**5.94** SD= 1.034	**5.53** SD= 0.95	Min = 5.58 Max = 6.3	Min = 5.14 Max = 5.92
Reading speed (syl/sec) for non-words (N = 60). *Group: t* (59) = 2.054, p = 0.02	**3.80** SD= 0.873	**3.573** SD. 0.03	Min = 3.49 Max = 4.12	Min = 3.23 Max = 3.91
Reading speed (syl/sec) for text (N = 60) Group: t (59) = 2.053, p = 0 0.02	**6.9** SD=1.0	**6.625** SD= 0.86	Min = 6.54 Max = 7.25	Min = 6.24 Max = 7.01

Table 1

This table provides the mean, standard deviation, minimum, and maximum values for age, laterality (Later.), and age of acquisition (AoA) across musician and control groups, separated by gender and combined.

Participants		Females			Males			Sample		
		Age	*Later.*	*AoA*	*Age*	*Later.*	*AoA*	*Age*	*Later.*	*AoA*
MUSICIANS	Mean	**24,3**	**0,67**	**9,9**	**25,6**	**0,76**	**9,5**	**25,1**	**0,72**	**9,7**
22 M, 16 F	SD	*6,5*	*0,19*	*4,5*	*9,7*	*0,17*	*3,42*	*8,4*	*0,18*	*3,89*
	Min	20	0,43	4	19	0,38	4	19	0,38	4
	Max	47	1	21	57	1	16	57	1	21
CONTROLS	Mean	**21,9**	**0,82**	–	**26,7**	**0,82**	–	**23,1**	**0,82**	–
10 M, 28 F	SD	*1,7*	*0,14*	-	*11,2*	*0,21*	-	*6,1*	*0,16*	–
	Min	19	0,43	–	21	0,29	–	19	0,29	–
N = 76	Max	27	1	–	58	1	–	58	1	–

2.2. Stimuli and procedure

The study employed a visual presentation paradigm in which 300 Italian words of varying length and complexity were randomly displayed on a computer screen, (the same paradigm used by Proverbio et al. (2013). The words, written in uppercase letters, ranged from 4 to 10 letters in length. Participants were instructed to silently read each word and respond by means of a button press to the presence of a given target letter (among B, G, L, M, and S) while refraining from responding in the absence of it, as quickly and accurately as possible. Half words contained target letters while the others did not. Words lasted 1.600 ms and inter-stimulus interval (ISI) randomly varied from 1.000 to 1.200 ms. The stimuli were matched for duration, length and frequency of use across target/non-target categories. Participants were required to establish the presence/absence of target characters (attentional task) to ensure that they performed accurate orthographic analysis of words, which would not have been possible with a passive reading task. They received both verbal and visual cues before each trial and responded by pressing a joystick button with their index finger. 300 different words were presented randomly in 6 runs of 50, with an equal distribution of targets and non-targets. Two training sequences preceded the two experimental sessions, and a fixation point was employed to minimize movement. The response hand was alternated across runs. Stimuli presentation order were counterbalanced across participants.

2.3. EEG recordings

EEG signals were recorded and analyzed using *EEProbe* system for acquisition and analysis of EEG/ERP data (ANT, Enschede). Electric potentials were collected from 126 scalp sites mounted on electro-caps (ECI) according to the 10-5 International System (Oostenveld and Praamstra, 2001) at a sampling rate of 512 Hz. Vertical and horizontal eye movements (VEOG and HEOG) were also recorded, with average ears serving as the reference lead. The EEG and electro-oculogram (EOG) were band-bass filtered (0.16–70 Hz); electrode impedance was kept below 5–7 KOhm. Artifacts such as eye movements, blinks, and muscle potentials were rejected prior to averaging with a ± 50 μv threshold, for a rejection rate of ~7.5%. Event-related potentials (ERPs) were averaged from 100 ms before stimulus onset to 1500 ms post-stimulus. The average number of trials per EEG recording was 300. The N170 orthographic response to words (regardless of targetness) was identified and measured within the time window and scalp location where it reached its maximum amplitude, following established guidelines from the literature (e.g., Bentin et al., 1999; Proverbio et al., 2013; Rossion et al., 2003; Maurer et al., 2005). The mean amplitude of the N170 was quantified at occipito-temporal sites (PPO9h-PPO10h) between 150 and 190 ms in response to words, for both musicians and controls, across various attentional conditions, as described in Proverbio et al. (2024). Concomitantly, behavioral data were recorded in the form of response times (in milliseconds) and accuracy (percentage of correct responses).

2.4. Neuroimaging and source reconstruction

To localize the intracranial sources underlying surface electrical potentials, we applied Standardized Low-Resolution Electromagnetic Tomography (sLORETA; Pascual-Marqui, 2002) to Event-Related Potentials (ERPs) elicited by visually presented words. Specifically, LORETA was applied to mean voltages recorded within the 150–190 ms time window, corresponding to the N170 response. LORETA serves as a discrete linear solution to the inverse Electroencephalogram (EEG) problem, representing the 3D distribution of neural electric activity that maximizes synchronization in terms of orientation and strength between adjacent neuronal populations (represented by adjacent voxels). In this study, an enhanced version of sLORETA was used (swLORETA, Palmero-Soler et al., 2007), incorporating a singular value

decomposition-based lead field weighting method. For methodological details about the source reconstruction algorithm, please see the Supplementary file.

Both the head model's segmentation and generation were executed using Advanced Neuro Technology, a software program developed by ASA (Zanow and Knösche, 2004). The swLORETA analysis yielded results indicating the statistical activation of a subset comprising 1056 dipoles. These results provide information on both their Magnitude values (in nA) and spatial coordinates following the Talairach and Tournoux (1988) system. A dipole, in this context, represents the potential difference between the basal and apical portions of a cell, resulting in a positive and negative difference with an orthogonal orientation to the magnetic field. Utilizing the Collins dipole table (Collins et al., 1994), each electromagnetic dipole was associated with its respective Gyrus and Brodmann Area. The complete set of data (lists of the whole brain's swLORETA sources) can be found at this open repository https://data.mendeley.com/datasets/zmh93bf8g6/1) and accessed by scientists upon registration.

As each dipole corresponds to a specific brain area (Gyrus and BA), anatomically neighboring dipoles were grouped to identify a common Regions of Interest (ROI) presumably corresponding to the VWFA. The active swLORETA electro-magnetic dipoles explaining N170 component (150–190 ms) were identified for each of the seventy-six participants, separately for the musician and control groups. The ROI was delineated to encompass the most active sources within the occipito-temporal regions of the left and right hemispheres, targeting the VWFA (Brodmann areas 19 and 37, including the middle occipital and fusiform gyri), and, in cases of inactivity in these regions, the ROI was adjusted to include the largest sources in the lateral occipital (Brodmann area 18) or posterior temporal regions (Brodmann areas 21, 22, or 38). This procedure is similar the ROI definition applied by previous studies (Tzourio-Mazoyer et al., 2002; Bouhali et al., 2020) which defined a left occipito-temporal ROI, by taking an anatomical mask including the inferior occipital, inferior temporal, and fusiform gyri. In the rare case of no entry (especially for the right hemisphere), the source magnitude was set to 0 (refer to Table 3 for a comprehensive list of dipoles located within this region of interest (ROI), and consult Table 4 for an overview of the most active areas observed in the N170 latency range across the entire participant sample).

To identify the anatomical localization of putative VWFA the mean Talairach coordinates of the active regions were also computed for two groups of participants, in the left and right hemisphere, and are depicted in Fig. 1. This was achieved by averaging the individual x, y and z Talairach coordinates of the selected ROI. In all cases, the region corresponded to the medial occipital gyrus (MOG) BA19. Therefor the term 'MOG' would be used to refer to the putative word reading area in this task.

To comply for inter-individual variations, the time window of N170 (peak $\pm$ 20 ms) was set to 135–175 ms for control SS17, 170–210 ms for control SS16 and 200–240 ms for control SS08.

The same procedure was used for computing the average magnitude of activation (in nA) of the selected regions of interest (whose average Talairach coordinates corresponded to the 'MOG') for the two groups of participants and cerebral hemispheres, which is displayed in graphs of Fig. 2.

2.5. Statistical analyses

A two-way ANOVA was applied to magnitude values (in nA) relative to left and right 'MOG' sources in the two groups of participants. Factors of variability were: Hemisphere (within-subjects, 2 levels; left and right) and Musicianship (between-subjects, 2 levels: musicians and controls). Tukey post-hoc comparisons were carried out to test differences among means. The effect size for the statistically significant factors was estimated using partial eta squared (η_p^2) and the Greenhouse–Geisser correction was applied to account for non-sphericity of the data. All the

Table 3
Individual electromagnetic dipoles of strongest occipito/temporal sources found active in the 150–190 ms time window (N170 component) and included in the ROI of interest. Legend: Magn = Magnitude, Hem = hemisphere, Uncus = UNC, Precuneus = PREC, Angular gyrus = AG, Lingual gyrus = LG, Fusiform gyrus = FG, Superior occipital gyrus = SOG, Inferior occipital gyrus = IOG, Middle occipital gyrus = MOG, middle temporal gyrus = MTG, superior temporal gyrus = STG, inferior temporal gyrus = ITG.

CONTROLS (left hemisphere)

Ss	Magn	T-x [mm]	T-y [mm]	T-z [mm]	Hem	Lobe	Gyrus	BA
2	3,41	−18,5	−90,3	20,8	L	O	CUN	18
9	5,14	−18,5	−81,1	30,6	L	O	CUN	19
15	6,58	−8,5	−98,5	2,1	L	O	CUN	17/18
26	3,61	−8,5	−98,5	2,1	L	O	CUN	17/18
4	1,25	−48,5	−76,2	−11,7	L	T	FG	19
22	5,89	−48,5	−76,2	−11,7	L	T	FG	19
28	3,67	−48,5	−65,1	−18,4	L	T	FG	37
29	3,67	−48,5	−65,1	−18,4	L	T	FG	37
31	7,05	−48,5	−65,1	−18,4	L	T	FG	37
32	2,89	−38,5	−55	−17,6	L	T	FG	37
38	7,56	−48,5	−55	−17,6	L	T	FG	37
30	2,49	−38,5	−86,4	−12,4	L	O	IOG	18
36	1,8	−28,5	−86,4	−12,4	L	O	IOG	18
8	3,73	−58,5	−55,9	−10,2	L	T	ITG	37
16	5,37	−58,5	−9.4	−14.0	L	T	ITG	21
17	8,12	−58,5	−55,9	−10,2	L	T	ITG	37
20	8,91	−58,5	−55,9	−10,2	L	T	ITG	37
25	1,38	50,8	−33,7	−23,6	L	T	ITG	37
35	2,61	−58,5	−55,9	−10,2	L	T	ITG	37
3	5,75	−48,5	−78,2	3,8	L	O	MOG	19
5	6,33	−28,5	−80,1	21,7	L	O	MOG	19
6	2,81	−28,5	−80,1	21,7	L	O	MOG	19
7	2,54	−28,5	−90,3	20,8	L	O	MOG	19
11	1,95	−38,5	−88,3	3	L	O	MOG	18
12	4,8	−48,5	−78,2	3,8	L	O	MOG	19
13	1,27	−48,5	−78,2	3,8	L	O	MOG	19
21	1,29	−28,5	−90,3	20,8	L	O	MOG	19
24	5,94	−38,5	−79,2	12,7	L	O	MOG	19
27	2,38	−28,5	−88,3	3	L	O	MOG	18
33	2,9	−28,5	−80,1	21,7	L	O	MOG	19
34	2,73	−48,5	−56,9	−2,8	L	O	MOG	19
37	2,22	−28,5	−89,3	11,9	L	O	MOG	18
1	7,79	−38,5	−80,1	21,7	L	T	MTG	19
10	5,58	−48,5	−69	13,6	L	T	MTG	39
23	2,48	−38,5	−80,1	21,7	L	T	MTG	19
18	6,57	−28,5	−82,1	39,5	L	O	PREC	19
14	4,93	−58,5	−58,9	14,5	L	T	STG	22
19	1,54	−68,5	−18,2	0,1	L	T	STG	22
GROUP	4,13	−37,44	−73,03	2,96	L	O	MOG	19

CONTROLS (right hemisphere)

Ss	Magn	T-x [mm]	T-y [mm]	T-z [mm]	Hem	Lobe	Gyrus	BA
8	2,54	21,2	−91,3	29,7	R	O	CUN	19
19	3,28	1,5	−82,1	39,5	R	O	CUN	19
2	1,94	40,9	−76,2	−11,7	R	O	FG	19
11	0,93	31	−66,1	−10,9	R	O	FG	19
17	5,12	31	−66,1	−10,9	R	O	FG	19
25	3,51	−58,5	−55,9	−10,2	R	T	FG	20
31	2	50,8	−16,1	−22,2	R	T	FG	20
34	1,94	50,8	−33,7	−23,6	R	T	FG	20
30	2,02	40,9	−87,3	−4,9	R	O	IOG	18
14	1,46	60,6	−55,9	−10,2	R	T	ITG	37
28	1,15	60,6	−55,9	−10,2	R	T	ITG	37
23	2,1	11,3	−66,1	−10,9	R	O	LG	18
7	2,89	31	−90,3	20,8	R	O	MOG	19
12	2,82	31	−80,1	21,7	R	O	MOG	19
27	2,09	31	−88,3	3	R	O	MOG	18
33	1,96	40,9	−88,3	3	R	O	MOG	18
37	1,98	31	−88,3	3	R	O	MOG	18
38	3,43	31	−90,3	20,8	R	O	MOG	19
3	3,73	40,9	−80,1	21,7	R	T	MTG	19
5	3,65	50,8	−70	22,5	R	T	MTG	39
10	3,53	50,8	−70	22,5	R	T	MTG	39
15	1,18	50,8	−0,6	−28,2	R	T	MTG	21
16	5,3	60.6	−2.8	−5,9	R	T	MTG	21
22	3,09	70,5	−17,5	−7,3	R	T	MTG	21
24	4,08	60,6	−56,9	−2,8	R	T	MTG	21
9	4,87	31	−72	40,3	R	P	PREC	19

Table 3 (*continued*)

CONTROLS (right hemisphere)								
Ss	Magn	T-x [mm]	T-y [mm]	T-z [mm]	Hem	Lobe	Gyrus	BA
13	0,76	40,9	−81,1	30,6	R	O	SOG	19
18	6,35	40,9	−81,1	30,6	R	O	SOG	19
32	2,63	60,6	−3,5	1,8	R	T	STG	22
GROUP	2,11	36,99	−64,68	5,27	R	O	MOG	19

MUSICIANS (left hemisphere)								
Ss	Magn	T-x [mm]	T-y [mm]	T-z [mm]	Hem	Lobe	Gyrus	BA
17	2,98	−18,5	−98,5	2,1	L	O	CUN	18
25	3,97	−8,5	−91,3	29,7	L	O	CUN	18
27	6,58	−18,5	−90,3	20,8	L	O	CUN	18
33	2,75	−18,5	−98,5	2,1	L	O	CUN	18
1	8,04	−48,5	−55,9	−10,2	L	T	FG	37
3	4,36	−48,5	−65,1	−18,4	L	T	FG	37
4	3,92	−18,5	−86,4	−12,4	L	O	FG	18
5	4,76	−48,5	−65,1	−18,4	L	T	FG	37
7	7,18	−48,5	−55	−17,6	L	T	FG	37
8	3,54	−48,5	−76,2	−11,7	L	T	FG	19
9	3,39	−48,5	−65,1	−18,4	L	T	FG	37
10	3,02	−48,5	−76,2	−11,7	L	T	FG	19
34	1,76	−48,5	−33,7	−23,6	L	T	FG	20
2	1,71	−58,5	−55,9	−10,2	L	T	ITG	37
13	2,39	−58,5	−55,9	−10,2	L	T	ITG	37
16	4,3	−48,5	−78,2	3,8	L	O	MOG	19
18	7,05	−48,5	−77,2	−4,2	L	O	MOG	19
20	3,83	−28,5	−89,3	11,9	L	O	MOG	18
22	4,48	−38,5	−79,2	12,7	L	O	MOG	19
28	7,42	−38,5	−88,3	3	L	O	MOG	18
29	3,42	−48,5	−77,2	−4,2	L	O	MOG	19
31	1,3	−48,5	−77,2	−4,2	L	O	MOG	19
32	3,95	−28,5	−80,1	21,7	L	O	MOG	19
35	2,1	−28,5	−79,2	12,7	L	O	MOG	19
38	5,69	−28,5	−79,2	12,7	L	O	MOG	19
11	5,54	−48,5	−68	4,7	L	O	MOG	37
23	2,88	−48,5	−67,1	−3,5	L	O	MOG	37
24	1,07	−48,5	−67,1	−3,5	L	O	MOG	37
30	3,92	−48,5	−68	4,7	L	O	MOG	37
36	2,56	−48,5	−68	4,7	L	O	MOG	37
37	5,06	−48,5	−67,1	−3,5	L	O	MOG	37
6	0,66	−58,5	−1,4	−20,8	L	T	MTG	21
12	4,74	−38,5	−80,1	21,7	L	T	MTG	19
15	1,61	−48,5	−70	22,5	L	T	MTG	39
19	3,28	−38,5	−69	13,6	L	T	MTG	39
26	2,25	−38,5	−80,1	21,7	L	T	MTG	19
21	0,82	−68,5	−18,2	0,1	L	T	STG	22
17	2,98	−18,5	−98,5	2,1	L	O	CUN	18
GROUP	3,64	−42,01	−70,22	0,55	L	O	MOG	19

MUSICIANS (right hemisphere)								
Ss	Magn	T-x [mm]	T-y [mm]	T-z [mm]	Hem	Lobe	Gyrus	BA
26	2,25	50,8	−71	31,4	R	T	AG	39
11	4,1	21,2	−91,3	29,7	R	O	CUN	19
4	4,3	21,2	−86,4	−12,4	R	O	FG	18
7	5,53	50,8	−55	−17,6	R	T	FG	37
9	3,24	50,8	−33,7	−23,6	R	T	FG	20
34	1,77	31	−85,4	−19,8	R	O	FG	18
10	1,94	31	−97,5	−5,7	R	O	IOG	18
33	2,63	31	−97,5	−5,7	R	O	IOG	18
5	3,66	60,6	−44,8	−16,9	R	T	ITG	20
30	1,53	11,3	−96,5	−13,1	R	O	LG	17
35	2,34	1,5	−97,5	−5,7	R	O	LG	18
2	1,67	31	−89,3	11,9	R	O	MOG	19
8	3,44	31	−90,3	20,8	R	O	MOG	19
13	4,26	31	−79,2	12,7	R	O	MOG	19
14	6,55	40,9	−79,2	12,7	R	O	MOG	19
16	4,36	50,8	−68	4,7	R	O	MOG	37
17	3,04	40,9	−88,3	3	R	O	MOG	18
20	3,72	40,9	−79,2	12,7	R	O	MOG	19
23	2,08	40,9	−79,2	12,7	R	O	MOG	19
29	2,79	31	−88,3	3	R	O	MOG	18
31	0,45	40,9	−88,3	3	R	O	MOG	18
37	8,1	50,8	−68	4,7	R	O	MOG	37
1	5,31	50,8	−57,9	5,6	R	T	MTG	21

Table 3 (*continued*)

MUSICIANS (right hemisphere)								
Ss	Magn	T-x [mm]	T-y [mm]	T-z [mm]	Hem	Lobe	Gyrus	BA
3	4,31	60,6	−46,8	−2,1	R	T	MTG	21
6	1,42	70,5	−36,6	−1,3	R	T	MTG	21
15	2,46	70,5	−17,5	−7,3	R	T	MTG	21
22	4,69	40,9	−80,1	21,7	R	T	MTG	19
24	1,44	60,6	−56,9	−2,8	R	T	MTG	21
27	4,91	50,8	−57,9	5,6	R	T	MTG	21
36	2,39	60,6	−47,8	6,4	R	T	MTG	21
25	4,2	11,3	−73	49,2	R	P	PREC	7
21	1,99	31	−73	49,2	R	P	SPL	7
38	1,67	60,6	6,2	−5,2	R	T	STG	22
28	2,52	21,2	−8	−28,9	R	T	UNC	36
26	2,25	50,8	−71	31,4	R	T	AG	39
11	4,1	21,2	−91,3	29,7	R	O	CUN	19
GROUP	2,92	40,61	−67,74	3,90	R	O	MOG	19

Table 4

The number of left and right areas identified in areas that may fall within the putative VWFA (BA18, BA19, BA21, BA37) are reported here for musicians and controls (highlighted in azure). The frequency of activation of other posterior areas involved in reading (BA17, BA22, BA39, BA7, BA36) is also reported. The number of left or right sources that could not be identified is shown in the 'not found' row.

N = 76	Musicians N = 38		Controls N = 38	
	LH	RH	LH	RH
BA17	0	1	2	0
BA18	7	8	6	5
BA19	13	9	16	12
BA20	1	2	0	3
BA21	1	7	1	4
BA37	13	3	10	1
BA22	1	1	2	1
BA39	2	2	1	2
BA7	0	2	0	0
BA36	0	1	0	0
Not found	0	2	0	10

analyses were performed via *Statistica* software (version 10) by StatSoft. The assumption of sphericity was assessed for the repeated measures ANOVA involving hemisphere. The Greenhouse-Geisser epsilon (ε) value for hemisphere was found to be 1, indicating that the assumption of sphericity was met.

In further analyses the mean strength (magnitude) of active electromagnetic dipoles in different visual areas (left and right STG, left and right MTG, left and right MOG, left and right ITG, left and right FG, right parahippocampal gyrus) were compared between the two groups by Fisher test. Correlation analyses (Spearman Rho) were also performed between the individual strengths of activation (magnitude) recorded in the left and right 'MOG' and individual laterality scores from the Edinburgh inventory for the two groups of participants. The primary objective of this correlation analysis was to investigate whether the bilateral pattern of visual area activation was associated with a genetically determined lesser degree of laterality, as measured by the Edinburgh Inventory. A significant correlation would suggest that the genetic predisposition towards less lateralized brain function might be related to bilaterality in brain activation. This would reduce the relevance of environmental factors, such as musical training and experience (certified by music master degree), on the development of the second reading area; and vice versa.

3. Results

3.1. Analysis of variance

The analysis of variance (ANOVA) applied on individual 'MOG' activations revealed a significant main effect of Hemisphere [F $(1,74) = 26.43$, $p < 0.001$, $\eta^2 = 0.26$] indicating an overall stronger activation of the left (M = 3.88, SD = 2.09) vs. the right hemispheres (M = 2.54, SD = 1.81) in both groups of participants. The main effect of "Group" was not statistically significant [F $(1, 74) = 0.1545$, $p = 0.6954$] per se but in interaction with the cerebral hemisphere: "Group" x "Hemisphere" [F $(1, 74) = 5.8086$, $p < 0.018$, $\eta^2 = 0.108$]. Tukey post-hoc comparisons showed that while 'MOG' activity was strongly lateralized in controls (left 'MOG' = 4.13 nA, SD = 2.19, right 'MOG' = 2.11 nA, SD = 1.71, p value = 0.0001), it was relatively bilateral in musicians (left 'MOG' = 3.64 nA, SD = 1.97, right 'MOG' = 2.92 nA, SD = 1.85, p = 0.22), as shown in Fig. 3.

A further analysis was conducted by considering the totality of active dipoles at only posterior brain areas for dipole strength (Fig. 4). The repeated measure ANOVA (2 factors, group and hemisphere) showed the significant group × hemisphere interaction (F 3,12 = 6,34; p = 0.008). Post-hoc comparisons demonstrated an overall greater left than right hemispheric activation in controls (left > right, p = 0.0047), and greater right than left hemispheric activation in musicians (right > left, p = 0.02).

A further analysis examined the frequency of occurrence of active sources across participants and groups, by extending the focus to the whole brain (i.e., including anterior, central, parietal, occipital and temporal). Numerosity was defined as the number of times a given area was found active in the N170 latency range, as calculated by swLORETA, in healthy controls and musicians during word reading. Fig. 5 displays the data plotted on lateral brain maps using color-coding. Besides the greater right occipito/temporal engagement, it can be noted that anterior brain areas were more frequently engaged in musicians than controls, showing a left hemispheric asymmetry in engagement patterns. The more extended frontal engagement consistently observed in musicians included premotor areas (SMA and lateral premotor cortex, BA6), oculomotor areas (BA8) for ocular and attentional shifting, prefrontal areas for attentional and executive control (BA9 and BA10) and inferior frontal areas devoted to word production and reading (Cornelissen et al., 2009, BA47 and BA45). The group difference in the number of anterior brain areas found active in musicians (N = 38) vs. controls (N = 26) was proved significant according to a Kolmogorov-Smirnov test (p < 0.05). The same test did not show significant group differences in the strength of activation of anterior areas (at this early time range).
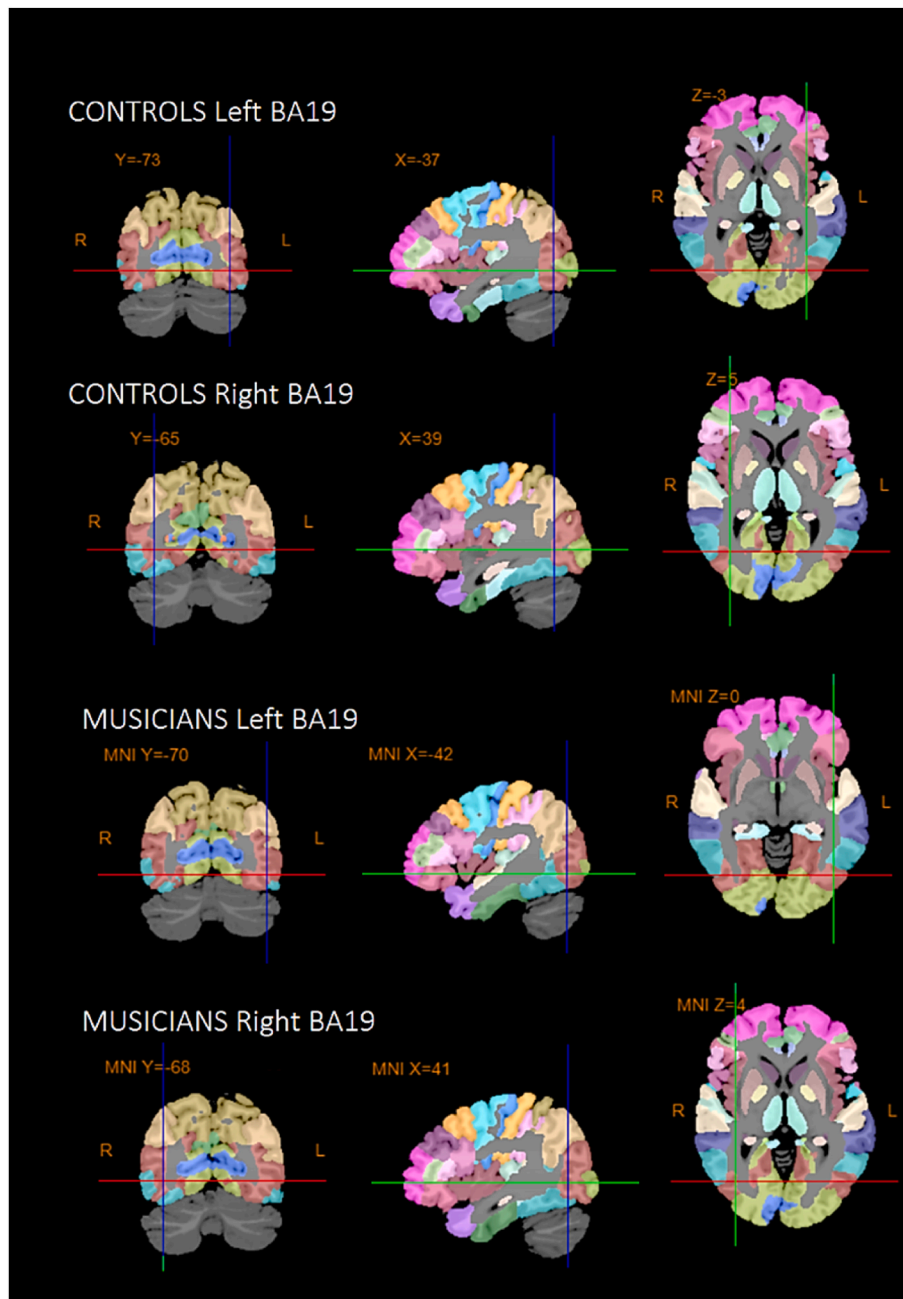
Fig. 1. Coronal, sagittal and axial brain sections showing the 3D localizations of the mean Talairach coordinates (group data) of the selected ROI in the two cerebral hemispheres and in the two groups of participants. The images were generated using the Yale BioImage Suite software.

3.2. Correlation analyses

For the control group, a statistically significant Spearman Rho correlation [r = 0.26, p < 0.05] was observed between strength of activation of the left 'MOG' and individual laterality scores from the Edinburgh inventory (see Fig. 6), so that the stronger the right-handedness of a participant the stronger the VWFA asymmetry in favor of the left 'MOG'. No significant correlation with laterality scores existed for the right 'MOG' in controls (r = 0.128), or for musicians within the left (r = 0.156) or the right 'MOG' (r = 0.037). This un-relatedness suggests that the 'MOG' bilaterality in musicians did not depend on handedness, but on music literacy. The significant correlation in controls suggests that without the specific need to develop an additional visual area (e.g., as a compensatory mechanism in dyslexics), more bilateral people may slightly activate right hemispheric visual

areas for reading. The lack of correlation in musicians suggests that, regardless of individual genetic predisposition, advanced musical literacy was associated with the development of bilateral reading areas.

To further investigate whether the development of bilateral reading system was related to musical literacy, a further correlation was performed, only in musicians, between the strength of activation of the left and right reading areas and music age of acquisition (AoA). The results (depicted in Fig. 7) showed that indeed there was a moderate inverse correlation [r = −0.2125, p < 0.05] between the strength of activation of the right MOG and their AoA: the earlier the AoA the larger the strength of activation of the right reading area. The nine musicians with the strongest right activation during word reading commenced musical training at an earlier age than 10 years. The four musicians with the strongest right activation had an age of acquisition (AoA) of ≤8 years; the two musicians with the strongest right MOG activation commenced
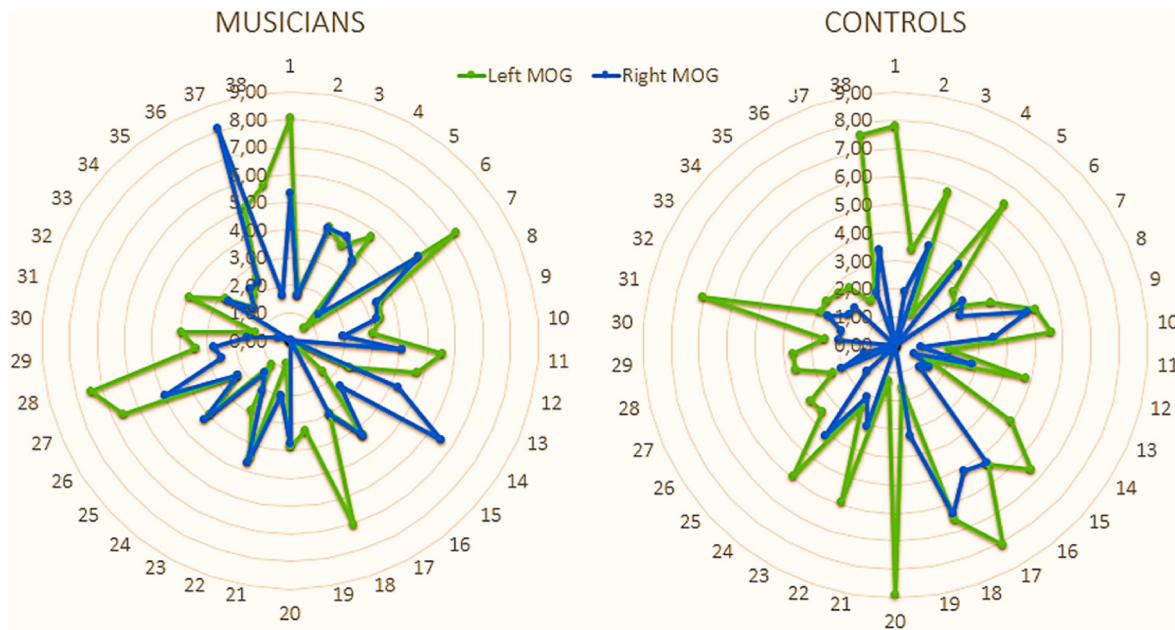
Fig. 2. The figure shows the individual strength of the selected ROI found active in the left and right hemispheres of professional musicians and control participants during the 150–190 ms time window during word reading. The numbers on the circumference of the circle indicate the individual subjects (N = 38). The bilateral activation of the visual word form area (VWFA) in the medial occipital gyrus (MOG) BA19 is clearly evident in musicians.
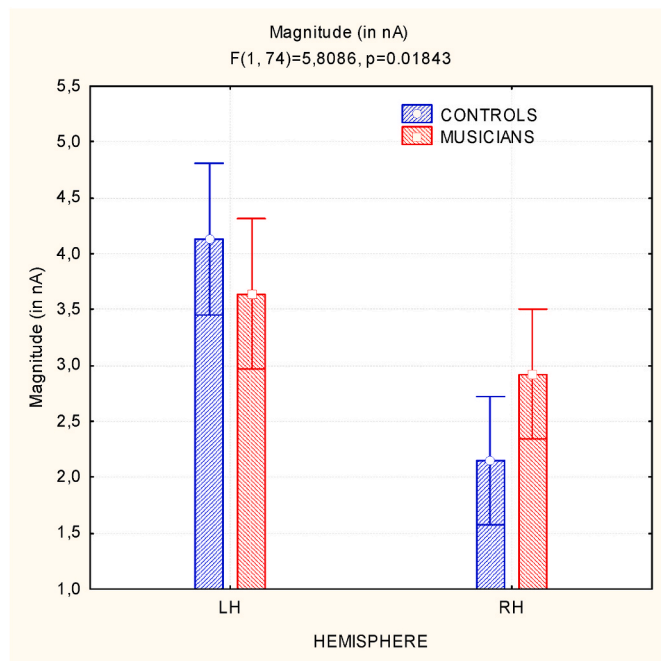

Fig. 3. Magnitude of activation of the selected ROI measured as a function of cerebral hemisphere and group of participants, in response to words.

musical training at 5 years of age. The bilaterality of visual area did not depend on musicians' brain laterality, as shown by a lack of significance between their AoA and lateral preference for hand, foot, eye and ear, as derived from the Edinburgh inventory (Regression analysis: R^2 corrected = 0.010176; p = 0.264).

3.3. SwLORETA source reconstruction

For each of the 76 participants, three-dimensional tomographic neuroimages were generated in the coronal, axial, and sagittal brain sections, centered on the strongest source, as reported in Table 3. The primary focus was on the active dipole within the identified ROI. The images presented in Fig. 8 illustrate the precise locations and strengths of electromagnetic dipoles linked to the surface N170 potential in eight participants. The whole set of tomographic images can be found at this link https://data.mendeley.com/datasets/zmh93bf8g6/1.

The analyses of neuroimaging data support the evidence of a bilateral engagement of left and right word reading areas in the brain of professional musicians, as opposed to the predicted left-lateralized orthographic mechanism found in musically-naïve participants.

4. Discussion

The primary aim of this study was to investigate whether intensive music study, specifically music literacy (the ability to read complex notation), among professional musicians, is associated with neuroplastic functional changes that directly affect the mechanisms of reading written language. To address this question, we compared the neural mechanisms involved in reading letters forming words (ranging in length from 4 to 10 letters) in musicians and a control group matched for age, mother tongue, sex composition and educational status. The objective was to evaluate potential plastic developmental changes in the brains of musicians resulting from their music training experience. To discern and identify patterns of brain activation during reading tasks, we specifically analyzed the inner sources of N170 component (150–190 ms poststimulus), known to reflect word orthographic processing (e.g., Rossion et al., 2003; Maurer et al., 2005).

The approach of conducting and contrasting EEG source reconstructions on individual data is notably innovative, although it has also been employed in specific contemporary research studies (e.g., Babiloni et al., 2004; Babiloni et al., 2006; Cannon et al., 2008, 2009).

The present study found that the regions around the left middle occipital gyrus (BA19) were involved in word reading and orthographic processing in both musicians and controls, indicating its role as the traditional VWFA. However, there was a certain degree of interindividual variation. The study found that the middle occipital and fusiform gyri (BA19 and BA37) were active in 67% of cases, the lateral occipital cortex (BA18) in 21% of cases, and the posterior temporal areas
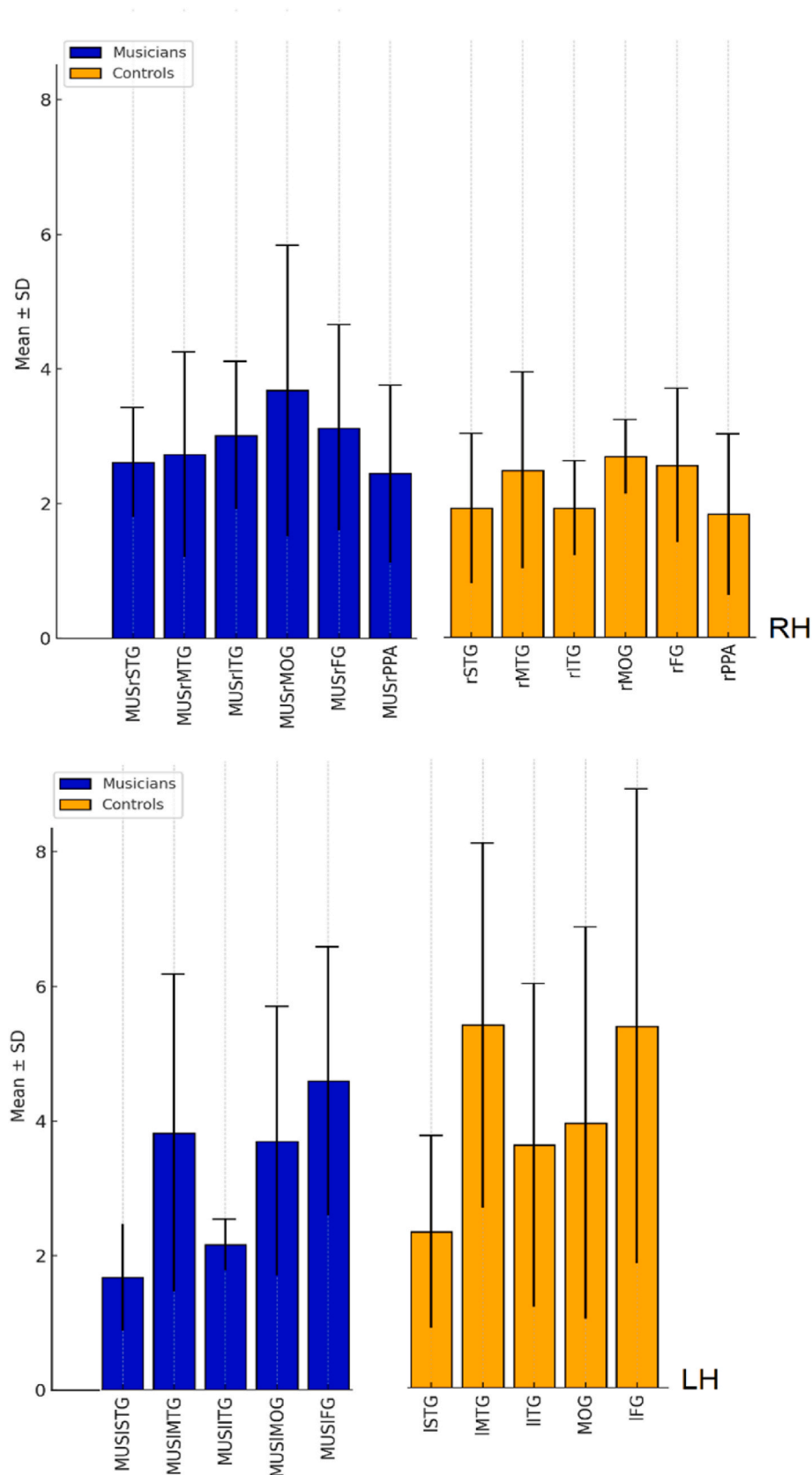
Fig. 4. Mean strength of occipito/temporal dipoles (along with SD values) found active in the two groups of participants (N = 76) as determined by swLORETA, and as a function of cortical gyrus and cerebral hemisphere. For the purpose of this specific analysis, all multiple active dipoles were considered (from the smallest to the largest), for each participant. (Note that the left parahippocampal gyrus was never found active).
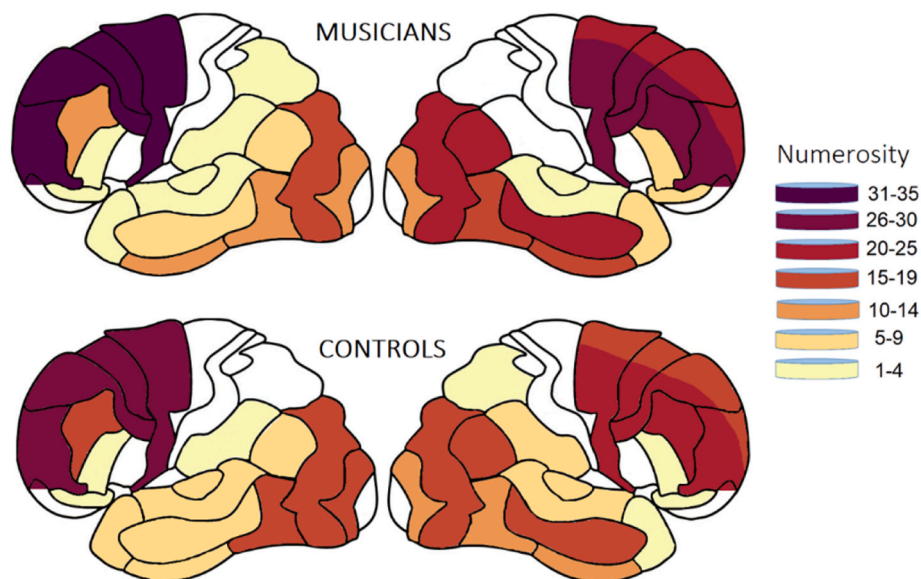
Fig. 5. Colour-coded left and right lateral maps indicating the frequency with which various Brodmann areas were reported to be significantly active during word orthographic processing in the 150–190 ms time epoch, in the 76 participants. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(BA21, 22, 38, 39) in the remaining cases, within the N170 time epoch. Timing differences across participants may also contribute to the variability observed. Notably, letter processing is thought to rely on more posterior occipital regions, including IOG, BA19, and posterior FG, whereas whole word processing engages more anterior regions, such as middle and anterior FG (Lochy et al., 2018). The localization of the selected ROI aligns the findings of numerous prior investigations identifying a region near the left occipitotemporal sulcus as crucial for visual word processing (e.g., Proverbio et al., 2008; Dehaene and Cohen, 2011; Kronbichler and Kronbichler, 2018; Murphy et al., 2019; Sabsevitz et al., 2020; Lu et al., 2021; Vin et al., 2024).

The results demonstrated that musicians exhibited bilateral activation of the mid/temporal cortex (centered on average over 'MOG' area), whereas the control group displayed lateralization with a stronger activation in the left hemisphere. This phenomenon might be attributed to functional neuroplasticity processes associated with the acquisition of notation reading ability (Proverbio et al., 2013). Interestingly, it was found a mild inverse correlation between music AoA and bilaterality of reading areas in musicians (the earlier the AoA the stronger the right 'MOG' activation), which further supports the hypothesis of a causal relationship between music literacy and bilaterality. In fact, the right OT cortex (and notably the right posterior FG) would play a pivotal role in notation reading (e.g., Proverbio et al., 2024). The literature consistently shows that bilateral neural processes, mainly involving the right OT cortex, are responsible for the skill of reading musical notation. Various studies have identified the *Visual Note Form Area* in different regions of the right hemisphere, including: the right transverse occipital sulcus, right occipital gyrus, right inferior occipital gyrus, right occipitotemporal junction, right fusiform gyrus, right superior parietal cortex, and supramarginal cortices (Proverbio et al., 2024; Mongelli et al., 2017; Nakada et al., 1998; Sergent et al., 1992; Schön et al., 2002).

Assuming an opposing viewpoint, one might argue that that the bilateral activation of the ventro-occipital network for reading is not dependent on musical literacy but rather on the fact that musicians are better readers, as evidenced by their superior performance on reading tests. However, this hypothesis appears weak for at least two reasons. First, musicians' reading habits seem limited compared to those of non-musicians, with musicians self-reporting an average of 1250 printed pages read per year, equivalent to approximately 3.5 books, while non-musicians report an average of 2915 printed pages read per year,

equivalent to about 8 books (see Supplementary Materials for more information). Therefore, we postulate that the more bilateral ventro-occipital network does not depend on word reading skills but on acquired music reading skills. Second, according to the literature on neurotypical readers, reading skills are correlated with enhanced left VWFA activation, not bilateral VOT (ventral occipitotemporal) activation. For example, Centanni et al. (2018) examined the early development of letter specialization in the left fusiform gyrus and its relationship with reading abilities and the size of the fusiform face area. The findings indicated that the early specialization of the left VWFA (for letters rather than faces) positively correlated with better word reading performance, highlighting the importance of this neural specialization for reading proficiency.

The bilateral activation observed in musicians during word reading, in this study, aligns with the results of Proverbio et al. (2013), who demonstrated that musicians displayed bilateral activation in the fusiform and inferior occipital gyri while processing both words and music. This finding is not surprising, as bilaterality has been often observed in musicians, as illustrated by a recent meta-analysis (Criscuolo et al., 2022). In this review, the authors analyzed fMRI and EEG data relative to 346 musicians and 345 non-musicians finding that, compared to non-musicians, musicians exhibited bilateral activation in several brain regions including the primary and secondary auditory areas of the temporal cortex, the premotor and prefrontal cortex and the basal ganglia. Quite similarly, Olsezvska et al. (2021) found that musicians who have received extensive musical training demonstrate greater bilateral activation in areas such as the motor cortex, premotor cortex, and auditory cortex. Bilateral activation of cortical areas may allow for greater flexibility and coordination between the two hemispheres, which is important for complex musical and motor tasks, but might be also relevant to notation reading and visuomotor transformation of written commands.

The present pattern of results is supported by the behavioral findings of Li and Hsiao (2018), who investigated the effects of musical reading on reading, in an English word and Chinese character-naming task presented in different visual fields. They found an effect of musical literacy on word reading lateralization with musicians performing significantly faster than controls for words presented in the left visual field (right hemisphere). Additionally, neuroimaging studies indicates that musical expertise affects the neural processing of visual objects
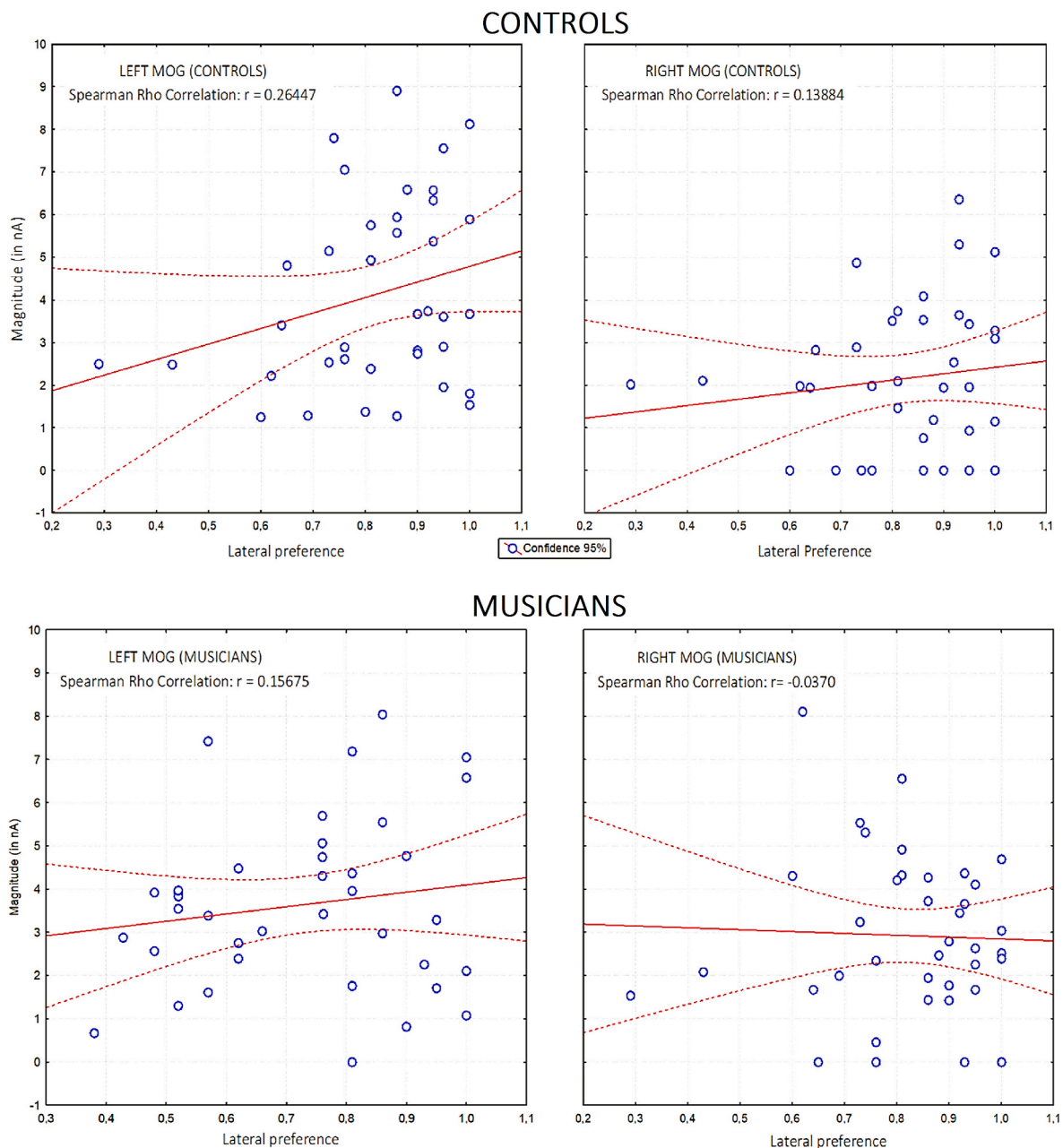
Fig. 6. Spearman Rho correlation between left and right 'MOG' source strengths and individual laterality scores according to the Edinburg Inventory in control and musician participants.

including music notation, faces and written words (e.g., Dehaene et al., 2010; Mongelli et al., 2017; Bouhali et al., 2017). In summary, musical literacy may reorganize brain function to promote more bilateral processing of language, particularly in the ventral visual cortex.

Overall, the present data indicate that an early and extensive engagement with music reading can bring about lasting alterations in the cerebral mechanisms dedicated to visual word recognition, thereby influencing the processing of alphabetic characters. Notably, this neuroplasticity is highlighted in the enhanced involvement of right-sided occipito/temporal regions during word reading among musicians, particularly in the right fusiform gyrus and the right inferior occipital gyrus, which fits with available literature (Bouhali et al., 2017; Li and Hsiao, 2015, 2018; Li et al., 2017; Wong and Gauthier, 2010; Proverbio et al., 2013). These regions, typically associated with the left hemisphere's visual word form area, showcase distinctive activity in musicians. This completely aligns with study conducted by Proverbio et al.

(2013). Additionally, Pantaleo et al. (2024) demonstrated that skilled readers, encompassing musicians and proficient readers, exhibit a distinctive link between word reading and the right occipitotemporal cortex, indicating that the existence of an orthographic area in the right hemisphere is associated with improved reading skill. The authors compared reading skills, and brain activations during a word orthographic task, in people with higher (good) and lower (poor) reading proficiency, as well as in musicians and non-musicians. The ERP data showed more extended and more intense brain signals in good than poor readers, and in musicians than in controls. Furthermore, good vs. poor readers showed larger activations in the VWFA, but also in bilateral anterior brain areas, including the premotor cortex (BA6), dorsolateral prefrontal (BA9), middle and superior frontal cortices and frontal eye fields (BA8, for shifts in attention and eye movements, Choi et al., 2014) similar to what found in the present study. Here, the comparisons between musicians and controls showed a more extended recruitment of
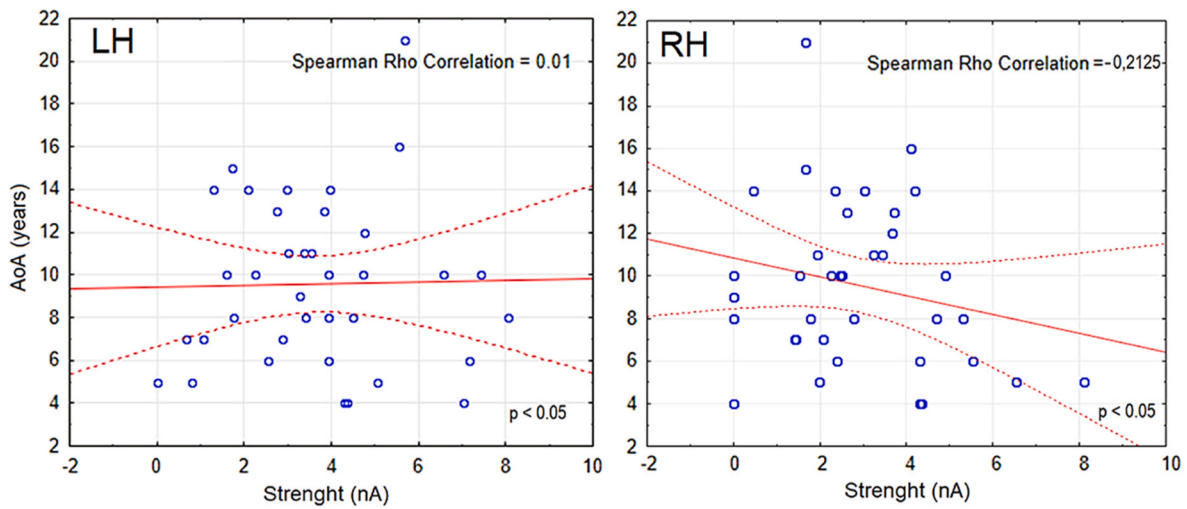
Fig. 7. Spearman Rho correlation analyses between left and right 'MOG' source strengths and musician age of acquisition (N = 38).
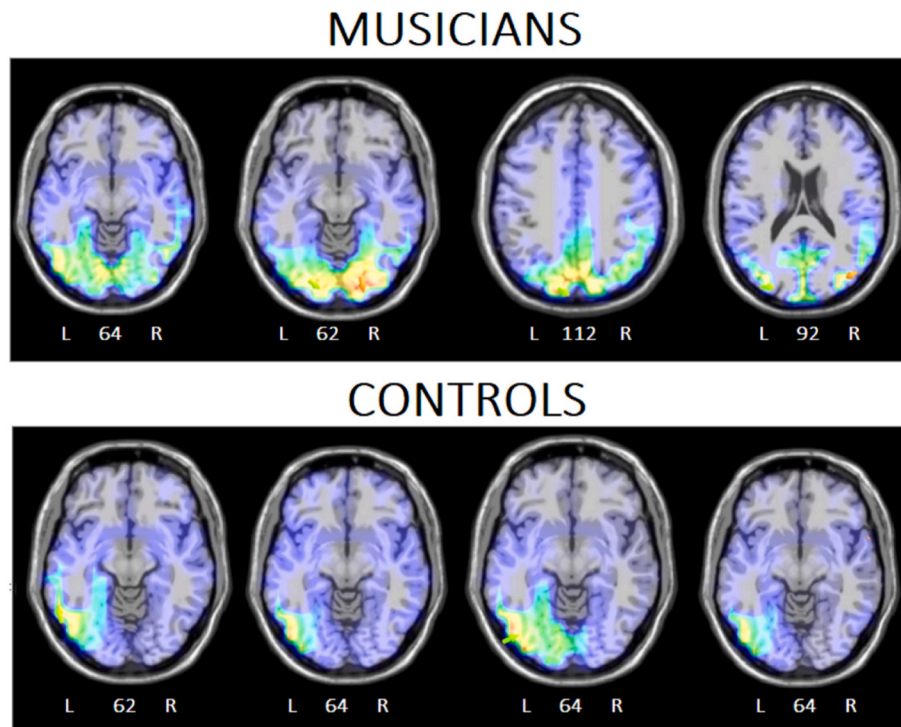

Fig. 8. Axial sections of swLORETA active sources in 4 musicians and 4 controls during an orthographic letter detection task, in which participants were presented with whole words and asked to identify specific letters, within the N170 time window (approximately 150–190 ms). The electromagnetic dipoles appear as arrows and indicate the position, orientation and magnitude of the dipole modelling solution applied to the ERP waveform in the specific time window. L, left; R, right; numbers refer to the displayed brain slice in the MRI imaging plane.

anterior brain areas in musicians than controls, although the strength of activation was similar across groups, at this early stage.

This study builds on the findings of Proverbio et al. (2013) and Pantaleo et al. (2024), who observed larger bilateral N170 potentials in musicians compared to controls. We extend this by showing that musical literacy consistently fosters functional development in a right visual area (MOG) involved in letter recognition and word reading. This region of interest (ROI) was systematically identified across participants recruited independently by different researchers at various time points. Notably, its activation strength was inversely correlated with the age of acquisition (AoA) of musical ability. Furthermore, by significantly increasing the sample size and broadening the variety of instruments played, we

strengthened the generalizability of our findings.

The general hypothesis is here advanced that the acquisition of music literacy could aid in improving reading skills in children who are at genetic risk for dyslexia or predisposed to it: indeed an insufficient and anomalous VWFA activation may result in 'surface' dyslexia (Salmelin et al., 1996). It can be postulated that the development of a bilateral orthographic area in conjunction with the acquisition of music reading ability, and additionally, the intensive training in attentional and ocular shifting, may serve as an enhancing and protective factor for reading ability (Pantaleo et al., 2024; Krafnick et al., 2014). Indeed here it was shown that musicians were more skilled in reading ability than educationally matched controls. Pantaleo et al. (2024) has also shown a

correlation between the amplitude of N170 at right occipito/temporal sites and individual reader proficiency, in control participants. According to a large literature music education can have a positive impact on reading abilities in individuals with dyslexia (e.g., Habib et al., 2016); in fact, dyslexic musicians would show better word reading skills than dyslexics non-musicians. Although this knowledge is quite consolidated, scarce evidence so far, were presented about direct effects of musicianship, and in particular music literacy, on visual word reading mechanisms. The present data may offer valuable insights for exploring reading disabilities, particularly surface dyslexia. Shaywitz and Shaywitz (2005) note that impairment of left hemisphere posterior reading systems, particularly in the parieto-temporal and occipito-temporal regions, contributes to the inability to develop reading proficiency in individuals with dyslexia. However, compensatory mechanisms emerge, involving reliance on ancillary systems in both left and right anterior regions, as well as right posterior regions. This compensatory strategy enables accurate word reading, even though automaticity remains a challenge (Shaywitz and Shaywitz, 2005). The development of right-sided word reading area, could potentially simplify the activation process in dyslexic readers or act as a protective factor against its susceptibility.

5. Study limits and future perspectives

Many investigations into the neuroplasticity of musicians have predominantly focused on the development of frontal and temporo/parietal regions of the brain associated with musical expertise (along with white matter and cerebellar changes). This structural variations has been consistently linked to enhancements in auditory and motor functions, as evidenced by structural studies (Gaser and Schlaug, 2003; Zatorre et al., 2007; Elmer et al., 2013; Sato et al., 2015; Karpati et al., 2017; Olszewska et al., 2021). However, there is a noticeable gap in the literature concerning plasticity in the reading mechanisms of musicians. The present study suggest a potential reshaping of the functional brain organization with benefits in written language reading by music training. Future research endeavors could further explore this aspect, considering factors like dyslexia proneness or interventions, including music therapy for dyslexic children.

Furthermore, it is crucial to acknowledge that the distinction between musicians and controls extends beyond their proficiency in reading musical notation. Additional abilities, including those related to visual processing, also play a significant role in shaping their cognitive profiles. Specifically, musicians possess enhanced capabilities in visual attention, spatial attention shifting, and visual-motor transformations, such as the ability to translate musical notation and fingering into motor commands. These visuospatial abilities may, in turn, influence the lateralization of visual processing areas, underscoring the importance of considering the multifaceted nature of musical cognition.

This study demonstrated a strong association between beginning the study of *solfeggio* and musical notation around the ages of 9/10—ideally in early childhood—and the development of a bilateral brain region for word reading in professional musicians. A longitudinal study capable of illustrating the genesis of this development in music students would, of course, be desirable to support this hypothesis and confirm the directionality of this sequence of events.

Data sharing

All ERP and neuroimaging data are available upon request at this link: Bicocca Open Archive Research Data, https://data.mendeley.com/datasets/zmh93bf8g6/1.

Funder

CRediT authorship contribution statement

Alice Mado Proverbio: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elham Sanoubari:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the data at this repository https://data.mendeley.com/datasets/zmh93bf8g6/1

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ynirp.2024.100219.

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