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Music Playing and Interhemispheric Communication: Older Professional Musicians Outperform Age-Matched Non-Musicians in Fingertip Cross-Localization Test

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Abstract

Objective: Numerous investigations have documented that age-related changes in the integrity of the corpus callosum are associated with age-related decline in the interhemispheric transfer of information. Conversely, there is accumulating evidence for more efficient white matter organization of the corpus callosum in individuals with extensive musical training. However, the relationship between making music and accuracy in interhemispheric transfer remains poorly explored. **Methods:** To test the hypothesis that musicians show enhanced functional connectivity between the two hemispheres, 65 professional musicians (aged 56–90 years) and 65 age- and sex-matched non-musicians performed the fingertip cross-localization test. In this task, subjects must respond to a tactile stimulus presented to one hand using the ipsilateral (intra-hemispheric test) or contralateral (inter-hemispheric test) hand. Because the transfer of information from one hemisphere to another may imply a loss of accuracy, the value of the difference between the intrahemispheric and interhemispheric tests can be utilized as a reliable measure of the effectiveness of hemispheric interactions. **Results:** Older professional musicians show significantly greater accuracy in tactile interhemispheric transfer than non-musicians who suffer from age-related decline. **Conclusions:** Musicians have more efficient interhemispheric communication than age-matched non-musicians. This finding is in keeping with studies showing that individuals with extensive musical training have a larger corpus callosum. The results are discussed in relation to relevant data suggesting that music positively influences aging brain plasticity.

Keywords: Corpus callosum, Connectivity, Musical training, Aging, Brain plasticity, Neuroprotection

INTRODUCTION

Music is one of the most complex human abilities and has been the object of numerous investigations from specialists in both the human and natural sciences. In recent years, neuroscience has made a substantial contribution to our understanding of the special characteristics of musical experience. Indeed, by using currently available brain imaging techniques, it is now possible to investigate the changes that music produces in the healthy human brain. From this point of view, a substantial amount of evidence converges to suggest that musical training is a powerful means for reorganization of brain structures (Jäncke, 2009; Schlaug, 2015). According to these investigations, it appears that changes linked to musical experiences take place in both the gray matter of specific cerebral regions and the size, volume, and composition of white matter fiber bundles (Pantev et al., 1998; Gaser & Schlaug, 2003; Oechslin, Imfeld, Loenneker, Meyer, & Jäncke, 2010; Halwani, Loui, Rüber, & Schlaug, 2011). As a result of this music-dependent rearrangement of neuronal networks, musicians seem to possess a different connectome than non-musicians (Schmithorst & Wyke, 2002).

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In this regard, the corpus callosum, the largest white matter fiber network in the human brain, has attracted a great deal of attention. It is well known that the corpus callosum mediates interactions between the hemispheres, which are essential for many aspects of human behavior (Gazzaniga, 2000, 2005). In particular, its role in mediating the transfer of information between the two hemispheres is strongly supported by studies that have examined the effects of partial or complete callosotomy (Myers & Sperry, 1985; Funnell, Corballis, & Gazzaniga, 2000).

Many studies have found that interhemispheric transfer is affected by development and aging (Davis, Kragel, Madden, & Cabeza, 2012; Jeeves & Moes, 1996; Schulte, Sullivan, Müller-Oehring, Adalsteinsson, & Pfefferbaum, 2005). The capacity for information transfer between hemispheres progressively improves until around the age of 10–14 years, when it reaches performance levels typical of adulthood. Starting around the sixth decade of life, there is a progressive decline in performance (Boyson, 2013; Reuter-Lorenz & Stanczak, 2000; Scally, Burke, Bunce, & Delvenne, 2018). For example, significant differences have been reported between adults aged 35–45 and 55–60 years (Bellis & Wilber, 2001). This age-related decline appears to occur in conjunction with the onset of atrophy of the corpus callosum. Indeed, the majority of neuroimaging studies have found that both the global surface of the callosal area and the integrity of the callosal fibers progressively decrease, following an inverted-U curve across the human lifespan (Hasan et al., 2008; Sullivan & Pfefferbaum, 2006). Furthermore, postmortem investigations have shown that from the sixth to eighth decade of life, there is a 37.9% reduction in the total number of myelinated fibers in the corpus callosum (Hou & Pakkenberg, 2012; Riise & Pakkenberg, 2011; Tang, Nyengaard, Pakkenberg, & Gundersen, 1997).

According to the disconnection hypothesis of cognitive aging (Bennett & Madden, 2014; O'Sullivan et al., 2001), these age-related structural and functional alterations of the corpus callosum may account for the onset of cognitive disorders in normal aging. In older populations, the severity of callosal atrophy correlates with the degree of cognitive impairment and there is accumulating evidence that callosal dysfunctions are associated with the impairment of memory and executive dysfunctions (Ryberg et al., 2011; Zahr, Rohlfing, Pfefferbaum, and Sullivan, 2009). Furthermore, severe callosal atrophy has been recorded in subjects with degenerative and vascular dementia (Hallam et al., 2008). Conversely, several investigations suggest that integrity of the corpus callosum predicts both better motor and cognitive abilities in old age (Johansen-Berg, Della-Maggiore, Behrens, Smith, & Paus, 2007; Kennedy & Raz, 2009). Moreover, several investigations have correlated successful aging with maintaining corpus callosum integrity (Madden et al., 2009; Penke et al., 2010; Wolf et al., 2012). In summary, while white matter atrophy seems to be a global phenomenon in typical aging (O'Sullivan et al., 2001; Salat et al., 2005; Salthouse, 2011), there appears to be a direct relationship between brain aging, cognitive functioning, and the function of the corpus callosum. Damage to the corpus callosum seems to be a strong predictor of cognitive and motor deterioration later in life, whereas its functional efficiency appears to protect against cognitive aging and can help explain, at least in part, the mechanisms underlying successful aging (Penke et al., 2010; Persson et al., 2006).

Due to the putative impact of corpus callosum integrity on general cognitive processes, it is important to examine its efficiency. It should be borne in mind that neuroradiological tests can only provide indirect information on connectivity. For example, it has been stressed that even when the size of the corpus callosum is normal, the effectiveness of connections can be reduced; abnormalities on a microscopic level, which cannot be detected by neuroimaging methods, can yet play an important functional role (Sullivan & Pfefferbaum, 2006). In this regard, neuropsychological and behavioural studies can be of additional value.

To explore the effectiveness of information transfer, different behavioral paradigms have been proposed (Poffenberger, 1912; Reuter-Lorenz & Stanczak, 2000; Saron & Davidson, 1989; Thompson, Narr, Blanton, & Toga, 2003) and a number of studies have correlated neuroradiological indexes of callosal integrity with behavioral measures of interhemispheric transfer (Schulte & Müller-Oehring, 2010; Westerhausen et al., 2006).

Currently, research shows a close relationship between the organization of the corpus callosum and musical training. There is evidence that individuals with extensive musical training have a larger corpus callosum and show more efficient white matter organization in the corpus callosum (Oztürk, Tasçioglu, Aktekin, Kurtoglu, & Erden, 2002; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995) and music can trigger plastic changes in the corpus callosum (Jäncke, 2009; Wan and Schlaug, 2010). Based on these findings, it is likely that professional musicians would perform differently on interhemispheric transfer tests than control subjects. However, it has not yet been clearly determined whether music-induced plastic changes in the corpus callosum correspond to more efficient interhemispheric interaction.

In the present study, we tested the hypothesis that musical training can enhance cross-hemispheric communication by comparing the performance of professional musicians and non-musicians in the fingertip cross-localization test, an experimental paradigm widely used in split-brain subjects to measure the transfer of somesthetic information (Bogen, 1979; Fabri et al., 2005). We hypothesized that changes in callosal plasticity induced by musical exercise would be associated with greater accuracy in the interhemispheric transfer of information. Our main working hypothesis was that older professional musicians should make significantly fewer errors during the fingertip cross-localization test than age-matched control subjects. This would be an indication that the functional efficiency of the corpus callosum was maintained despite age. Second, we tried to assess whether the musicians' test performance was correlated with a number of variables linked to individual musical competence.

METHODS

Participants

Sixty-five professional classical musicians (42 male and 23 female) aged >55 years old ($M = 68.89$, $SD = 10.33$, age range = 56–90) were recruited for this study at the Academy of Santa Cecilia in Rome, the Casa della Musica Giuseppe Verdi in Milan, and the music conservatories of Trento, Bolzano, Perugia, and L'Aquila. The control group of 65 participants (42 male and 23 female), aged 56–86 years ($M = 69.95$, $SD = 8.96$), was selected from a pool of 200 healthy, right-handed subjects examined in our laboratory to best correspond in terms of age and sex to each musician in the experimental group. All subjects were preliminarily examined in a clinical interview aimed at assessing their general state of health, general cognitive functioning, and independence in daily life. The general exclusion criteria were the following: an adjusted score of <24 on the Mini-Mental State Examination (Magni, Binetti, Bianchetti, Rozzini, & Trabucchi, 1996); the presence of cerebrovascular, cardiovascular, metabolic, oncologic, or neuropsychiatric diseases (pharmacological treatments, such as antihypertensive therapy, for keeping clinical conditions under control, were not considered a criterion for exclusion); and the presence of difficulty with hand movements (e.g., people suffering from arthritis). Additionally, control subjects were excluded if they were amateur musicians or if their profession was based on digital ability (e.g., typists). Musicians were also given a semi-structured interview aimed at evaluating some variables associated with musical performance. This interview took handedness into account as measured by the Edinburgh Inventory (Oldfield, 1971), type of professional activity (orchestral players or teachers), the instrument used (divided into four categories: keyboards, strings, brass, and multi-instrumentalist), the age at which musical training began, the average duration (in hours) of daily training extrapolated across their lifetime, and the presence of family musicians during childhood. All participants gave informed consent. The research was completed in accordance with the Declaration of Helsinki.

The Fingertip Cross-Localization Test

To properly study communication between the two hemispheres, it is necessary to utilize tasks in which the correct execution compels the subject to use interhemispheric transfer. In the fingertip cross-localization test, subjects must respond to a tactile stimulus presented to one hand using the ipsilateral or contralateral hand. With hands out of view, the tip of a finger is lightly touched with a sharpened pencil point. Subjects are then asked to indicate which finger was touched by using the thumb of the same hand (uncrossed condition) or by using the corresponding finger of the opposite hand to touch the thumb of the opposite hand (crossed condition). The crossed condition requires interhemispheric transfer of information because one hemisphere is presented with the stimulus, which the other hemisphere has to use to respond correctly. The uncrossed conditions do not require any transfer since both the stimulus and response are lateralized to the same hemisphere. Performance can be measured in terms of accuracy by calculating the difference in the number of correct answers to crossed and uncrossed tests (crossed–uncrossed difference; CUD). Theoretically, if the transfer between the two hemispheres was entirely efficient, the performance under crossed (interhemispheric) and uncrossed (intrahemispheric) conditions should not be different. Conversely, the value of the CUD is expected to increase proportionally with reduction in functional efficiency.

Data from the literature indicate that the number of errors, measured as the CUD, gradually decreases during childhood and adolescence due to progressive improvement in the interaction between the two hemispheres (Innocenti, 1981); progressive changes concern the number and myelination of fibers on the one hand and synaptic organization on the other, until the specificity of connections typical of adulthood is reached around age 14 (Galin, Johnston, Nakell & Herron, 1979; O'Leary, 1980; Quinn & Geffen, 1986). Healthy adult subjects make a number of errors that varies from 0% to 10% and increases progressively with increasing age (Bogen, 1979; Fabri et al., 2005; Piccirilli, Finali, & Sciarma, 1989; Piccirilli et al., 2020). In patients, the number of errors varies depending on pathological condition (Brown & Paul, 2019; Fabbro et al., 2001; Roebuck, Mattson & Riley, 2002). As expected, the performance of patients with a total callosotomy does not differ from a random response, that is the number of errors is about 75% (Funnell et al., 2000; Geffen et al., 1985; Myers & Sperry, 1985), However, patients with a partial callosotomy show various degrees of abnormalities depending on the site of the cut (Caillé, Sauerwein, Schiavetto, Villemure, & Lassonde, 2005; Devinsky & Laff, 2003; Lassonde, Sauerwein, Geoffroy, & Décarie, 1986). In particular, after surgical resection of different portions of the midbody, in subjects with intact genu and splenium, the occurrence of poor transfer has been documented only when the lesion was located in the portion posterior to the interventricular foramen (Bentin, Sahar, & Moscovitch, 1984). Also, data derived from functional MRI confirm that the tactile channel passes through the corpus callosum at the posterior midbody before the splenium (Hofer & Frahm, 2006; Polonara et al., 2015).

Procedure

Subjects were seated at a table, placing their forearms directly in front of them on the table, with palms facing upwards. They looked at a blank screen, which kept their hands out of view. The experimenter touched the tip of one of four fingers with the point of a sharpened pencil, asking the subject to then touch that same finger with the tip of the thumb of the same hand (uncrossed condition) or to touch the corresponding finger on the opposite hand with the thumb of that opposite hand (crossed condition). Subjects responded immediately after stimulation, and the examiner recorded each response on his answer sheet. No feedback was given concerning performance accuracy. The test was first demonstrated with the subject's hand in full view until he/she understood what was required.

There were 192 trials altogether, in sets of 48 trial sequences for each hand/task (right-to-right, right-to-left, left-to-left, and left-to-right). Each finger was stimulated the same number of times (12 times each for the four hand/task conditions). All subjects performed the uncrossed localization condition trials first and the crossed localization condition trials afterward. Choice of the hand on which stimulation was carried out was counterbalanced across all subjects. Trial sequences for each condition were different. The examination took around 10–15 minutes.

The score was based on the number of correct responses (with 48 as the maximum value for each condition). The CUD (difference in the overall number of errors between uncrossed and crossed tasks) was calculated by using the following formula: (uncrossed test on the right hand − crossed test on the right hand) + (uncrossed test on the left hand − crossed test on the left hand).

Data Analysis

First, a mixed ANOVA with Group (controls vs. musicians) as the between factor and Hand (right vs. left) and Condition (uncrossed-hand vs. crossed-hand) as repeated measures was run using the number of correct responses. The effect size was measured using partial eta-squared, with 0.0099, 0.0588, and 0.1379 being small, medium, and large effects, respectively (Cohen, 1988). *Post hoc* analyses were run using two independent-sample and two dependent-sample *t* tests. To account for multiple comparisons, the threshold at which *p*-values were deemed significant was halved (.05/2 = .025).

Second, to compare the CUD between controls and musicians, an independent-sample *t* test was carried out. The effect size was measured using Cohen's *d* for independent and dependent samples, respectively, in which benchmarks are small ($d \leq .2$), medium ($d \leq .5$), and large ($d \leq .8$). As a further index of the efficiency of interhemispheric transfer, the number of control and musician subjects who performed the test without making any mistakes was calculated.

A ceiling effect in musicians made it difficult to analyze the potential impact of personal variables on their test performance (see below). Thus, musicians were split into two separate groups (errors vs. no-errors) based on the presence or absence of differences in scores between crossed and uncrossed conditions. A series of independent-sample *t* tests were run to compare the errors vs. no-error groups in terms of handedness, the age at which musical training began, and the average daily number of hours practiced. A Chi-squared test was carried out to test associations between errors and the type of professional activity, instrument played, and presence of family musicians during childhood.

Finally, since there was no ceiling effect in the control group and thus greater sensitivity to age-related changes, Pearson's correlations between age and score (i.e., number of corrected responses and CUD) were calculated to test for age-related changes in performance.

RESULTS

Number of Correct Responses

There was a significant main effect of Group ($F_{(1)} = 63.27$, $p < .001$, $\eta_p^2 = .331$) on the number of correct responses. As shown in Table 1, the musicians reported higher scores than the controls. The main effect of group indicates that, if we ignore all other variables, musicians' scores were significantly higher than controls. The main effect of Hand ($F_{(1)} = 1.00$, $p = .318$, $\eta_p^2 = .008$) was not significant, showing that there were no differences between performance with the right and left hand. There was a significant main effect of Condition ($F_{(1)} = 117.04$, $p < .001$, $\eta_p^2 = .478$), with higher scores for the uncrossed than the crossed condition.

With regard to interaction effects, there was no significant interaction between Hand and Condition ($F_{(1)} = 0.66$, $p = .416$, $\eta_p^2 = .005$), or between Hand and Group ($F_{(1)} = 1.00$, $p < .318$, $\eta_p^2 = .008$), while there was a significant interaction between Condition and Group ($F_{(1)} = 57.89$, $p < .001$, $\eta_p^2 = .311$) with respect to the number of correct responses. The latter interaction means that uncrossed and crossed conditions had a different effect on performance in musicians and controls. Finally, there was no significant interaction between Hand, Condition, and Group ($F_{(1)} = 0.99$, $p = .321$, $\eta_p^2 = .008$).

Post hoc analyses indicated significant differences between musicians and controls, both in uncrossed [$t(128) = -2.55$, $p = .012$, $d = 0.45$] and crossed [$t(128) = -8.02$, $p < .001$, $d = 1.41$] conditions. Furthermore, two paired-sample *t* tests showed significant differences between uncrossed and crossed conditions, both among the controls [$t(64) = 11.09$, $p < .001$, $d = 1.37$] and the musicians [$t(64) = 2.88$, $p = .005$, $d = 0.35$]. Although musicians had higher scores than controls in both conditions (group effect), the effect size was higher in the crossed condition (large) than the uncrossed condition (small). Furthermore, although the differences between the uncrossed and crossed conditions were significant both for controls and musicians (condition effect), the effect size of this difference was small for musicians and large for controls (Figure 1).

CUD (Difference in the Overall Number of Errors between Uncrossed and Crossed Tasks)

There was a significant difference with a large effect size between the controls and musicians in the number of errors between uncrossed and crossed tasks [$t(128) = 7.85$, $p < .001$, $d = 1.38$]. The CUD was lower in the musicians ($M = 0.91$, $SD = 2.27$) than in the controls ($M = 4.85$, $SD = 3.34$).

The comparison of the CUD values explicitly shows that the two groups differed in the crossed condition.

Moreover, the distribution of participants who performed the task without making any mistakes across groups was not equal [$\chi^2_{(1)} = 60.27$, $p < .001$], with 7 (10.8 %) controls and

Table 1. Fingertip localization test, with mean correct scores (standard deviations and percentages) for each hand condition

Hand	Right		Left		Total	
Condition	Uncrossed	Crossed	Uncrossed	Crossed	Uncrossed	Crossed
Group						
Musicians	47.89 (0.40) (99.77%)	47.46 (1.16) (98.87%)	47.88 (0.37) (99.75%)	47.48 (1.16) (98.91%)	47.88 (0.34) (99.76%)	47.47 (1.16) (98.89%)
Controls	47.72 (0.57) (99.41%)	45.49 (2.35) (94.77%)	47.71 (0.55) (99.39%)	45.17 (2.10) (94.1%)	47.71 (0.41) (99.4%)	45.33 (1.81) (94.43%)

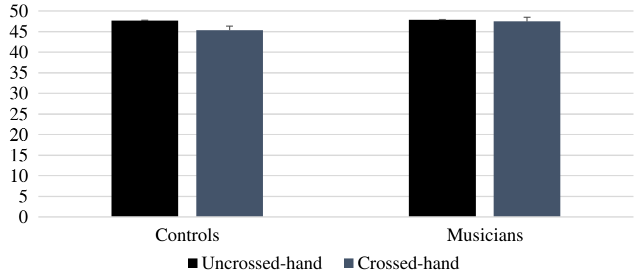

Fig. 1 . Number of correct responses related to Group × Condition. The error bars depict the standard error of the mean.

51 (78.5%) musicians; 14 musicians and 54 non-musicians made at least one error.

Individual Variables

As for the potential effect of personal variables on performance within the musician group (error vs. no-error), there were no significant differences in terms of handedness, age at onset of musical practice, and daily duration of training (Table 2). Regarding handedness, 54 of the 65 musicians had the Edinburgh Handedness Inventory laterality index ≥ 80; the musician group included 7 ambidextrous and 4 left-handed subjects. Moreover, there was no significant association between errors vs. no-errors and type of professional work [$\chi^2_{(1)} = 0.11, p = .736$], instrument played [$\chi^2_{(3)} = 2.05, p = .563$], or the presence of family musicians during childhood [$\chi^2_{(1)} = 0.53, p = .468$] (Table 3).

Based on these findings, musicians' performance is apparently not influenced by individual variables.

Correlations between Age and Scores in the Control Group

Within the control group, age was not associated with the number of correct responses in the uncrossed condition ($r = -.09$, $p = .487$), but was significantly and negatively associated with the number of correct responses in the crossed condition ($r = -.31$, $p = .011$) and significantly and positively associated with CUD ($r = .27$, $p = .028$).

These findings indicate that, in the control group, the number of errors in the crossed condition increases with increasing age.

DISCUSSION

In the present research, efforts were made to verify if playing a musical instrument is associated with enhanced interaction between the two hemispheres in older healthy subjects. Our results indicate that, in contrast to age-matched control subjects, professional musicians perform significantly better on the test of interhemispheric transfer.

It is worth mentioning that the fingertip cross-localization test has proven to be a reliable behavioral index of the functional effectiveness of interhemispheric communication. Since the scores obtained from the crossed test were significantly lower than the scores obtained from the uncrossed test, regardless of the hand used, the experimental paradigm supports the hypothesis of greater difficulty in the crossed interhemispheric condition and suggests that transfer of information from one hemisphere to another implies a significant loss of accuracy. Therefore, the degree of difference between the uncrossed and crossed conditions can be considered an adequate measure of information transfer processes.

In interpreting our results, it must be underlined that the musicians we examined showed a ceiling effect, which could indicate that the finger cross-localization test lacked sensitivity. The significant group difference in CUD indicates that the test was adequate to reveal differences between musicians and control subjects in interhemispheric transfer efficiency. Because the task measures (number of crossed errors and CUD) were significantly associated with age in the non-musician group, it is likely that the non-musician group declined in this measure of interhemispheric transfer as a consequence of increasing age. Given the evidence in the literature that music affects the corpus callosum, the data could be interpreted as demonstrating that in musicians, the efficiency of interhemispheric communication is protected from age-related decline. However, it should be noted that the ceiling effect may have obscured age-related decline in musicians. In short, the ceiling effect does not allow us to distinguish between a stable non-age-related group difference and a group difference related to significantly less impairment in performance in musicians than non-musicians. In other words, younger musicians may already enjoy a much higher level of interhemispheric efficiency which also reduces with age. A longitudinal investigation or the use of a more complex transfer test would help determine whether music playing confers specific protection from age-related changes in interhemispheric connectivity.

Table 2. No effect of individual variables on interhemispheric transfer performance within the musician group (no-error vs. error group)

	No error ($n = 51$)		Error ($n = 14$)		*t*-test	
Group ($n = 65$)	Mean	SD	Mean	SD	t (63)	p
Handedness	85.10	28.45	80.00	36.58	0.56	.579
Age at onset of musical practice	9.92	4.14	9.86	3.18	0.05	.957
Daily duration of training extrapolated across lifetime	4.10	1.49	4.07	1.49	0.06	.953

Table 3 . Contingency table showing no effect of individual variables on interhemispheric transfer performance within the musician group (no-error vs. error group)

	Professional activity		Musical instrument				
Groups	Orchestral players	Teachers	Keyboards	Strings	Brass	Multi-instrumentalist	Musicians in family during childhood
No error ($n = 51$)	34	17	11	11	5	24	20
Error ($n = 14$)	10	4	2	4	3	5	7

It should also be noted that the test requires the transfer of both tactile and motor information and that, in our investigation, musicians obtained higher scores than controls, not only in the crossed condition but also in the uncrossed condition. Superior tactile and motor performance have previously been reported in professional musicians in comparison to non-musicians, and these findings were assumed to arise from cortical reorganization induced by musical training (Fling & Seidler, 2011; Ragert, Schmidt, Altenmüller, & Dinse, 2004). However, since this study is concerned with CUD and the crossed scores are significantly lower than the uncrossed ones, it is likely that this suggestion is not critical to data interpretation: tactile acuity and motor ability cannot explain the excellent performance in the uncrossed task, regardless of hand used and the decrease of scores in the crossed task.

Based on this experimental paradigm, we can conclude that the data of our study present evidence for more efficient interhemispheric transfer of tactile sensory information in older musicians compared to non-musicians; moreover, they suggest that musical practice improves connectivity between the two hemispheres.

Our findings are in accordance with studies showing that playing an instrument may influence neuroplasticity (Münte, Altenmüller, & Jäncke, 2002; Wan & Schlaug, 2010). By now, it is well documented that making music is accompanied by a remarkable rearrangement of brain structures (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Herholz & Zatorre, 2012; Hyde et al., 2009; Schlaug, 2015). This brain reorganization concerns both gray and white matter and seems to be justified by the peculiar complexity of musical practice: performing music necessitates a wide array of brain regions, which must work in a coordinated manner throughout both hemispheres (Peretz & Zatorre, 2005). In this perspective, the accuracy of interhemispheric exchanges plays an irreplaceable role (Schulte & Müller-Oehring, 2010; Moore, Schaefer, Bastin, Roberts, & Overy, 2014).

Changes induced by musical training may justify the protective benefits on cognition documented by current research (Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh, 2007; Diaz Abrahan, Shifres, & Justel, 2019; Hanna-Pladdy & MacKay, 2011; Koelsch, 2009). For example, individualized piano instruction enhanced executive functioning and working memory in musically naïve older adults aged 60–85 years (Seinfeld, Figueroa, Ortiz-Gil, & Sanchez-Vives, 2013). In this view, making music is considered a factor that can mitigate or even prevent the consequences of brain aging (Fauvel, Groussard, Eustache, Desgranges, & Platel, 2013; Jäncke, 2013). Furthermore, musical training protects aging individuals from pathological cognitive decline. In a population-based twin study (Balbag, Pedersen, & Gatz, 2014), playing a musical instrument was significantly associated with less likelihood of dementia and cognitive impairment, supporting suggestions that differences observed between musician and non-musician twins are likely due to musical training rather than pre-existing biological differences (de Manzano & Ullén, 2018). From this point of view, music playing has been considered a transformative technology of the mind (Patel, 2019). In other words, making music appears to preserve brain functions (Rogenmoser, Kernbach, Schlaug, & Gaser, 2017).

These effects of individual musical expertise on brain connectome and cognitive functions can be of great significance with regard to brain aging. There is noteworthy inter-individual variability in aging (Raz, Ghisletta, Rodrigue, Kennedy, & Lindenberger, 2010), a finding that has been interpreted in relation to the notion of reserve capacity: brain reserve is thought to be related to the structural characteristics of the individual nervous system, and cognitive reserve to more efficient configuration of the neural network (Stern, 2009; Valenzuela, 2008). In this view, the same number of neurons can form networks that are connected in diverse ways and a well-connected network can more easily mitigate the effects of aging (Madden et al., 2009; Raz et al., 2010). Thus, the same degree of brain atrophy may manifest itself in distinctly different ways in different individuals (Barulli & Stern, 2013; Park & Reuter-Lorenz, 2009). A growing body of literature indicates that interventions with the capacity to integrate multiple neural networks may be an effective way to enhance reserve capacity (Stern, 2009), as occurs with musical training (Boyke, Driemeyer, Gaser, Büchel, & May, 2008). Through musical exercise, neuronal networks began to operate in an integrated manner (Bangert & Altenmuller, 2003; Bangert et al., 2006; Baumann et al., 2007). It is reasonable to assume that differences in the efficiency of the configuration of neural networks induced by musical training may lead to the differences in brain-aging profiles found for musicians (Balbag et al., 2014; Rogenmoser et al., 2017). Musical engagement seems to shape brain structures in such a way as to maintain better reserve capacity (Hanna-Pladdy & Gajewski, 2012). For example, musicians showed no or smaller decreases in grey matter density in the frontal cortex compared with non-musicians (Jäncke, 2013; Sluming et al., 2002). In our opinion, musical performance can promote a similar use-dependent retention of white matter involving the corpus callosum: making music may be able to protect the efficiency of the corpus callosum (Moore et al., 2014). Brain plasticity depends, in large part, on experiences that have taken place over the course of a lifetime and continue throughout the individual's life if adequate incentives are available (Park & Bischof, 2013). Music could be an incentive of this kind (Fukui & Toyoshima, 2008).

A limitation of our study is that the participants did not undergo in-depth neuropsychological assessment, which prevents any consideration of the relationships between individual interhemispheric information transfer capacity and cognitive performance. The findings of our study do not allow us to ascertain the cognitive significance of interhemispheric transfer efficiency. However, it should be underlined that, in comparison to the control subjects, a significant percentage of the musicians performed the transfer test without errors. We hypothesize that individuals who maintain interhemispheric transfer test performance at levels similar to those achieved at younger ages may have avoided any negative influence of aging on the efficiency of their brain function. To confirm this hypothesis – that musicians are able to demonstrate both successful aging and perform significantly better on interhemispheric transfer tests than subjects with typical aging – further research is required.

Furthermore, it is important to bear in mind that our data refer only to the transfer of tactile information and cannot be generalized to other functions. In fact, the corpus callosum should be considered a collection of fiber bundles with specific functions and structural properties, rather than a single bundle of fibers (Aboitiz & Montiel, 2003; Sperry, Gazzaniga, & Bogen, 1969). Therefore, it is possible that the analysis of other modes of transfer might provide different results in relation to the functional differences of the different subunits contained within the corpus callosum. Further research would be useful in order to establish whether interhemispheric transfer tests are reliable and easy-to-use clinical tools for monitoring aging-related brain changes.

Another question raised by our study concerns the relationship between musical expertise and the efficiency of callosal functions (Merrett, Peretz, & Wilson, 2013). In the available scientific literature, brain changes due to musical training have been shown to correlate with a number of variables linked to individual musical competence: musical instrument played (e.g., the sensorimotor representation of the hands is different for violinists and pianists); age of onset (which distinguishes musicians who began their musical training before or after 7 years of age); duration and intensity of training (which could differentiate professional musicians from those who just play for fun); and so on (Bangert & Schlaug, 2006; Skoe & Kraus, 2012; Vaquero et al., 2016). Our study has not been able to discriminate between the roles of these different variables in individual expertise. It must be underlined that the musicians we examined showed a ceiling effect, which can prevent correct analysis of the data, that is, differences may have been non-significant due to the ceiling effect. It remains to be assessed whether the role of the various individual factors can be better revealed using a more complex interhemispheric transfer test. However, it is also possible that the expertise acquired over years of continuous musical practice by professional musicians can reduce the importance of individual differences (Oechslin, Van De Ville, Lazeyras, Hauert, & James, 2013).

CONCLUSION

One of the most promising areas of current research is the identification of strategies, which can favorably alter plasticity to cope with age-related changes (Christie et al., 2017; Gow et al., 2012; Piccirilli, Pigliautile, Arcelli, Baratta & Ferretti, 2019; Wirth, Haase, Villeneuve, Vogel, & Jagust, 2014). The literature suggests that music is one of the most effective interventions for positively shaping organization in the aging brain (Diaz Abrahan et al., 2019; Hanna-Pladdy & Gajewski, 2012; Jäncke, 2013; Rogenmoser et al., 2017; Seinfeld et al., 2013). In our study, older professional musicians made significantly fewer errors on the tactile interhemispheric transfer test than age-matched non-musicians. This finding is in line with a great deal of investigations showing that individuals with extensive musical training have a larger corpus callosum. It may indicate a relationship between music playing, music-induced changes in plasticity, and the efficiency of interhemispheric communication.

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CONFLICT OF INTEREST

The authors have nothing to disclose.

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REFERENCES

Aboitiz, F. & Montiel, J. (2003). One hundred million years of interhemispheric communication: The history of the corpus callosum. *Brazilian Journal of Medical and Biological Research*, *36*, 409–420. doi: 10.1590/s0100-879x2003000400002

Balbag, M.A., Pedersen, N.L., & Gatz, M. (2014). Playing a musical instrument as a protective factor against dementia and cognitive impairment: A population-based twin study. *International Journal of Alzheimer's Disease*, *2014*, 836748. doi: 10.1155/2014/836748

Bangert, M. & Altenmuller, E.O. (2003). Mapping perception to action in piano practice: A longitudinal DC-EEG study. *BMC Neuroscience*, *4*, 26. doi: 10.1186/1471-2202-4-26

Bangert, M., Peschel, T., Schlaug, G., Rotte, M., Drescher, D., Hinrichs, H., . . . , Altenmüller, E. (2006). Shared networks for auditory and motor processing in professional pianista: Evidence from fMRI conjunction. *Neuroimage*, *30*, 917–926. doi: 10.1016/j.neuroimage.2005.10.044

Bangert, M. & Schlaug, G. (2006). Specialization of the specialized in features of external human brain morphology. *The European Journal of Neuroscience*, *24*, 1832–1834. doi: 10.1111/j.1460-9568.2006.05031.x

Barulli, D. & Stern, Y. (2013). Efficiency, capacity, compensation, maintenance, plasticity: Emerging concepts in cognitive reserve. *Trends in Cognitive Sciences*, *17*, 502–509. doi: 10.1016/j.tics.2013.08.012

Baumann, S., Koeneke, S., Schmidt, C.F., Meyer, M., Lutz. K., & Jäncke, L.L. (2007). A network for audio-motor coordination in skilled pianists and non-musicians. *Brain Research*, *1161*, 65–78. doi: 10.1016/j.brainres.2007.05.045

Bellis, T.J. & Wilber, L.A. (2001). Effects of aging and gender on interhemispheric function. *Journal of Speech, Language and Hearing Research*, *44*, 246–263. doi: 10.1044/1092-4388(2001/021)

Bennett, I.J. & Madden, D.J. (2014). Disconnected aging: Cerebral white matter integrity and age-related differences in cognition. *Neuroscience*, *276*, 187–205. doi: 10.1016/j.neuroscience.2013.11.026

Bentin, S., Sahar, A., & Moscovitch, M. (1984). Intermanual information transfer in patients with lesions in the trunk of the corpus callosum. *Neuropsychologia*, *22*, 601–611. doi: 10.1016/0028-3932(84)90024-1

Bogen, J.E. (1979). The callosal syndrome. In K.M. Heilman & E. Valenstein (Eds.), *Clinical neuropsychology* (pp. 295–338). New York: Oxford University Press.

Boyke, J., Driemeyer, J., Gaser, C., Büchel, C., & May, A. (2008). Training-induced brain structure changes in the elderly. *The Journal of Neuroscience*, *28*, 7031–7035. doi: 10.1523/JNEUROSCI.0742-08.2008

Boyson, A. (2013). The effect of age on interhemispheric transfer time: An event related potential study. *The Plymouth Student Scientist*, *6*, 79–97.

Brown, W.S. & Paul, L.K. (2019). The neuropsychological syndrome of agenesis of the corpus callosum. *Journal of International Neuropsychological Society*, *25*, 324–330. doi: 10.1017/S135561771800111X

Bugos, JA., Perlstein, W.M., McCrae, C.S., Brophy, T.S., & Bedenbaugh, P.H. (2007). Individualized piano instruction enhances executive functioning and working memory in older adults. *Aging and Mental Health*, *11*, 464–471. doi: 10.1080/13607860601086504

Caillé, S., Sauerwein, H.C., Schiavetto, A., Villemure, J.G., & Lassonde M. (2005). Sensory and motor interhemispheric integration after section of different portions of the anterior corpus callosum in nonepileptic patients. *Neurosurgery*, *57*, 50–59. doi: 10.1227/01.neu.0000163089.31657.08

Christie, G.J., Hamilton, T., Manor, B.D., Farb, N.A.S., Farzan, F., Sixsmith, A., . . . , Moreno, S. (2017). Do lifestyle activities protect against cognitive decline in aging? A review. *Frontiers in Aging Neuroscience*, *9*, 381. doi: 10.3389/fnagi.2017.00381

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Davis, S.W., Kragel, J.E., Madden, D.J., & Cabeza, R. (2012). The architecture of cross-hemispheric communication in the aging brain: Linking behavior to functional and structural connectivity. *Cerebral Cortex*, *22*, 232–242. doi: 10.1093/cercor/bhr123

de Manzano, Ö. & Ullén, F. (2018). Same genes, different brains: Neuroanatomical differences between monozygotic twins discordant for musical training. *Cerebral Cortex*, *28*, 387–394. doi: 10.1093/cercor/bhx299

Devinsky, O. & Laff, R. (2003). Callosal lesions and behavior: History and modern concepts. *Epilepsy & Behavior*, *4*, 607–617. doi: 10.1016/j.yebeh.2003.08.029

Diaz Abrahan V, Shifres F, & Justel N. (2019). Cognitive benefits from a musical activity in older adults. *Frontiers in Psychology*, *10*, 652. doi: 10.3389/fpsyg.2019.00652

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science*, *270*, 305–307. doi: 10.1126/science.270.5234.305

Fabbro, F., Pesenti, S., Facoetti, A., Bonanomi, M., Libera, L., & Lorusso, M.L. (2001). Callosal transfer in different subtypes of developmental dyslexia. *Cortex*, *37*, 65–73. doi: 10.1016/s0010-9452(08)70558-6

Fabri, M., Del Pesce, M., Paggi, A., Polonara, G., Bartolini, M., Salvolini, U., & Manzoni, T. (2005). Contribution of posterior corpus callosum to the interhemispheric transfer of tactile information. *Cognitive Brain Research*, *24*, 73–80. doi: 10.1016/j.cogbrainres.2004.12.003

Fauvel, B., Groussard, M., Eustache, F., Desgranges, B., & Platel, H. (2013). Neural implementation of musical expertise and cognitive transfers: Could they be promising in the framework of normal cognitive aging? *Frontiers in Human Neuroscience*, *7*, 693. doi: 10.3389/fnhum.2013.00693

Fling, B.W. & Seidler, R.D. (2011). Fundamental differences in callosal structure, neuro-physiologic function, and bimanual control in young and older adults. *Cerebral Cortex*, *22*, 2643–2652. doi: 10.1093/cercor/bhr349

Fukui H. & Toyoshima K. (2008). Music facilitate the neurogenesis, regeneration and repair of neurons. *Medical Hypotheses*, *71*, 765–769. doi: 10.1016/j.mehy.2008.06.019

Funnell, M.G., Corballis, P.M., & Gazzaniga, M.S. (2000). Cortical and subcortical interhemispheric interactions following partial and complete callosotomy. *Archives of Neurology*, *57*, 185–189. doi: 10.1001/archneur.57.2.185

Galin, D., Johnston, J., Nakell, L., & Herron, J. (1979). Development of the capacity for tactile information transfer between hemispheres in normal children. *Science*, *204*, 1330–1332. doi: 10.1126/science.451542

Gaser, C. & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *The Journal of Neuroscience*, *23*, 9240–9245. doi: 10.1523/JNEUROSCI.23-27-09240.2003

Gazzaniga, M.S. (2000). Cerebral specialization and interhemispheric communication: Does the corpus callosum enable the human condition? *Brain*, *123*, 1293–1326. doi: 10.1093/brain/123.7.1293

Gazzaniga, M.S. (2005). Forty-five years of split-brain research and still going strong. *Nature. Reviews of Neuroscience*, *6*, 653–659. doi: 10.1038/nrn1723

Geffen, G., Nilsson, J., Quinn, K., & Teng, E.L. (1985). The effect of lesions of the corpus callosum on finger localization. *Neuropsychologia*, *23*, 497–514. doi: 10.1016/0028-3932(85)90004-1

Gow, A.J., Bastin, M.E., Muñoz Maniega, S., Valdés Hernández, M.C., Morris, Z., Murray, C., . . . , Wardlaw, J.M. (2012). Neuroprotective lifestyles and the aging brain: Activity, atrophy, and white matter integrity. *Neurology*, *79*, 1802–1808. doi: 10.1212/WNL.0b013e3182703fd2

Hallam, B.J., Brown, W.S., Ross, C., Buckwalter, J.G., Bigler, E.D., Tschanz, J., . . . Breitner, J.C.S. (2008). Regional atrophy of the corpus callosum in dementia. *Journal of International Neuropsychological Society*, *14*, 414–423. doi: 10.1017/S1355617708080533

Halwani, G., Loui, T., Rüber, P., & Schlaug, G. (2011). Effects of practice and experience on the arcuate fasciculus: Comparing singers, instrumentalists and non musicians. *Frontiers in Psychology*, *2*, 156. doi: 10.3389/fpsyg.2011.00156

Hanna-Pladdy, B. & Gajewski, B. (2012). Recent and past musical activity predicts cognitive aging variability: Direct comparison with general lifestyle activities. *Frontiers in Human Neuroscience*, *6*, 198. doi: 10.3389/fnhum.2012.00198

Hanna-Pladdy, B. & MacKay, A. (2011). The relation between instrumental musical activity and cognitive aging. *Neuropsychology*, *25*, 378–386. doi: 10.1037/a0021895

Hasan, K.M., Kamali, A., Kramer, L.A., Papnicolaou, A.C., Fletcher, J.M., & Ewing-Cobbs, L. (2008). Diffusion tensor quantification of the human midsagittal corpus callosum subdivisions across the lifespan. *Brain Research*, *1227*, 52–67. doi: 10.1016/j.brainres.2008.06.030

Herholz, S.C. & Zatorre, R.J. (2012). Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron*, *76*, 486–502

Hofer, S. & Frahm, J. (2006). Topography of the human corpus callosum revisited: Comprehensive fiber tractography using diffusion tensor magnetic resonance imaging. *Neuroimage*, *32*, 989–994. doi: 10.1016/j.neuroimage.2006.05.044

Hou, J. & Pakkenberg, B. (2012). Age-related degeneration of corpus callosum in the 90+ years measured with stereology. *Neurobiology of Aging*, *33*, 1009.e1–1009.e9. doi: 10.1016/j.neurobiolaging.2011.10.017

Hyde, K.L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A.C., & Schlaug, G. (2009). Musical training shapes structural brain development. *The Journal of Neuroscience*, *29*, 3019–3025. doi: 10.1523/JNEUROSCI.5118-08.2009

Innocenti, G.M. (1981). The development of interhemispheric connections. *Trends in Neurosciences*, *4*, 142–144. doi: 10.1016/0166-2236(81)90047-3

Jäncke, L. (2009). Music drives brain plasticity. *F1000 Biology Reports*, *1*, 78. doi: 10.3410/B1-78

Jäncke, L (2013) Music making and the aging brain. *Zeitschrift für Neuropsychologie*, *24*, 113–121. doi: 10.1024/1016-264X/a000095

Jeeves, M.A. & Moes P. (1996). Interhemispheric transfer time differences related to aging and gender. *Neuropsychologia*, *34*, 627–636. doi: 10.1016/0028-3932(95)00157-3

Johansen-Berg, H., Della-Maggiore, V., Behrens, T.E., Smith, S.M., & Paus, T.J. (2007). Integrity of white matter in the corpus callosum correlates with bimanual co-ordination skills. *Neuroimage*, *36*, T16–T21. doi: 10.1016/j.neuroimage.2007.03.041

Kennedy, K.M. & Raz, N. (2009). Aging white matter and cognition: Differential effects of regional variations in diffusion properties on memory, executive functions, and speed. *Neuropsychologia*, *47*, 916–927. doi: 10.1016/j.neuropsychologia.2009.01.001

Koelsch, S. (2009). A neuroscientific perspective on music therapy. *Annals of New York Academy of Sciences*, *1169*, 374–384. doi: 10.1111/j.1749-6632.2009.04592.x

Lassonde, M., Sauerwein, H., Geoffroy, G., & Décarie, M. (1986). Effects of early and late transection of the corpus callosum in children: A study of tactile and tactuomotor transfer and integration. *Brain*, *109*, 953–967. doi: 10.1093/brain/109.5.953

Madden, D.J., Spaniol, J., Costello, M.C., Bucur, B., White, L.E., Cabeza, R., . . . , Huettel, S.A. (2009). Cerebral white matter integrity mediates adult age differences in cognitive performance. *Journal of Cognitive Neuroscience*, *21*, 289–302. doi: 10.1162/jocn.2009.21047

Magni, E., Binetti, G., Bianchetti, A., Rozzini, R., & Trabucchi M. (1996). Mini-mental state examination: A normative study in Italian elderly population. *European Journal of Neurology*, *3*, 198–202. doi: 10.1111/j.1468-1331.1996.tb00423.x

Merrett, D.L., Peretz, I., & Wilson, S.J. (2013). Moderating variables of music training-induced neuroplasticity: A review and discussion. *Frontiers in Psychology*, *4*, 606. doi: 10.3389/fpsyg.2013.00606

Moore, E., Schaefer, R.S., Bastin, M.E., Roberts, N., & Overy K. (2014). Can musical training influence brain connectivity? Evidence from diffusion tensor MRI. *Brain Sciences*, *4*, 405–427. doi: 10.3390/brainsci4020405

Münte, T.F., Altenmüller, E., & Jäncke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience*, *3*, 473–478. doi: 10.1038/nrn843

Myers, J.J. & Sperry, R.W. (1985). Interhemispheric communication after section of the forebrain commissures. *Cortex*, *21*, 249–260. doi: 10.1016/s0010-9452(85)80030-7

Oechslin, M.S., Imfeld, A., Loenneker, T., Meyer, M., & Jäncke, L. (2010). The plasticity of the superior longitudinal fasciculus as a function of musical expertise: A diffusion tensor imaging study. *Frontiers in Human Neuroscience*, *3*, 76. doi: 10.3389/neuro.09.076.2009

Oechslin, M.S., Van De Ville, D., Lazeyras, F., Hauert, C.A., & James, C.E. (2013). Degree of musical expertise modulates higher order brain functioning. *Cerebral Cortex*, *23*, 2213–2224. doi: 10.1093/cercor/bhs206

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113. doi: 10.1016/0028-3932(71)90067-4

O'Leary, D.S. (1980). Development study of interhemispheric transfer in children aged 5 to 10. *Child Development*, *51*, 743–750.

O'Sullivan, M., Jones, D.K., Summers, P.E., Morris, R.G., Williams, S.C.R., & Markus, H.S. (2001). Evidence for cortical "disconnection" as a mechanism of age-related cognitive decline. *Neurology*, *57*, 632–638. doi: 10.1212/wnl.57.4.632

Oztürk, A.H., Tasçioglu, B., Aktekin, M., Kurtoglu, Z., & Erden, I. (2002). Morphometric comparison of the human corpus callosum in professional musicians and non-musicians by using in vivo magnetic resonance imaging. *Journal of Neuroradiology*, *29*, 29–34.

Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L.E., Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature*, *392*, 811–814. doi: 10.1038/33918

Park, D.C. & Bischof, G.N. (2013). The aging mind: Neuroplasticity in response to cognitive training. *Dialogues in Clinical Neuroscience*, *15*, 109–119.

Park, D.C. & Reuter-Lorenz, P. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*, 173–196. doi: 10.1146/annurev.psych.59.103006.093656

Patel, A.D. (2019). Music as a transformative technology of the mind: An update. In H. Honing (Ed.), *The origins of musicality* (pp. 141–156). Cambridge, MA: MIT Press.

Penke, L., Muñoz Maniega, S., Houlihan, L.M., Murray, C., Gow, A.J., Clayden, J.D., . . . , Deary, I.J. (2010). White matter integrity in the splenium of the corpus callosum is related to successful cognitive aging and partly mediates the protective effect of an ancestral polymorphism in ADRB2. *Behavior Genetics*, *40*, 146–156. doi: 10.1007/s10519-009-9318-4

Peretz, I. & Zatorre, R.J. (2005). Brain organization for music processing. *Annual Review of Psychology*, *56*, 89–114. doi: 10.1146/annurev.psych.56.091103.070225

Persson, J., Nyberg, L., Lind, J., Larsson, A., Nilsson, L.G., Ingvar, M., & Buckner, R.L. (2006). Structure-function correlates of cognitive decline in aging. *Cerebral Cortex*, *16*, 907–915. doi: 10.1093/cercor/bhj036

Piccirilli, M., D'Alessandro, P., Germani, A., Boccardi, V., Pigliautile, M., Ancarani, V., & Dioguardi, M.S. (2020). Age-related decline in interhemispheric transfer of tactile information: The fingertip cross-localization task. *Journal of Clinical Neuroscience*, *77*, 75–80. doi: 10.1016/j.jocn.2020.05.035

Piccirilli, M., Finali, G., & Sciarma, T. (1989). Negative evidence of difference between right- and left- handers in interhemispheric transfer of information. *Neuropsychologia*, *27*, 1023–1026. doi: 10.1016/0028-3932(89)90079-1

Piccirilli, M., Pigliautile, M., Arcelli, P., Baratta, I., & Ferretti, S. (2019). Improvement in cognitive performance and mood in healthy older adults: A multimodal approach. *European Journal of Ageing*, *16*, 327–336. doi: 10.1007/s10433-019-00503-3

Poffenberger, A.T. (1912). Reaction time to retinal stimulation with special reference to the time lost in conduction through nervous centers. *Archives of Psychology*, *23*, 1–73

Polonara, G., Mascioli, G., Foschi, N., Salvolini, U., Pierpaoli, C., Manzoni, T., . . . , Barbaresi, P. (2015). Further evidence for the topography and connectivity of the corpus callosum: An FMRI study of patients with partial callosal resection. *Journal of Neuroimaging*, *25*, 465–473. doi: 10.1111/jon.12136

Quinn, K. & Geffen, G. (1986). The development of tactile transfer of information. *Neuropsychologia*, *24*, 793–804. doi: 10.1016/0028-3932(86)90078-3

Ragert, P., Schmidt, A., Altenmüller, E., & Dinse, H.R. (2004). Superior tactile performance and learning in professional pianists: Evidence for meta-plasticity in musicians. *The European Journal of Neuroscience*, *19*, 473–478. doi: 10.1111/j.0953-816x.2003.03142.x

Raz, N., Ghisletta, P., Rodrigue, K.M., Kennedy, K.M., & Lindenberger, U. (2010). Trajectories of brain aging in middle-aged and older adults: Regional and individual differences. *Neuroimage*, *51*, 501–511. doi: 10.1016/j.neuroimage.2010.03.020

Reuter-Lorenz, P.A. & Stanczak, L. (2000). Differential effects of aging on the functions of the corpus callosum. *Developmental Neuropsychology*, *18*, 113–137. doi: 10.1207/S15326942DN1801_7

Riise, J. & Pakkenberg, B. (2011). Stereological estimation of the total number of myelinated callosal fibers in human subjects. *Journal of Anatomy*, *218*, 277–284.

Roebuck, T.M., Mattson, S.N., & Riley, E.P. (2002). Interhemispheric transfer in children with heavy prenatal alcohol exposure. *Alcoholism: Clinical and Experimental Research*, *26*, 1863–1871. doi: 10.1097/01.ALC.0000042219.73648.46

Rogenmoser, L., Kernbach, J., Schlaug, G., & Gaser, C. (2017). Keeping brains young with making music. *Brain Structure and Function*, *223*, 297–305. doi: 10.1007/s00429-017-1491-2

Ryberg, C., Rostrup, E., Paulson, O.B., Barkhof, F., Scheltens P, van Straaten, E.C., . . . , LADIS Study Group. (2011). Corpus callosum atrophy as a predictor of age-related cognitive and motor impairment: A 3-year follow-up of the LADIS study cohort. *Journal of Neurological Sciences*, *307*, 100–105. doi: 10.1016/j.jns.2011.05.002

Salat, D.H., Tuch, D.S., Greve, D.N., van der Kouwe, A.J., Hevelone, N.D., Zaleta, A.K., . . . , Dale, A.M. (2005). Age-related alterations in white matter microstructure measured by diffusion tensor imaging. *Neurobiology of Aging*, *26*, 1215–1227. doi: 10.1016/j.neurobiolaging.2004.09.017

Salthouse, T.A. (2011). Neuroanatomical substrates of age-related cognitive decline. *Psychological Bulletin*, *137*, 753–784. doi: 10.1037/a0023262

Saron, C.D. & Davidson, R.J. (1989). Visual evoked potential measures of interhemispheric transfer times in humans. *Behavioural Neuroscience*, *103*, 1115–1138. doi: 10.1037//0735-7044.103.5.1115

Scally, B., Burke, M.R., Bunce, D., & Delvenne, J.F. (2018). Visual and visuomotor interhemispheric transfer time in older adults. *Neurobiology of Aging*, *65*, 69–76. doi: 10.1016/j.neurobiolaging.2018.01.005

Schlaug, G. (2015). Musicians and music making as a model for the study of brain plasticity. *Progress in Brain Research*, *217*, 37–55. doi: 10.1016/bs.pbr.2014.11.020

Schlaug, G., Jäncke, L., Huang, Y., Staiger, J.F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, *33*, 1047–1055. doi: 10.1016/0028-3932(95)00045-5

Schmithorst, V.J. & Wilke, M. (2002). Differences in white matter architecture between musicians and non-musicians: A diffusion tensor imaging study. *Neuroscience Letters*, *321*, 57–60. doi: 10.1016/s0304-3940(02)00054-x

Schulte, T. & Müller-Oehring, E.M. (2010). Contribution of callosal connections to the interhemispheric integration of visuomotor and cognitive processes. *Neuropsychology Review*, *20*, 174–190. doi: 10.1007/s11065-010-9130-1

Schulte, T., Sullivan, E.V., Müller-Oehring, E.M., Adalsteinsson, E., & Pfefferbaum, A. (2005). Corpus callosal microstructural integrity influences interhemispheric processing: A diffusion tensor imaging study. *Cerebral Cortex*, *15*, 1384–1392. doi: 10.1093/cercor/bhi020

Seinfeld, S., Figueroa, H., Ortiz-Gil, J., & Sanchez-Vives, M.V. (2013). Effects of music learning and piano practice on cognitive function, mood and quality of life in older adults. *Frontiers in Psychology*, *4*, 810. doi: 10.3389/fpsyg.2013.00810

Skoe, E. & Kraus, N. (2012). A little goes a long way: How the adult brain is shaped by musical training in childhood. *The Journal of Neuroscience*, *32*, 11507–11510. doi: 10.1523/JNEUROSCI.1949-12.2012

Sluming, V., Barrick, T., Howard, M., Cezayirli, E., Mayes, A., & Roberts, N. (2002). Voxel-based morphometry reveals increased gray matter density in Broca's area in male symphony orchestra musicians. *Neuroimage*, *17*, 1613–1622. doi: 10.1006/nimg.2002.1288

Sperry, R.W., Gazzaniga, M.S., & Bogen, J.E. (1969). Interhemispheric relationships: The neocortical commissures syndromes of hemisphere disconnection. In P.J. Vinken & C.W. Bruyn (Eds.), *Handbook of clinical neurology* (pp. 273–290). Amsterdam: North Holland.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*, 2015–2028. doi: 10.1016/j.neuropsychologia.2009.03.004

Sullivan, E.V. & Pfefferbaum, A. (2006). Diffusion tensor imaging and aging. *Neuroscience and Biobehavioral Reviews*, *30*, 749–761. doi: 10.1016/j.neubiorev.2006.06.002

Tang, Y., Nyengaard, J.R., Pakkenberg, B., & Gundersen, H.J. (1997). Age-induced white matter changes in the human brain: A stereological investigation. *Neurobiology of Aging*, *18*, 609–615. doi: 10.1016/S0197-4580(97)00155-3

Thompson, P.M., Narr, K.L., Blanton, R.E., & Toga, A.W. (2003). Mapping structural alterations of the corpus callosum during brain development and degeneration. In E. Zaidel & M. Iacoboni (Eds.), *The parallel brain: The cognitive neuroscience of the corpus callosum* (pp. 93–130). Cambridge, MA: MIT Press.

Valenzuela, M.J. (2008). Brain reserve and the prevention of dementia. *Current Opinion in Psychiatry*, *21*, 296–302. doi: 10.1097/YCO.0b013e3282f97b1f

Vaquero, L., Hartmann, K., Ripollés, P., Rojo, N., Sierpowska, J., François, C., . . . , Altenmüller, E. (2016). Structural neuroplasticity in expert pianists depends on the age of musical training onset. *Neuroimage*, *126*, 106–119. doi:10.1016/j.neuroimage.2015.11.008

Wan, C.Y. & Schlaug, G. (2010). Music making as a tool for promoting brain plasticity across the life span. *Neuroscientist*, *16*, 566–577. doi: 10.1177/1073858410377805

Westerhausen, R., Kreuder, F., Woerner, W., Huster, R.J., Smit, C.M., Schweiger, E., & Wittling, W. (2006). Interhemispheric transfer time and structural properties of the corpus callosum. *Neuroscience Letters*, *409*, 140–145. doi: 10.1016/j.neulet.2006.09.028

Wirth, M., Haase, C.M., Villeneuve, S., Vogel, J., & Jagust, W.J. (2014). Neuroprotective pathways: Lifestyle activity, brain pathology, and cognition in cognitively normal older adults. *Neurobiology of Aging*, *35*, 1873–1882. doi: 10.1016/j.neurobiolaging.2014.02.015

Wolf, D., Fischer, F.U., Fesenbeckh, J., Yakushev, I., Lelieveld, I.M., Scheurich, A., . . . , Fellgiebel, A. (2012). Structural integrity of the corpus callosum predicts long-term transfer of fluid intelligence-related training gains in normal aging. *Human Brain Mapping*, *35*, 309–318. doi: 10.1002/hbm.22177

Zahr, N.M., Rohlfing, T., Pfefferbaum, A., & Sullivan, E.V. (2009). Problem solving, working memory, and motor correlates of association and commissural fiber bundles in normal aging: A quantitative fiber tracking study. *Neuroimage*, *44*, 1050–1062. doi: 10.1016/j.neuroimage.2008.09.046