Brain and Cognitive Differences between Musicians and Non-musicians

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Abstract

Playing a musical instrument requires a host of skills and therefore many brain regions are involved during musical performance. Because the brain is plastic, learning to play an instrument leads to structural and functional differences in the brain that consequently influence the performance.

This review discussed what structural and functional brain differences are present between musicians and non-musicians and compared studies that observed cognitive performances of musicians and non-musicians. It was expected that musicians show enhanced performance on cognitive domains closely related to musical abilities (i.e., auditory, visual, and reaction time performance) but also on cognitive domains that are less obviously associated with those abilities (i.e., memory, learning, thinking, attention, and expressive performance).

Enhanced auditory performances and shorter reaction times were found for musicians, but effects on visual performance are still inconsistent. Furthermore, in contrast to what was expected, results did not reveal better performances for memory and learning, thinking, attention or expressive abilities in musicians compared to non-musicians.

Future research should clarify whether these latter associations exist. Furthermore the direction of found associations should be explored, to determine whether musical training can actually function as a cognitive enhancer.

Keywords: Musicians – Brain – Structural – Functional- Cognition – Intelligence

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1. Introduction

Playing a musical instrument requires a host of skills. First, one should be able to read notes and has to translate this musical information in the right movements to perform a musical piece. Secondly, one has to receive auditory, visual, and tactile feedback from what he or she is playing to adjust his or her movement and therefore change the musical output. In addition, all this information has to be integrated to provide a unified image of the performance.

These skills call on many brain regions. The motor system controls the hands and fingers to manipulate the musical instrument and the auditory system processes the musical sounds (Jäncke, 2009). The sensory cortex receives tactile feedback from the finger placement on the instrument and the visual cortex collects visual feedback of one's own performance (Levitin & Tirovolas, 2009). Additionally, the visual cortex is involved in reading the musical notes. The cerebellum, the basal ganglia and the supplementary motor area are involved in rhythmical movement (Zatorre et al., 2007). The prefrontal cortex creates the expectations of the performance and the corpus callosum plays an important role in unifying the performance by connecting the two hemispheres (Levitin & Tirovolas, 2009). The hippocampus contributes to the memory of music and therefore plays an important role in the learning process. Finally, the cerebellum, the nucleus accumbens and the amygdala contribute to the emotional reaction to music (Levitin & Tirovolas, 2009). These regions are the core regions that are associated with playing a musical instrument and are represented in figure 1, page 7.

Musical experience and brain plasticity

The brain is the source of the entire performance but the experience itself also shapes the anatomy and physiology of the brain (Jäncke, 2009). This process is called 'brain plasticity' and entails any adjustment of a brain system to the environment or a performance, or is a compensation of impaired cerebral structures as a result of an injury or deafferentiation (Schlaug, 2001).

Because the brain is plastic, learning to play an instrument can lead to structural and functional differences in the brain which consequently influences the performance (Jäncke, 2009). Structural plasticity entails changes in the structure of the brain, whereas functional plasticity is about changes in neurophysiologic activation and associated behavioural consequences (Jäncke, 2009). Because professional musicians have developed the skills that are required to play a musical instrument, it is expected that structural and functional differences in the brain exist between musicians and non-musicians. In this case a musician is generally considered as a person that plays a musical instrument as their job or hobby and who has been training as an instrumentalist for a number of years while consistently practicing. A person who has never played any musical instrument and received no formal music lessons is considered as a non-musician. However, several researchers use different conditions for ascribing subjects to the non-musician or the musician group.

Musical experience and transfer effects

Hyde et al. (2009) suggest that the experience of playing a musical instrument can enhance skills in other areas as well. The enhancement of skills in other areas as a result of a certain experience is called 'transference'. When there is a close association between the training domain and the transfer domain it is called 'near transfer' (e.g., a professional pianist taps his fingers at a high rate, because he is used to fast finger movements while playing a musical piece). One refers to 'far transfer' if the association between the training domain and the transfer domain is less obvious (e.g., the same pianist has advanced mathematical abilities due to musical experience) (Hyde et al., 2009).

Because transference can appear as a result of experience, it is suggested by some researchers that musical experience can enhance cognitive performance as a result of changes in the brain (Hyde et al., 2009; Jäncke, 2009; Lappe, Herholz, Trainor, & Pantev, 2008). Cognition is the mental process involved in knowing, learning, and understanding things (Lezak, Howieson, & Loring, 2004). Lezak et al. (2004) describe receptive functions, memory and learning, thinking, and expressive functions as the four major classes of cognitive functioning. Additionally, attention and reaction time influence the efficiency of the cognitive performance (Lezak et al., 2004).

A way to explore whether musical experience is associated with cognitive performance is to compare the performance of musicians to non-musicians on cognitive tasks. It is expected that musicians differ from non-musicians in receptive functioning as auditory and visual performance, since these are skills that are used while playing a musical instrument. Furthermore, it is expected that musicians have faster reaction times, because refined and fast finger movements are required while playing an instrument. Some researchers, also suggest that musical experience can positively influence your intelligence (Anvari, Trainor, Woodside, & Levy, 2002; Schellenberg, 2004; 2006). However, since no direct relationship has been established so far, one should also consider the possibility that the relation is in reverse order. Predispositional intelligence and cognitive performance could influence the ability to learn how to play a musical instrument. Regardless of the direction of the association, it is expected that musicians show enhanced performance in memory and learning, thinking, attention and expressive functions, compared to non-musicians.

Research questions and hypotheses

In this review, after describing the search process (§2), an evaluation is given of studies that compare structural and functional brain characteristics of musicians to that of non-musicians (§3.1). It is interesting to look at this because insight in brain differences between musicians and non-musicians might contribute to more understanding about the mechanism that is responsible for any present relationship between cognitive performance and musical experience. The research questions are:

1. What structural differences exist between musicians and non-musicians?
2. What functional differences exist between musicians and non-musicians?

This review further explores whether observed differences in cognitive performance between musicians and non-musicians exist (§3.2). The hypotheses are:

3. Musicians perform better on auditory, visual, and reaction time tasks than non-musicians.
4. Musicians perform better on memory, learning, thinking, attention, and expressive tasks than non-musicians.

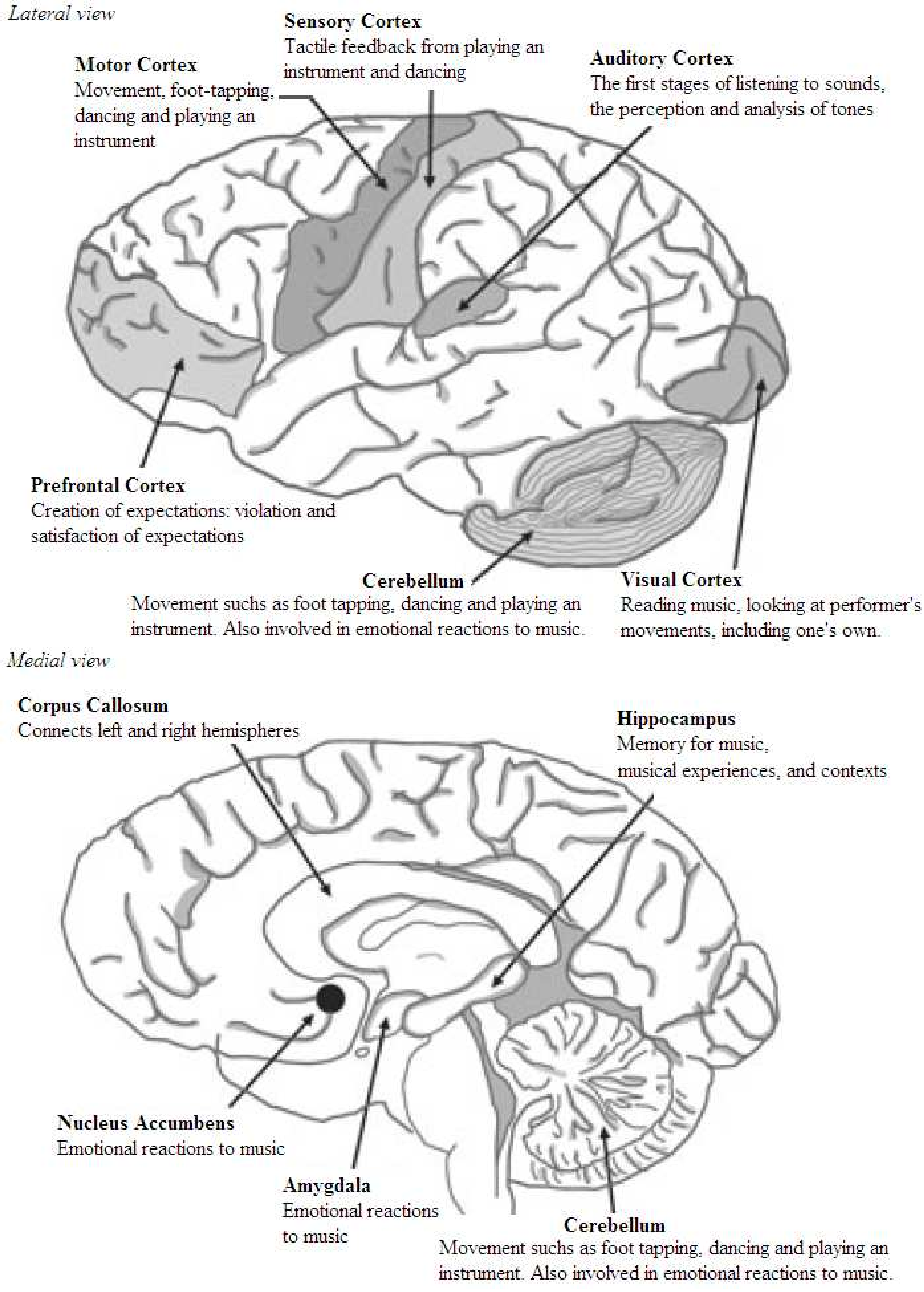
In the discussion, the answers on the research questions (§4.1; §4.2) and hypotheses (§4.3; §4.4) are critically evaluated and limitations of this review are mentioned (§4.5). Finally, recommendations for future research are made (§4.6).

2. Methods

Search process

In search for useful articles concerning brain and cognitive differences between musicians and non-musicians the following search engines were used: Pubmed, ScienceDirect, PsychInfo and the UvT Catalogue for Books. Keywords that were used in the search process were ‘musicians’, ‘brain’, ‘functional’, ‘structural’, and ‘cognition’. Animal studies were excluded from this review and only articles in English were used. Furthermore, during the reading process, many useful references in the articles attracted the attention and were consequently included in this review. This search process has been repeated several times because often new studies with renewing views appeared that contribute to a complete and up to date review.

Figure 1: T*he core brain regions associated with playing a musical instrument (Levitin & Tirovolas, 2009)*



3. Results

3.1. Structural and functional brain differences between musicians and non-musicians

Sensory cortex

The sensory system is one of the core regions that is involved in playing a musical instrument. Gaser and Schlaug (2003) observed structural gray matter brain differences in somatosensory areas between three matched groups of male subjects that differed in musical experience and practice intensity. The first group consisted of twenty professional musicians that were performing artists, full-time music teachers or conservatory students with a practice average of at least one hour a day. The second group of subjects were amateur musicians ($n=20$) that regularly played a musical instrument but did not have a musical profession. All musicians were keyboard players. The third group, consisting of non-musicians ($n=40$), had never played a musical instrument. Average practice times per day significantly differed between the three groups. The researchers found a positive correlation between somatosensory areas and musical experience ($p<.05$) which means that grey matter volume was highest in professional musicians, moderate in amateurs and lowest in non-musicians. This suggests that the amount of practice influences grey matter volumes in somatosensory areas.

Motor cortex

Amunts et al. (1997) compared the motor cortex of a group of professional male musicians ($n=21$) to the motor cortex of a group of male non-musicians ($n=30$) and found greater right intrasulcal length in the motor cortex in musicians ($p<.05$). The group of musicians consisted of keyboard and string players that either enrolled as a student in a music school or had a professional career in music. The non-musicians were matched for age and handedness and did not have any formal musical training, had never played a musical instrument, or played an instrument for less than one year after the age of ten. The greater right intrasulcal length in the motor cortex could be the result of more complex left hand movement required while playing a keyboard or a stringed instrument. Amunts et al. (1997) also found strong correlations between the time at which musical training had begun and right ($r=-.63$, $p<.01$) and left ($r=-.60$, $p<.01$) intrasulcal length of the posterior bank of the precentral gyrus. The previously mentioned study of Gaser and Schlaug (2003) observed positive correlations between musical experience and gray matter in primary motor and premotor areas ($p<.05$). These results suggest that years of experience and amount of practice both influence the amount of structural differences in the motor cortex.

Besides structural differences, researchers also reported functional differences in the motor cortex. Lotze et al. (2003) observed cerebral blood oxygen level dependent (BOLD) signal changes using functional Magnetic Resonance Imaging (fMRI) during the performance of sixteen bars of a familiar piece from Mozart. Musicians (n=8) played in a professional orchestra, started practice early in life, and still practiced without a period of interruption. Amateurs (n=8) practiced significantly less years (p<.001) compared to the professional musicians. Both groups showed activations in the secondary motor areas and the premotor cortex. In professionals this study found only contra lateral motor activations in the hand area, whereas primary motor cortical activities in amateurs were bilateral.

Meister et al. (2005) compared cerebral activation in musicians to non-musicians while playing simple and complex motor sequences on a keyboard. They observed BOLD signal changes using fMRI during the sequence performances. The group of musicians consisted of twelve students of a music school that played the piano as their principal instrument. The control group consisted of twelve subjects without any experience in music performance. Meister et al. (2005) showed higher activations of the presupplementary motor area (pre-SMA) and the rostral part of the dorsal premotor cortex in complex motor sequences compared to simple motor sequences in musicians, but not in non-musicians. This difference is possibly due to a higher level of visualmotor integration in musicians. Meister et al. (2005) did not notice cerebral activity differences in the primary motor cortex.

Corpus callosum

Schlaug, Jäncke, Huang, Staiger and Steinmetz (1995) observed size differences of the corpus callosum (CC) between professional classical musicians who were students at a musical school (n=30) and a non-musical control group that matched for age, gender, and handedness (n=30). The CC consists of white matter and is the main interhemispheric fiber tract that plays an important role in interhemispheric integration and communication (Schlaug et al., 1995). The anterior half of the CC was significantly larger in the group of musicians compared to the matched control group (p=.031). A further post-hoc analysis showed a significantly larger anterior CC in musicians that started musical training earlier than musicians that started musical training later in life (p=.009). This could indicate that the brain changes are larger in childhood but it could also point at more changes in the brain as a result of more years of experience.

Schmithorst and Wilke (2002) also found differences in white matter organization in the CC of musicians compared to non-musicians. Musicians (n=5) had continuous musical training during childhood and adolescence for more than ten years. The control group of non-musicians (n=6) did not have such a musical training. The researchers found more white matter in musicians in the left inferior part of the genu of the CC (p=.003).

Visual cortex

Gaser and Schlaug (2003) found positive correlations between amount of practice and gray matter volume in the superior parietal region that contributes to visuospatial processing. They also observed a positive relation between practice hours and volumes in the inferior temporal gyrus involved in the visual ventral stream. Schmithorst and Wilke (2002) observed greater left and right inferior longitudinal fasciculi (p<.05) in musicians compared to non-musicians. The inferior longitudinal fasciculus connects the occipital lobe with the temporal lobe and is associated with intermodal sensory integration (Lezak et al., 2004). These results suggest that the amount of practice influences gray matter volumes in visual areas.

Sluming, Brooks, Howard, Downes and Roberts (2007) observed brain activation in musicians and non-musicians during a non-musical spatial ability test. The group of musicians (n=10) consisted of right-handed males that played in an orchestra. The control group (n=10) was matched for age, gender, handedness and verbal intelligence and did not have any previous musical training. The researchers reported similar BOLD signals, measured by fMRI, in bilateral visual association cortex in both musicians and non-musicians. Musicians did show a significant increased activation in Broca's area where non-musicians did not. According to Sluming et al. (2007) Broca's area is part of the neural network that underlies sight-reading.

Cerebellum

Schmithorst and Wilke (2002) observed greater white matter volume in musicians in central aspects of the cerebellum compared to non-musicians (p<.05). In a study by Schlaug (2001) a significantly higher mean relative cerebellar volume was observed in male musicians compared to male non-musicians (p=.014). No such trend was found in the female subgroup (p=.71) possibly due to a smaller group size and a less well-matched sample. Schlaug (2001) also found a positive trend between life time and daily practice and relative cerebellar volume. Gaser and Schlaug (2003) noticed a positive correlation between practice hours and gray matter volume in the left cerebellum (p<.05). These results suggest that total amount of practice and daily practice both influence white matter volume size of the cerebellum.

Basal ganglia

In the aforementioned study, Schmithorst and Wilke (2002) detected greater white matter volume in the caudate and putamen in musicians compared to non-musicians ($p<.05$). The caudate and putamen are components of the basal ganglia and are involved in rhythmical movement.

Lotze et al. (2003) observed brain activity in the left caudate nucleus in the group of amateurs but not in the group of musicians. They speculate that the basal ganglia could be involved in the transformation process of learned sensorimotor associations into more automatic and smooth actions.

Auditory cortex

Lotze et al. (2003) found that musicians and non-musicians both show comparable activities in the bilateral superior parietal lobes, the left anterior superior temporal lobe and the right Heschl's gyrus. The group of musicians however showed higher activity in the right primary auditory cortex. Additionally, a positive correlation was observed between the time that professionals began music training and higher BOLD signals ($r=0.67$; $p<.05$). This indicates that it is the number of training years that influences the amount of functional changes. Lotze et al. (2003) suggest that this finding could indicate an increased recruitment of the stored auditory associations that are considered to be more present in musicians.

Prefrontal cortex

Lotze et al. (2003) observed similar activation in the left frontal operculum in musicians and non-musicians. Amateurs however, showed activations in bilateral middle, and frontal areas where professionals did not.

Limbic cortex

Additionally, Lotze et al. (2003) found more activity in the limbic regions (within the bilateral orbitofrontal lobes and the right amygdala) of amateurs compared to professionals during the execution of a musical piece. This could reflect the differences in tension during the musical performance since amateurs generally have less experience in public performances.

3.2. Differences in cognitive performance between musicians and non-musicians

Visual performance

Brochard, Dufour and Després (2004) compared visuospatial abilities in musicians and non-musicians by using a perceptual and a mental imagery task. The musician group (n=10) consisted of musical school students that received formal music lessons for at least eight years, practiced more than four hours per week and were able to sight-read music. The group of non-musicians (n=10) were psychology students without any formal music training and could not play a musical instrument nor read music. Observers had to report the side of a reference line on which a target dot was flashed. Some stimuli were horizontal and others were vertical, which required discrimination and detection. The stimuli were shown in two conditions. In the ‘perception’ condition the reference line stayed on the screen until the target dot was presented. In the ‘imagery’ condition the reference line disappeared before the target dot appeared so that participants had to keep a mental image of the presented line. As shown in table 1 in the appendix, musicians performed significantly better than non-musicians on overall visuospatial abilities ($p<.05$). This result was mainly explained by better visuospatial vertical discrimination in the imagery condition ($p<.01$). According to the researchers this could be a result of long-term musical score reading practice. Reading tone differences on a horizontal line requires vertical discrimination too, because the notes are situated on different heights on the staff.

Sluming et al. (2007) also found enhanced visuospatial performance in musicians compared to non-musicians. Musicians performed better on a 3-dimensional mental rotation (3DMR) task that measures complex visuospatial performance, compared to non-musicians. In the 3DMR task, participants received stimuli that were rotated relatively to each other. The participants had to judge whether the shapes were identical or not, and therefore the task required mental rotation of the stimuli. As shown in table 2 in the appendix, musicians were more accurate ($p<.01$) and exhibited faster reaction times ($p<.05$) than non-musicians on the 3DMR task. These differences probably reflect better visuospatial performance because no significant group differences were found on a 2-dimensional shape-matching control task.

Brandler and Rammsayer (2003) however, found contradictive results when they compared mental rotation and perceptual speed abilities in musicians and non-musicians using the Leistungspruefsystem (LPS). The musician group (n=35) consisted of graduate students at a music school and members of an orchestra. They all had an academic degree in music and had been training as instrumentalists for more than fourteen years. The group of non-musicians (n=35) were students that never played a musical instrument and had no special musical interest. Brandler and Rammsayer (2003) did not report significant differences in the performance on a mental rotation task ('space') nor on a perceptual speed task (i.e., letter and digit comparison). For statistical results see table 1 in the appendix.

Contradictive results were reported regarding differences in visual performance. Brochard et al. (2004) and Sluming et al. (2007) observed enhanced visuospatial abilities in musicians compared to non-musicians while Brandler and Rammsayer (2003) did not. Individual peaks could contribute to the fact that Brochard et al. (2004) and Sluming et al. (2007) did find differences, since they used small sample sizes. If enhanced visuospatial abilities do exist, this would be in line with enhanced gray matter volume in the superior parietal region that is associated with visuospatial processing found in the study of Gaser and Schlaug (2003).

Auditory performance

Chartrand and Belin (2006) examined timbre processing in musicians and non-musicians for sounds of musical instruments and human voices. Subjects had to judge whether two provided sounds came from the same sound source (i.e., from the same instrument or voice). Musicians (n=17) had more than three years of regular instrumental (n=14) or singing (n=3) practice. Non-musicians (n=19) never practiced with an instrument or with singing. Results (table 1 in the appendix) showed that musicians performed better than non-musicians on both discrimination tasks ($p<.05$). Moreover, the musicians had an overall longer response time than the non-musicians but this difference was not significant.

Špajdel, Jariabková and Riečanský (2007) investigated dichotic listening performances of musicians and non-musicians. Musicians (n=33) had active musical experience (i.e., playing in an ensemble or singing in a choir for at least three years), non-musicians (n=27) were individuals with no active musical experience. In a dichotic listening task two different auditory stimuli are presented, one in each ear. Špajdel and colleagues used three different types of stimuli; environmental sounds (e.g., a starting car), two-tone sequences (i.e., one two-tone sequence in each ear), and constant-vowel (CV) syllables (e.g., 'ba', 'da', 'pa'). Table 3 in the appendix shows the percentages of correct responses for musicians and non-musicians on the three tasks. Musicians had a significant higher number of correct responses from both ears for two-tone sequences compared to non-musicians ($p<.001$). This auditory benefit for musicians is a near transfer effect because tone discrimination is commonly used by musicians while they are playing an instrument.

Strait, Kraus, Parbery-Clark and Ashley (2010) compared the performance of musicians to non-musicians on the IHR Multicentre Battery for Auditory Processing (IMAP). Subjects in the group of musicians (n=18) began musical training before the age of nine and had been consistently practicing for more than ten years. The group of non-musicians (n=15) consisted of subjects that received less than four years of formal musical training throughout their lifespan. As can be seen in table 1 in the appendix, significant enhanced performance in musicians compared to non-musicians on the subtests for temporal resolution (i.e., 'backward masking' and 'backward masking with a gap'), and frequency discrimination were reported but not on the frequency selectivity tasks (i.e., 'simultaneous masking' and 'simultaneous masking with a notch'). Strait et al. (2010) also observed a correlation with years of musical practice and performance on backward masking, which suggests that musical training influences temporal resolution. Additionally, musicians showed enhanced performance on an auditory attention task that will be further described in the 'attention' section.

Memory and learning

Pallesen et al. (2010) observed working memory (WM) load of musical sounds in musicians and non-musicians. The group of musicians (n=11) consisted of students and graduates of a music academy. The non-musicians (n=10) had no more musical training than the obligatory musical education at primary school. The WM load was assessed by two n-back tests in which the participants had to memorize easy (1-back task), and difficult (2-back task) octaves by pushing a button in case they previously heard the octave. Results (table 1 in the appendix) show significant shorter response times and smaller error rates in musicians compared to non-musicians.

The aforementioned study of Strait et al. (2010) also compared the performance of musicians to non-musicians on an auditory working memory subtest of the IMAP but no significant differences were observed.

Brandler and Rammsayer (2003) assessed the memory abilities of musicians and non-musicians using four memory subscales of the Berliner Intelligenzstruktur-Test – Form 4 (BIS). Musicians outperformed the non-musicians on the 'verbal memory' task ($p<.05$). No significant differences were seen on the subtests 'number', 'numerical memory' and 'spatial memory' (see table 1 in the appendix). Furthermore, results of all the memory subtests together did not show any significant differences.

Thinking abilities

Thinking is defined by Lezak et al. (2004) as "any mental operation that relates two or more bits of information explicitly or implicitly" (p. 30). The enhanced musicians' performance on the mental rotation tasks in comparison with the performance of non-musicians (Brochard et al., 2004; Sluming et al. 2007) therefore does not only indicate enhanced visuospatial abilities but it also points at enhanced thinking abilities in musicians compared to non-musicians.

Strait et al. (2010) however, did not report better mean performances at a significant level on a matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI) that serves as a measure of non-verbal intelligence in musicians compared to non-musicians.

Brandler and Rammsayer (2003) applied the Cattell's culture Free Intelligence Test, Scale 3 (CFT3) as a measure of reasoning performance to the group of musicians and the group of non-musicians. On all four subtests (i.e., 'series', 'classsification', 'matrices', and 'topologies') the non-musicians outperformed the musicians ($p<0.001$). Additionally no significant differences were reported on the tasks 'verbal comprehension' and 'closure' (i.e., a detection task) by the two researchers (Brandler and Rammsayer, 2003).

Expressive functions

Spilka, Steele and Penhune (2010) compared musicians and non-musicians on the ability to imitate manual gestures. Musicians (n=15) had more than three years of musical experience and still practiced more than two times per week. Non-musicians (n=15) had less than three years of total musical experience and were not currently playing. Subjects had to imitate complex arm and hand gestures presented on a computer screen. Performance accuracy and discrepancy between response duration and model gesture duration were assessed (see table 2 for mean scores). In general, musicians performed better at gesture imitation than non-musicians ($p<.05$). Post hoc comparisons showed that performance accuracy of finger movements in gestures was significantly better in musicians compared to non-musicians ($p<.005$). No such findings were present for the arm and hand gestures. Additionally, musicians were better at preserving the duration of the model gesture during the imitation of the gesture than non-musicians ($p<.01$).

Brandler and Rammsayer (2003) did not notice a significant difference on the subtest 'word fluency' of the LPS between musicians and non-musicians. They did report enhanced verbal memory in musicians compared to non-musicians whilst no differences were found in other memory tasks. If enhanced verbal abilities are present, these could contribute to the contradictive results in the memory tasks.

Reaction time

In the study of Brochard et al. (2004) musician's overall reaction time on the axis discrimination task was shorter than that of non-musicians. Brochard et al. (2004) conducted another study with general simple and choice reaction time tasks. In the simple task subjects had to press a button when a circle emerged. During the choice task the subjects had to press the left key of a keyboard when a green dot appeared and the right arrow when they saw a red dot. As can be seen in table 1 in the appendix, musicians showed significant shorter reaction times in the choice condition ($p<.05$) and the overall performance comparison ($p<.01$) compared to non-musicians, but not in the simple condition.

Hughes and Franz (2007) examined reaction time differences between musicians and non-musicians on unimanual (i.e., left hand alone and right hand alone) and bimanual tasks. Pianists (n=10) and guitarists (n=10) that had been instrumentalists for a number of years (i.e., averages of 11.95 and 8.4 years respectively) and practiced approximately 3.6 (i.e., pianists) and 5.3 (i.e., guitarists) hours a week formed the musician group. The control group of non-musicians (n=20) had never played a musical instrument and had never received any formal musical training. Musicians responded faster on the overall reaction time performance ($p<.001$). No differences in performance between guitarists and pianists were found. Hughes and Franz (2007) further observed better bimanual performances in groups that started musical training earlier in life compared to groups that started musical training later in life. This could indicate that an earlier start of musical lessons influences reaction time performance, but it is also possible that it is the number of years that influences the performance. No statistical results concerning the levels of significance were reported regarding the comparison between musicians' and non-musicians' performances on the bimanual tasks or the unimodal tasks separately. Other results are shown in table 1 in the appendix.

Shorter discrimination reaction times in musicians could be explained by better sensorimotor skills as a result of experience in translating musical notes into proper finger movements. This suggestion however is inconsistent with results from Brandler and Rammsayer (2003) since they did not report enhanced performance in perceptual speed in musicians compared to non-musicians. Another explanation for shorter reaction times in musicians is enhanced motor skills of the fingers. Results of Amunts et al. (1997) showed that right-handed musicians (i.e., actively performing, classically trained musicians) performed better at an index finger tapping test than non-musician controls who had never played a musical instrument or had played an instrument for less than one year after the age of ten (p<.05; see table 1 in the appendix). The ability to make faster finger movements in musicians could therefore contribute to better performances on reaction time tasks.

Attention performance

Strait et al. (2010) assessed visual and auditory attention performances of musicians and non-musicians using the Test of Attentional Performances (TAP). In the visual attention task subjects had to respond as soon as a computer character raised his arm. In the auditory attention task subjects saw the same character but had to respond when they heard a beep. Secondary auditory and visual stimuli were cued in some trials but no response had to be made in that case. As shown in table 1 in the appendix, musicians showed significant shorter reaction times on the auditory attention performance (p<.05) compared to non-musicians. Additionally, the researchers found a positive correlation between years of musical practice and performance on the auditory attention tasks. This suggests that musical training influences auditory attention performances. The shorter reaction times for musicians compared to non-musicians on the visual attention task were not significant.

4. Discussion

4.1. What structural differences exist between musicians and non-musicians?

Larger gray matter volumes in musicians compared to non-musicians were observed in somatosensory, primary motor and premotor areas, the superior parietal region, the inferior temporal gyrus and the cerebellum. Furthermore, greater white matter volumes were found in the right intrasulcus of the motor cortex, the precentral gyrus, the corpus callosum, the cerebellum and the basal ganglia.

Positive associations were found between grey and white matter volumes and the amount of practice and the time that musicians started their musical training. These results indicate that the amount of practice influences the amount of structural brain differences.

4.2. What functional differences exist between musicians and non-musicians?

Contra lateral brain activations in the motor hand area were found in musicians and bilateral activations in that of non-musicians. Musicians further showed higher activity in the right primary auditory cortex and limbic regions while higher activity in the prefrontal cortex was observed in non-musicians. Higher pre-SMA and dorsal premotor activations in complex motor sequences were observed in musicians compared to non-musicians but no differences were found in the primary cortex. Furthermore, increased brain activation in Broca's area in musicians was found but not in non-musicians.

Because associations were found regarding differences in brain activity between musicians and non-musicians and years of musical training, it is suggested that the amount of training influences the amount of functional changes as well.

4.3. Performance on auditory, visual, and reaction time tasks

Enhanced auditory performances in musicians compared to non-musicians were found in timbre processing, tone discrimination, frequency discrimination and temporal resolution but not in frequency selectivity. Keeping in mind that Lotze et al. (2003) reported higher activity in the right primary auditory cortex, which they linked to increased auditory associations, it could be possible that enhanced auditory performance is the result of better learned auditory associations due to musical experience.

Shorter reaction times were reported on general simple and choice reaction time tasks and overall unimanual and bimanual reaction time tasks. This could be the result of greater inferior longitudinal fasciculi that connect the occipital lobe with the temporal lobe and are associated with intermodal sensory integration. Due to greater intermodal sensory integration, it is possible that musicians can respond faster to visual stimuli. Moreover, greater white and gray matter volumes and higher brain activities in motor areas in musicians indicate enhanced motor abilities which consequently can influence reaction times. This suggestion is supported by faster finger tapping rates that were found in musicians.

Contradictory results regarding enhanced visuospatial abilities in musicians were observed. If they do exist, enhanced visuospatial abilities in musicians could be linked to more gray matter volumes in the superior parietal region which is associated with visuospatial processing. More research should first shed more light on the existence of such a relationship.

Observed positive relations between years of musical practice on the one hand and auditory performance and reaction time performance on the other hand, indicate that musical practice influences auditory and reaction time performances. These results suggest that near transfer effects of musical experience are present for auditory performances and reaction time but effects on visual performance are still ambiguous. Therefore, more research should go out to enhanced visual performance in musicians in the future.

4.4. Performance on memory, learning, thinking, attention, and expressive tasks

This review found no indications that musicians differ in memory and learning performance compared to non-musicians on tasks with non-musical stimuli.

Results on differences in thinking abilities between musicians and non-musicians are conflicting. Enhanced performances on mental rotation tasks were reported in musicians but not on reasoning task performances. It is possible that primary thinking skills are enhanced in musicians but that more advanced thinking abilities required in difficult tasks show no differences.

Better attention performances for musicians were only reported on an auditory attention task and not on a visual attention task. It is possible that the enhanced performances on the auditory attention task are (partly) the result of enhanced auditory processing. This would also explain the absence of differences in the visual attention task.

Enhanced finger gesture imitation performance in musicians point at better finger movement accuracy and not at enhanced expressive functions because no differences were found in arm and hand gesture imitation performances. The greater white and gray matter volumes in the motor cortex found in musicians could play an important role in the enhanced accuracy in finger movements. No indications of differences in word fluency between musicians and non-musicians were present. Therefore, no foundations for enhanced expressive functions were found.

Against expectations, no differences were found for any of the above mentioned cognitive performances. Therefore, no foundation for the presence of far transfer effects is offered. This in contrast with modern assumptions that musical training can function as a cognitive enhancer (Anvari et al., 2002; Schellenberg, 2004;2006).

4.5. Limitations

Different assignment criteria for musicians and non-musicians among several studies make it hard to properly compare different outcomes of the studies. Merely a single study (Gaser and Schlaug, 2003) controlled for number of training years. Some researchers for instance, define non-musicians as naïve participants that never played a musical instrument nor had any special musical interest (Brandler & Rammsayer, 2003; Brochard et al., 2004; Hughes & Franz, 2007; Meister et al., 2005; Schlaug et al., 1995; Špajdel et al., 2007). Others describe non-musicians as amateurs that had significantly less years of musical experience than professional musicians (Lotze et al., 2003; Spilka et al., 2010; Strait et al., 2010). Yet other researchers consider non-musicians as naïve subjects without any musical experience or with significantly less years of music lessons compared to professionals (Amunts et al., 1997; Gaser & Schlaug, 2003). Chartrand and Belin (2006), Schmithorst and Wilke (2002), and Sluming et al. (2007) do not report their criteria for non-musicians. Future research should control for the number of years a person played a musical instrument.

Because all studies used existing groups it is difficult to conclude that musical experience directly contributes to brain differences and differences in cognitive performance.
It is for instance also possible that pre-existing individual differences (e.g., personality and intelligence) between musicians and non-musicians influence the chance for children to follow music lessons, or contribute to the perseverance and the amount of practice at home. Family income, parental education and family pressure can also have an influence.

Some correlational studies conclude that structural differences are correlated with training intensity (Gaser & Schlaug, 2003; Schlaug, 2001), or an earlier start in musical training (Amunts et al., 1997; Schlaug et al., 1995) which suggests that musical training does influence the amount of structural differences. However, innate neural markers could contribute to the choice to begin to learn to play a musical instrument.

To explore the possibility for pre-existing neural differences between musicians and non-musicians Norton et al. (2005) searched for neural differences between children that sought music lessons (n=39) and children that did not seek any music lessons (n=31). No differences were found between the two groups in total brain volume, total gray matter, total white matter, or corpus callosum size (Norton et al., 2005). This outcome suggests that the structural differences consistently found between the two groups are a result of long-term and intensive practice on a musical instrument rather than innate neural markers for musical expertise.

To additionally examine the presence of pre-existing cognitive markers for musical ability Norton et al (2005) compared the cognitive performances of the children. They assessed spatial-temporal performance, spatial recognition, vocabulary performance, non-verbal reasoning performance, phonemic awareness, left- and right-hand tapping rate, and music audiation. No significant differences between the performances of children that chose to participate in music training and children that did not were present in any of the tests. Therefore Norton et al. (2005) conclude that cognitive differences between musicians and non-musicians cannot be entirely contributed to pre-existing cognitive markers.

4.6. Recommendations

Future research should pay more attention to differences in performance on domains that are less associated with the musical training domain (i.e., memory and learning, thinking, attention, and expression) and visual performance. It would also be interesting to explore the direction of the reported associations to be able to draw conclusions concerning near and far transfer effects as a result of musical training.

A longitudinal study with multiple moments of measurement could explore changes that occur over time. For instance, if one can select enough children from first grade and their parents that are prepared to cooperate, it would be possible to follow these children and assess their cognitive performance and brain characteristics at the beginning of the study, and at later moments in life. Then it would be possible to examine what comes first, musical skills or brain and cognitive differences. Variables that should be considered are number of years children take music lessons, number of hours that children practice a week, structural and functional brain characteristics, and cognitive performances. One should also consider possible confounding variables as age, gender, hand preference, parental education and income. This research would be highly relevant for society because it gives insight in factors that could influence cognitive development and intelligence. It is however time consuming and the costs of research are high.

Another possibility could be to experimentally administer music lessons to children and compare the results with a control group of children that did not receive any music lessons. Costa-Giomi (1999) conducted such a study by administering three years of piano instruction in nine year old children (n=43) and compared their cognitive performances with a peer group of controls (n=35). Motivation problems and drop out numbers however appeared to be confounding factors. Furthermore random assignment to both conditions is not ethical, because this would restrain many children from the possibility to explore their musical abilities while classmates do get the opportunity to develop their musical skills.

It would also be interesting to compare structural and functional characteristics and cognitive performance between musicians that play different instruments. Because skill requirements to play a musical instrument depend on the kind of instrument, it could be possible that different cognitive performances exist amongst professional musicians. Anyway, it is clear that more research should go out to differences in visual, memory and learning, thinking, attention, and expressive performances between musicians and non-musicians in the future. The direction of the found associations has to be determined to make further conclusions regarding near and far transference.

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6. Appendix

Table 1: *Mean scores (M) and standard deviations (SD) of musicians and non-musicians on cognitive tasks of reviewed studies*

Study	Subjects	Instrument	Subtest	Results		
				Musicians M(SD)	**Non-Musicians M(SD)**	**Δ Mean mus – Mean non-mus**
Amunts et al., 1997	Musicians N=21	Index finger tapping test	Left hand	118.9 (2.44)	96.3 (2.44)	22.6*
	Non-musicians N=30		Right Hand	128.1 (2.44)	111.6 (2.44)	16.5*
			Overall performance	123.5 (2.31)	103.9 (2.31)	19.6*
Brandler and Ramm-sayer, 2003	Musicians N=35	LPS	Verbal comprehension	26.34 (1.05)	27.63 (.85)	-1.29
	Non-musicians N=35		Word fluency	31.00 (1.13)	33.20 (.88)	-2.2
			Space	25.71 (1.17)	23.29 (1.30)	2.42
			Perceptual speed	27.51 (.80)	26.51 (.78)	1
			Closure	32.46 (1.01)	32.37 (1.01)	.09
		BIS	Number	27.09 (1.31)	26.17 (1.11)	.92
			Verbal memory	9.43 (.44)	8.26 (.37)	1.17*
			Numerical memory	7.49 (.45)	7.77 (.52)	-.28
			Spatial memory	15.23 (.75)	15.54 (.90)	-.31
			Overall memory	50.11 (1.92)	49.14 (2.10)	.97
		CFT3	Series	4.23 (.48)	7.23 (.20)	-3***
			Classifications	5.20 (.33)	7.17 (.41)	-1.97***
			Matrices	4.20 (.49)	6.83 (.28)	-2.63***
			Topologies	4.60 (.26)	6.14 (.22)	-1.54***
Brochard et al., 2004 Exp 1	Musicians N=10	Reaction times (ms) on Axis discrimination	On-Vertical	330 (-)	380 (-)	-50
	Non-musicians N=10		On-Horizontal	310 (-)	350 (-)	-40
			Off-Vertical	450 (-)	550 (-)	-100**
			Off-Horizontal	430 (-)	480 (-)	-50
			Total average	380 (-)	440 (-)	-60*
Brochard et al., 2004 Exp 2	Musicians N=12	Reaction times (ms)	Simple task	176 (-)	185 (-)	-9
	Non-musicians N=12		Choice task	282 (-)	320 (-)	-38*
			Overall performance	229 (-)	253 (-)	-24**
Chartrand and Belin, 2006	Musicians N=17	Discrimination task accuracy	Instrument discrimination	1.75 (-)	1.25 (-)	0.5*
	Non-musicians N=19		Voice discrimination	1.20 (-)	0.90 (-)	0.3*
Hughes and Franz, 2007	Musicians N=20	Reaction times (ms)	Unimodal Left hand	213 (51)	246 (59)	-33 (-)
	Non-musicians N=20		Unimodal Right hand	216 (50)	245 (72)	-29 (-)

			Bimanual Left hand	219 (46)	251 (57)	-32 (-)
			Bimanual Right hand	219 (46)	249 (58)	-30 (-)
			Total mean performance	217 (-)	248 (-)	-31***
Pallesen et al., 2010	Musicians N=11	N-back task				
	Non-musicians N=10	Response time (ms)	1-Back task	790.9 (23.1)	945.1 (43.6)	-154.2**
			2-Back task	954.1 (36.6)	1130.2 (47.5)	-176.1***
		Error rate (%)	1-Back task	1.6 (0.3)	5.3 (1.0)	-3.7***
			2-Back task	7.1 (0.8)	10.4 (1.4)	-3.3
Spilka et al., 2010	Musicians N=15	Performance accuracy	Accuracy arms	4.07 (.24)	3.97 (.37)	0.1
	Non-musicians N=15		Accuracy hands	4.03 (.22)	3.93 (.20)	0.1
			Accuracy fingers	4.09 (.13)	3.87 (.22)	0.22**
			Overall accuracy	12.20 (.52)	11.72 (.61)	0.48*
		Gesture discrepancy	Response duration %	26.87 (15.03)	44.09 (18.66)	-17.22**
Strait et al., 2010	Musicians N=18	IMAP	Freq discrimination (%)	.85 (.37)	3.12 (3.38)	-2.27*
			Backward masking	31.15 (8.93)	37.67 (6.21)	-6.52*
			Backward masking gap	25.60 (4.10)	29.14 (4.44)	-3.5*
			Simult masking	65.33 (6.06)	65.44 (4.20)	-.11
	Non-musicians N=15		Simult masking notch	41.98 (2.47)	43.17 (3.69)	-1.19
		TAP	Auditory attention (RT)	322.96 (47.38)	368.29 (72.49)	-45.33*
			Visual attention (RT)	267.87 (27.96)	271.17 (33.03)	-3.3
			AWM	9.61 (1.94)	10.13 (61.60)	-.52
		WASI	Non-verbal Intelligence	64.06 (4.21)	61.60 (8.31)	2.46

* p<.05; ** p<.01; *** p<.001; (-)= unknown data Δ= absolute mean difference ms= milliseconds

AWM= Auditory Working Memory; **BIS**= Berliner Intelligenzstruktur-Test; **CFT3**= Culture Free Intelligence Test, Scale 3; **IMAP**= IHR Multicentre Battery for Auditory Processing; **LPS**= Leistungspruefsystem; **RT**= Reaction Time; **TAP**= Test of Attentional Performance; **WASI**= Wechsler Abbreviated Scale of Intelligence

Table 2: *Sluming et al. (2007) show that musicians outperform non-musicians in number of trials and accuracy rate on a mental rotation task.*

Instrument	Subtest	Trials (accuracy) Musicians (n=10)	Trials (accuracy) Non-musicians (n=10)	Trials (accuracy) ΔMus-Non
2DSM	Perceptual matching	141(94%)	139(95%)	2(1)
3DMR	Mental rotation	94(81%)	71(73%)	23*(8)**

* p<.05;   ** p<.01

2DSM=2-Dimensional Shape-Matching; **3DMR**=3-Dimensional Mental Rotation

Table 3*: Percentage of correct responses for musicians and non-musicians on three dichotic listening tasks (Špajdel et al., 2007)*

		Left ear musicians	Right ear musicians	Left ear non-musicians	Right ear non-musicians
Musicians (N=33)	Environmental	82%	79%	80%	76%
Non-musicians	Two-tone	82%	76%	68%	62%
(N=27)	CV syllables	40%	52%	36%	54%

CV=Constant-Vowel