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RESEARCH ARTICLE

Rhythm synchronization performance and auditory working memory in early- and late-trained musicians

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Abstract Behavioural and neuroimaging studies provide evidence for a possible "sensitive" period in childhood development during which musical training results in long-lasting changes in brain structure and auditory and motor performance. Previous work from our laboratory has shown that adult musicians who begin training before the age of 7 (early-trained; ET) perform better on a visuomotor task than those who begin after the age of 7 (late-trained; LT), even when matched on total years of musical training and experience. Two questions were raised regarding the findings from this experiment. First, would this group performance difference be observed using a more familiar, musically relevant task such as auditory rhythms? Second, would cognitive abilities mediate this difference in task performance? To address these questions, ET and LT musicians, matched on years of musical training, hours of current practice and experience, were tested on an auditory rhythm synchronization task. The task consisted of six woodblock rhythms of varying levels of metrical complexity. In addition, participants were tested on cognitive subtests measuring vocabulary, working memory and pattern recognition. The two groups of musicians differed in their performance of the rhythm task, such that the ET musicians were better at reproducing the temporal structure of the rhythms. There were no group differences on the cognitive measures. Interestingly, across both groups, individual task performance correlated with auditory working memory abilities and years of formal training. These results support the idea of a sensitive period during the early years of childhood for developing sensorimotor synchronization abilities via musical training.

Keywords Sensitive period · Early-trained · Late-trained · Sensorimotor · Musicians · Rhythm synchronization · Working memory · Cognitive abilities

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Introduction

Many professional musicians have been training since a very young age. As a result, there is a common assumption that superior musical performance is associated with early training. However, is this because starting at a young age allows for more years of training? Or, is there something specific about being exposed to this type of experience during an early, sensitive period of development? Behavioural evidence in support of a sensitive period for musical training comes from a phenomenon known as "absolute" or "perfect pitch". Individuals with "perfect pitch" are able to identify a note in the absence of a standard, and the development of this ability is strongly associated with experience during early childhood (Takeuchi and Hulse 1993; Trainor 2005; Zatorre 2003). Neuroanatomical differences between early- and late-trained musicians have also been observed, supporting the idea of a sensitive period (Amunts et al. 1997; Pantev et al. 1998; Schlaug et al. 1995). However, these studies did not control for differences between early- and late-trained groups in terms of years of musical experience, which may have contributed to the observed differences in neuroanatomical structure. In a recent study from our laboratory, Watanabe et al. (2007) observed increased sensorimotor synchronization abilities in early-trained musicians compared to late-trained musicians, even after matching the two groups on years of musical experience. The present study further investigates the idea of a sensitive period for sensorimotor abilities.

The concept of a sensitive period must be defined in relation to the narrower concept of a "critical" period. A critical period differs from a sensitive period in that during this restricted window of time, sensory input is required for normal functioning to develop. The effects that follow deprivation of sensory input during a critical period cannot be reversed by sensory exposure at a later time (Innocenti 2007). For example, there are critical periods very early during development of the visual system when stimulation or experience is necessary to develop normal binocular vision (Hooks and Chen 2007; Wiesel and Hubel 1965). What is being proposed in this paper in terms of the development of musical abilities is not a critical period, but a sensitive period. A sensitive period is a window of time during which experience is particularly influential on development of functioning (Knudsen 2004). Evidence suggests that the mechanisms involved in sensitive periods are highly influenced by experience in addition to biological determinants (Hooks and Chen 2007; Tomblin et al. 2007).

A large portion of the evidence for sensitive periods in human development comes from the study of speech and language development, as well as second-language acquisition. The idea of a sensitive period for language development was initially inspired by two main observations. Case studies showed that children who had been deprived of exposure to language in early childhood failed to fully develop language abilities even after being exposed later in life (Curtiss 1977) and evidence showed that children who underwent surgical removal of the left hemisphere were able to develop normal language abilities as long as surgery occurred early in childhood. Lenneberg (1967) suggested that the effects associated with deprivation of speech can be overcome if stimulation is restored early enough during development. As a result, he proposed the idea of a "sensitive" period for language development. This idea has been applied to second-language acquisition, and evidence suggests that exposure to a second language in early childhood is associated with greater levels of adult proficiency than exposure later in life (Weber-Fox and Neville 2001). Further support for the existence of sensitive periods in development has come from work with congenitally deaf children who receive cochlear implants. Several large-scale studies have shown that children who receive implants before the age of 3–4 show better auditory and speech perception than later recipients (Kral et al. 2001; Sharma et al. 2007; Svirsky et al. 2004). This is consistent with the developmental changes in the anatomy of the auditory system that have been linked to different stages of speech and language development (Moore and Linthicum 2007).

Additional support for the existence of sensitive periods in development comes from studies of trained musicians. While studies have examined the influence of musical training on brain development during childhood (Hyde et al. 2009; Shahin et al. 2004), some of the strongest evidence for a sensitive period comes from the study of "absolute" or "perfect" pitch in adults. This ability has been strongly associated with musical training during the early years of childhood (Takeuchi and Hulse 1993; Trainor 2005; Zatorre 2003). Further evidence comes from studies showing a relationship between musical training and changes in brain structure (e.g. Bangert and Schlaug 2006; Bermudez and Zatorre 2005; Gaab and Schlaug 2003; Gaser and Schlaug 2003; Hutchinson et al. 2003; Schlaug et al. 1995, 2005). Among the literature demonstrating this relationship, three studies in particular support the idea of a sensitive period. Schlaug et al. (1995) observed volumetric differences in the anterior corpus callosum between early- and late-trained musicians. Pantev et al. (1998) observed increased auditory and motor cortical representations among musicians compared to non-musicians and reported that these increases were correlated with age at which musical training began. Finally, Amunts et al. (1997) reported changes in the morphology of the motor cortex in musicians related to training of the non-dominant hand. More importantly, they showed that these changes were related to the age of commencement of training. Overall, the evidence suggesting that musical experience influences structural development of the auditory and motor systems is convincing. Given that there is a maturational timeline for neuroanatomical development of both auditory and motor systems and that musical experience is associated with structural differences, there may be a window of time in early childhood development during which the influence of musical training on aspects of structural development of sensorimotor networks is strongest.

Taken together, these findings suggest that there may be a sensitive period for musical training, similar to that observed for language acquisition. However, none of these studies were designed to directly address the impact of early versus late training, and thus did not control for differences between early- and late-trained musicians in the total number of years of musical training and experience. By definition, a musician who begins training early has more years of experience than one who begins later when both are the same age. Therefore, it is possible that the observed differences in performance and brain structure could simply be accounted for by the group difference in duration of musical training. A previous experiment in our laboratory examined possible behavioural differences in early- and late-trained musicians who were matched for years of musical training and experience. Watanabe et al. (2007) observed sensorimotor performance differences between the two groups of adult musicians using a visually presented sequence. Participants were asked to synchronize their mouse button presses with a temporally complex sequence presented on a computer monitor. The early-trained group performed significantly better than the late-trained group in terms of response synchronization, supporting the idea that musical training during a sensitive period in early childhood results in superior sensorimotor synchronization abilities. The observed group difference persisted across 5 days, suggesting that this superior synchronization ability remains even after individual performances plateau. While this experiment provides evidence that early training can affect adult motor performance, the visuomotor sequencing task used is unlike the integration abilities required in a typical musical performance. Therefore, it is possible that early-trained musicians might only outperform late-trained musicians on this relatively unusual and difficult task. To address this question, the present experiment aimed to replicate these findings using a more musically relevant auditory rhythm synchronization task.

A second question that could be raised about our previous findings (Watanabe et al. 2007) is whether the performance difference observed between groups was mediated by enhanced overall cognitive functioning in the early-trained group. Correlational studies have demonstrated positive associations between music lessons in school-aged children and cognitive abilities such as verbal memory, non-verbal reasoning, spatial–temporal reasoning, reading, spelling, speech recognition and mathematics (e.g. Anvari et al. 2002; Forgeard et al. 2008; Jentschke and Koelsch 2009; Moreno et al. 2009; Saffran 2003; Schellenberg 2001, 2004, 2006; Schlaug et al. 2005). More specifically, Schellenberg (2004, 2006) showed a positive association between duration of music lessons in school-aged children and Intelligence Quotient (IQ) scores, while controlling for socio-economic status and effects associated with participation in a non-musical activity. Although the musicians in our previous study had been matched for years of musical training and other practice variables, it is possible that they also differed in cognitive function. Therefore, a secondary goal of the present study was to investigate whether early- and late-trained musicians differ in terms of specific cognitive abilities. Within a group of undergraduate students, above and beyond the relationship with overall IQ scores, the specific cognitive measures that were most commonly associated with musical training were working memory and non-verbal reasoning (Schellenberg 2006). Based on these findings, musicians in the current study were asked to complete a non-verbal reasoning task and two auditory working memory tasks. In addition, a vocabulary test was included as a measure of crystallized knowledge.

The main goal of this experiment was to replicate and extend the findings observed by Watanabe et al. (2007) that support the idea of a sensitive period for sensorimotor integration abilities to the more familiar and more musically relevant auditory domain. A secondary goal was to investigate whether these two groups of equally trained musicians would differ in terms of their overall cognitive abilities, given that their musical training took place during different developmental windows.

Method

Participants

Twenty-four currently practicing, neurologically healthy musicians between the ages of 18 and 34 ($M = 26.4$ years old, $SD = 4.4$) participated in this study. Participants were screened for significant head injuries, history of neurological disease or medication that could affect task performance by completing a Medical Screening Information form. The musical training and experience of each participant was determined through a Musical Experience Questionnaire (MEQ) that was developed within our laboratory. The MEQ quantifies the amount of instrumental, vocal or dance training an individual has received in their lifetime, at what age this training occurred and the amount of time currently dedicated to practicing music on a weekly basis. All musicians had extensive musical experience ($M = 17.5$ years; $SD = 4.4$), as evaluated by the MEQ. The sample was selected to form two groups of musicians: early-trained (ET; $n = 12$) and late-trained (LT; $n = 12$). Those who began their musical experience prior to or at the age of 7 were placed in the ET group, and those who began after the age of 7 were considered LT. The age of seven was chosen based on the previous study conducted by Schlaug et al. (1995). The two groups were individually matched on years of musical experience, years of formal training and hours of current practice, as determined by the MEQ. All participants gave informed consent, and the Concordia University Research Ethics Committee had approved the protocol.

Stimuli

Due to the high degree of musical training obtained by our participants, the 6 woodblock test rhythms were selected to cover a range of complexity. Essens and Povel (1985) and Essens (1995) developed a model by which musical rhythms can be classified into levels of difficulty based on their metrical structure. Each test rhythm consisted of 11 woodblock notes and had a total duration of 6 s. These rhythms differed in their temporal structure, such that the intervals between musical notes varied, but not the length of notes themselves. In musical terminology, each rhythm consisted of five-eighth notes (each 250 ms), three quarter notes (each 500 ms), one dotted quarter note (750 ms), one half note (1,000 ms) and one dotted half note (1,500 ms). Manipulation of the temporal structure of the notes resulted in progressively more complex and less metrically structured rhythms. Three levels of metrical complexity were chosen, and participants were exposed to two rhythms at each level: metrically simple (MS), metrically complex (MC) and non-metrical (NM). An auditory stimulus delivery program was used to counterbalance the rhythms. These rhythms were played through a pair of earphones, and participants used a computer mouse to tap out the rhythms. A similar auditory rhythm paradigm was previously used for an fMRI study conducted by Chen et al. (2008) examining the network of activation during auditory–motor synchronization.

In addition to the rhythmic stimuli, the experimental protocol included two subtests from the Wechsler Adult Intelligence Scale—III (WAIS; Wechsler 1997), Digit-Span (DS) and Letter-Number Sequencing (LN), as well as two subtests from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler 1999), Vocabulary (VC) and Matrix Reasoning (MR). The DS requires individuals to recall strings of numbers, and the LN requires individuals to recall and mentally manipulate strings of letters and numbers. Both of these subtests tap into working memory abilities. The VC assesses an individual's ability to orally define words, and the MR assesses non-verbal reasoning and visual pattern recognition abilities. Both VC and MR are strongly correlated with global IQ and can also be considered as measures of crystallized and fluid intelligence, respectively.

Procedure

Participants alternated between listening and tapping along while each rhythm played twice in row (Fig. 1). Participants were instructed to use their right index finger and the

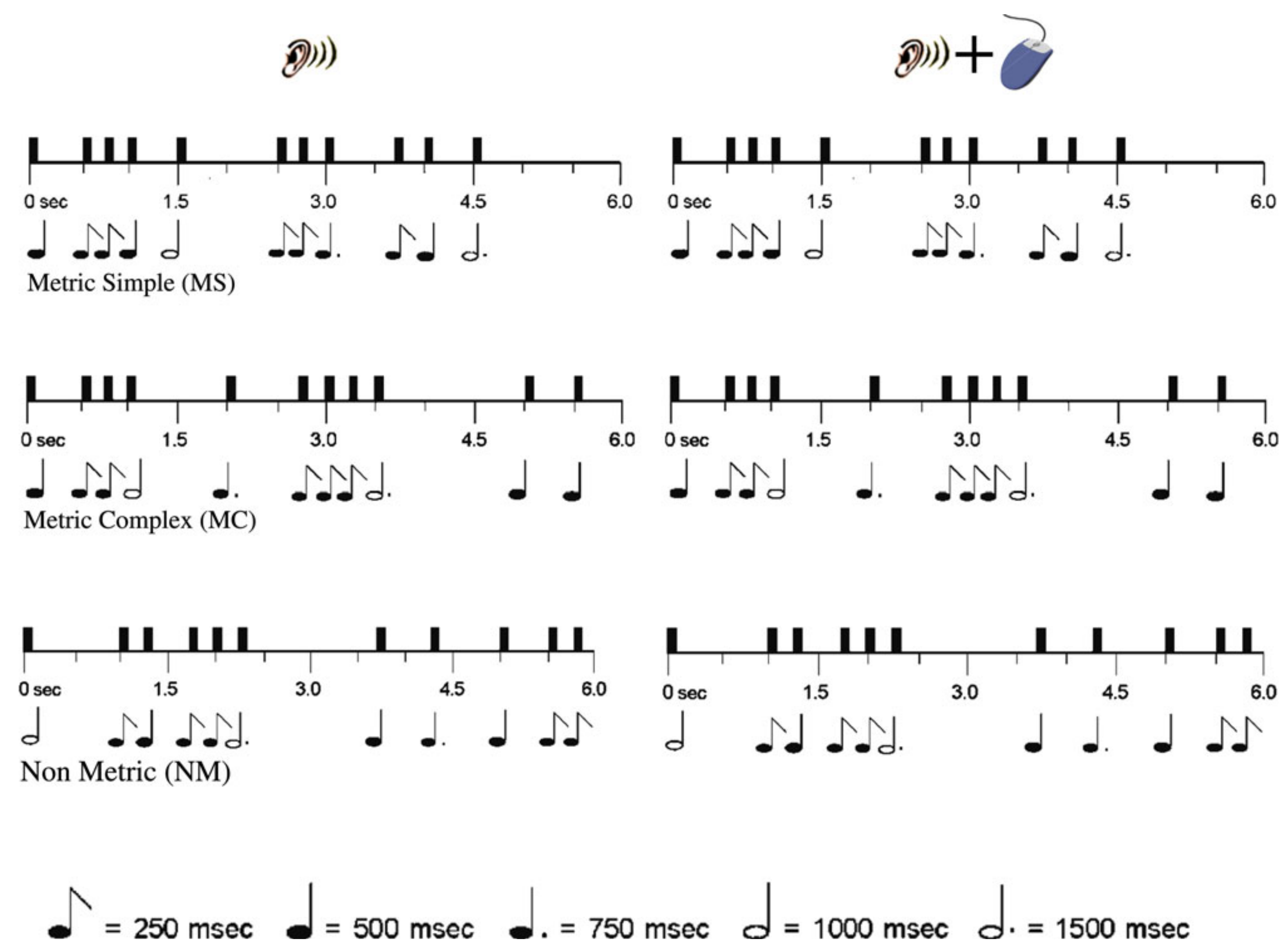

Fig. 1 Illustration of the rhythm task. Participants were exposed to six rhythms presented in random order for approximately two 12-min blocks. Two different rhythms of each rhythmic complexity were used (i.e., 2 MS rhythms, 2 MC rhythms, and 2 NM rhythms). Each trial consisted of a listening component followed by a listening and tapping component

left button of the computer mouse to tap along with the rhythm as it played during the tapping repetition. Two very basic practice rhythms were administered to familiarize participants with the task. A block consisted of the six rhythms repeatedly presented in a counterbalanced fashion for 12 min. Each rhythm was performed 6 times in each block. Once participants had completed the first block of the task, they were asked to perform the DS. Participants then performed a second block of the rhythm synchronization task, followed by the VC, the LN and finally, the MR.

Measures

Musical information was quantified for each participant in terms of years of experience, years of formal training and hours of current weekly practice. Individual cognitive abilities were measured using the four chosen cognitive subtests (DS, LN, VC and MR). Results were scored according to standard procedure; however, raw scores were used for each cognitive measure in order to provide a measure of ability regardless of participant age and because of increased variance. Performance on the rhythm synchronization task was measured using three dependent variables: percent correct (PC), asynchrony (ASYN) and inter-tap interval (ITI) deviation. A tap was considered correct if it was made within half of the onset-to-onset interval before or after a woodblock note (Fig. 2). The ASYN measure was defined as the absolute value of temporal difference between the onset of each woodblock note and the associated mouse key press. The ITI deviation measure indicated the extent of deviation from the actual interval between each pair of woodblock notes. It was calculated by dividing the interval between each pair of the participant's taps by the interval between each corresponding pair of woodblock notes in the rhythms. This measure is indicative of how well participants are reproducing the temporal structure of the rhythms.

Data analysis

To compare rhythm synchronization across groups, a repeated-measures analysis of variance (ANOVA) for each of the dependent variables was conducted, with group as the between-subjects factor and rhythm type as the within-subjects factor. Significant differences across rhythm types for the two groups were analysed using simple Bonferroni correction for multiple comparisons. Group differences in musical experience, years of formal training, hours of current practice and cognitive measures were assessed using *t*-test analyses. The relationships among musical demographics, cognitive measures, age and task performance were examined using Pearson and partial correlation analyses. Raw scores on the cognitive subtests were used in order to examine cognitive abilities, regardless of age.

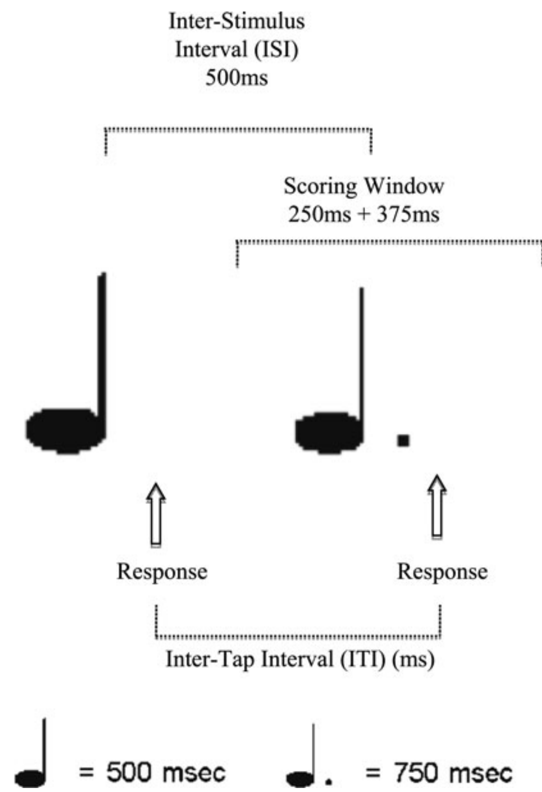

Fig. 2 Illustration of the scoring method used to evaluate rhythm task performance. A response was scored correctly if the mouse tap was made within half of the onset-to-onset interval before and after a woodblock note. Asynchrony was measured as the difference between each woodblock note and the participant's response. ITI deviation was calculated as a ratio of the ITI and the ISI

Follow-up analysis

A hierarchical regression analysis was conducted in order to assess whether group explains a significant amount of variance in task performance, above and beyond that explained by working memory abilities. A model was created with total inter-tap interval (ITI) deviation across rhythms as the dependent measure and both group and working memory as predictors. A composite score for each participant's working memory abilities was created using their Letter-Number Sequencing (LN) and Digit-Span (DS) scores and was used as the working memory predictor variable in the regression model. In step 1 of the model, the working memory composite score was entered as the sole predictor of task performance. In step 2, group was added as a second predictor to determine whether any additional variance was explained by the age of training onset, above and beyond the variance accounted for by working memory abilities.

Results

Group comparisons of matching variables

Comparison of the ET and LT musicians confirmed that the two groups were well matched in terms of years of musical experience, formal training and hours of current practice (Table 1). Another set of analyses comparing the two groups on their cognitive subtest performance scores demonstrated that the two groups did not differ in their cognitive abilities, as assessed by the VC, MR, DS and LN (Table 2). Raw scores are reported; however, it should be made explicit that no group differences were found when using scaled scores either (VC: $t = 0.377$, $P = 0.710$; MR: $t = -0.643$, $P = 0.527$; DS: $t = 0.725$, $P = 0.476$; LN: $t = 1.522$, $P = 0.142$). As expected, the two groups differed in terms of age of onset ($P < 0.01$).

Behavioural measures

Analysis comparing accuracy (PC) of the rhythm reproduction between the two groups showed a significant main effect of rhythm type (F (2, 21) = 19.5, $P < 0.001$), with no main effect of group (Fig. 3). Pair-wise comparisons revealed that performance decreased as metrical complexity increased (simple > complex > non-metrical), such that accuracy on the MS rhythms was higher than the MC and NM rhythms ($P = 0.026$ and $P < 0.01$, respectively), and accuracy on the MC rhythms was higher than the NM rhythms ($P < 0.01$). These results confirm our manipulation of metricality, such that regardless of group, accuracy decreased as the metrical complexity of the rhythms increased.

Analysis comparing the reproduction of the temporal structure of the rhythms measured by inter-tap interval (ITI) deviation between the two groups showed a significant main effect of group (F (1, 22) = 6.0, $P < 0.05$) such that the ET group was better able to reproduce the temporal intervals of the rhythms than the LT group (Fig. 3). A main effect of rhythm type was observed as well (F (2, 21) = 43.6, $P < 0.001$), indicating that, regardless of group, the ITI deviation on the MS rhythms was lower than the MC and NM rhythms ($P < 0.01$ for both), and ITI deviation on the MC rhythms was lower than the NM rhythms ($P < 0.01$).

A similar pattern of results was revealed on the synchronization measure (ASYN). There was no main effect of group, but a significant main effect of rhythm type (F (2, 21) = 71.6, $P < 0.001$). Pair-wise comparisons revealed that ASYN on the MS rhythms was lower than ASYN on the MC and NM rhythms (both comparisons $P < 0.01$), and ASYN on the MC rhythms was lower than on the NM rhythms ($P < 0.01$) (Fig. 3).

Correlations

In order to examine the relationship between task performance and cognitive variables, raw scores for PC, ASYN and ITI were correlated with raw scores for VC, MR, DS and LN (Table 3). No significant correlations were found between the behavioural measures and VC or MR scores. However, LN scores were found to be significantly correlated with PC,

Table 1 Group demographics of musical variables

Group	Age	Age of onset	Years of musical experience	Years of formal training	Hours of current weekly practice
Early-trained	25.0 (±3.8)	5.92 (±1.0)	18.67 (±4.5)	10.00 (±4.2)	19.50 (±10.9)
Late-trained	27.8 (±4.7)	10.67 (±3.0)	16.42 (±4.3)	7.33 (±4.2)	23.75 (±16.3)
t-values	−1.62	−5.17**	1.26	1.54	−0.75

Standard deviation values are in brackets

** $P < 0.01$

Table 2 Group cognitive subtest raw scores

Group	Vocabulary (VC)	Matrix reasoning (MR)	Digit span (DS)	Letter-number sequencing (LN)
Early-trained	63.6 (±5.7)	29.8 (±4.3)	22.3 (±4.8)	13.3 (±2.4)
Late-trained	63.3 (±7.0)	29.8 (±2.6)	19.8 (±4.2)	11.6 (±2.7)
t-values	0.128	−0.057	1.36	1.61

Standard deviation values are in brackets

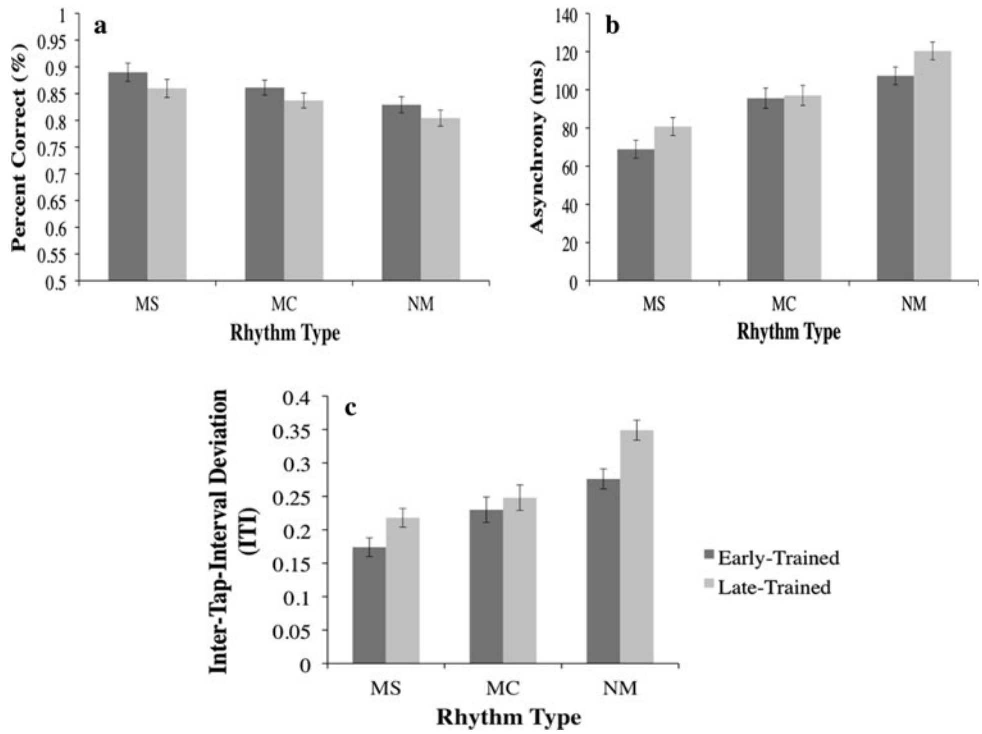

Fig. 3 Performance results of the rhythm task as measured by **a** percent correct (PC), **b** asynchrony (ASYN) and **c** inter-tap interval deviation (ITI). Repeated-measures ANOVA analyses on each performance measure revealed a significant main effect of rhythm type and a significant main effect of group for ITI deviation

Table 3 Pearson correlations of cognitive subtest raw scores and behavioural measures

Behavioural measure	Vocabulary (VC)	Matrix reasoning (MR)	Digit span (DS)	Letter-number sequencing (LN)
Percent correct (PC)	−0.218	0.173	0.256	0.423*
Asynchrony (ASYN)	0.088	−0.297	−0.499*	−0.557**
Inter-tap interval (ITI) deviation	−0.022	−0.348	−0.549**	−0.563**

* $P < 0.05$, ** $P < 0.01$

Table 4 Pearson correlations of musical demographics and behavioural measures

Behavioural measure	Age	Age of onset	Years of musical experience	Years of formal training	Hours of current weekly practice
Percent correct (PC)	−0.130	−0.204	0.114	0.490**	−0.074
Asynchrony (ASYN)	0.147	0.060	0.003	−0.486**	0.025
Inter-tap interval (ITI) deviation	0.190	0.190	−0.035	−0.627**	0.134

** $P < 0.01$

ASYN and ITI deviation, and DS scores were significantly correlated with ASYN and ITI deviation.

Results of the correlational analyses between the behavioural measures and musical variables (Table 4), as well as behavioural measures and age variables indicated a significant correlation between formal training and PC, ASYN and ITI deviation ($r = 0.49$, $P < 0.05$; $r = -0.49$, $P < 0.05$; $r = 0.63$, $P < 0.01$). Neither age variable (age of onset and age) showed a significant relationship with task performance. In order to examine the association between years of formal training, cognitive scores and task performance, correlations were performed between years of formal training and each cognitive measure (Table 5). This set of analyses revealed a significant correlation between years of formal training and both DS and LN, but no significant correlation with VC or MR. In addition, partial correlation analyses between ITI deviation, years of formal training and LN raw scores were conducted in order to examine the partial contributions of formal training and working memory to task performance (Table 6). These results indicated that working memory abilities and years of formal training each accounted for unique portions of the variance in task performance.

Table 5 Pearson correlations of cognitive subtest raw scores and years of formal training

	Vocabulary (raw)	Matrix reasoning (raw)	Digit span (raw)	Letter-number sequencing (raw)
Years of formal training	0.152	0.375	0.510*	0.429*

* $P < 0.05$

Table 6 Partial correlation analyses between task performance, years of formal training and working memory

Control variable		Correlation
Letter-number sequencing (raw)	Total ITI deviation (%)	−0.516*
	Years of formal training	
Years of formal training	Total ITI deviation (%)	−0.419*
	Letter-number sequencing (raw)	

* $P < 0.05$

Table 7 Hierarchical regression analysis predicting ITI deviation scores from working memory composite scores and group

	R^2	β	R^2 change	F
Step 1	0.352		0.352	11.927
Working memory composite score		−0.593**		
Step 2	0.436			8.124
Working memory composite score		−0.496**		
Group		0.307*	0.085	

* $P < 0.05$, ** $P < 0.01$

Regression analysis

In order to determine whether the amount of variance in ITI deviation during task performance accounted for by group was above and beyond what was explained by working memory abilities, a hierarchical regression analysis was conducted. As the values indicate in Table 7, group accounted for a significant amount of variance unexplained by the individual working memory composite scores. These results confirm that, while individual working memory abilities were associated with ITI deviation scores, the grouping variable determined by age at which training onset began accounted for additional portions of the variance in ITI deviation scores.

Discussion

The results from this study show that ET musicians have enhanced auditory rhythm synchronization abilities compared to LT musicians, even when matched for years of experience, formal training and hours of current practice. The greatest difference between the two groups was seen on the measure of ITI deviation, indicating that the ET musicians were better able to reproduce the temporal structure of the rhythms. These group differences cannot be attributed to differences in verbal abilities, non-verbal reasoning or working memory, as there were no differences on these measures. These results support the existence of a possible sensitive period during development associated with long-lasting enhancement of sensorimotor integration and timing. While differences in task performance between the two groups were not mediated by cognitive ability, across all musicians, both working memory and years of formal training were associated with task performance.

Given that the two groups of musicians were matched in terms of musical experience, the enhanced performance on the rhythm synchronization task observed in the ET group cannot be attributed to greater years of training, but instead to the developmental window during which training began. The performance difference between the ET and LT groups observed in the present study, taken together with previous results from our laboratory (Watanabe et al. 2007), supports the presence of a sensitive period in development during which musical training results in long-lasting improvements in sensorimotor integration and movement timing. This is consistent with the idea that experience during a sensitive period contributes differentially to later learning and performance (Knudsen 2004; Trainor 2005). This could be related to the interaction between developmental changes occurring in the brain during the sensitive period and specific training that stimulates this development, resulting in greater potential for future maturation or more efficient integration. This is consistent with developmental changes in motor performance, and structural maturation of fibre pathways supporting sensorimotor functions (Barnea-Goraly et al. 2005; Garvey et al. 2003; Savion-Lemieux et al. 2009; Thomas and Nelson 2001; Paus et al. 1999). For example, the anterior portion of the corpus callosum was reported to be larger in musicians who began training before age 7 compared to those who began later in childhood (Schlaug et al. 1995). A model predicting the growth trajectory of the corpus callosum from structural MRI scans demonstrated that development of the anterior portion of the corpus callosum precedes the posterior portion and that growth in the anterior region continues until approximately age 7 (Thompson et al. 2000). A study examining white matter differences among adult piano players showed that a larger number of brain regions correlated with practice in the group that began training earlier (≤11 years old) compared to those who began later (Bengtsson et al. 2005). Among the brain regions demonstrating this correlation in those who began training earlier were the isthmus and the body of the corpus callosum. The isthmus contains fibres connecting auditory regions, and the body of the corpus callosum connects frontal and premotor regions important for movement sequences and bimanual coordination. Support for the fact that musical training can result in rapid changes in the brain during childhood comes from a recent study showing that structural changes were observed in children after 15 months of music lessons and that these changes were associated with increases in performance on auditory and motor tasks (Hyde et al. 2009). All of these findings illustrate the potential for a sensitive period in childhood, when motor and sensory regions are still undergoing maturation during which musical training has an optimal effect on structural development.

The results of the current experiment are an extension of the findings from a previous study showing that ET musicians performed better than LT musicians on a visuomotor synchronization task (Watanabe et al. 2007). As described in the Introduction, one goal of the present experiment was to assess whether this difference would be observed using a more musically relevant task. These results clearly show that ET musicians have enhanced performance on the more familiar auditory rhythm reproduction task, indicating that training during the putative sensitive period is associated with improved sensorimotor integration in both the auditory and visual modalities. It should be noted that group differences on a measure of asynchrony were observed on the second day in our previous study (Watanabe et al. 2007). Group differences were observed on the ITI deviation measure of synchronization in the current study, which only examined task performance on a single day. One could predict that, given a second day of the auditory–motor task, the two groups would deviate in performance on the ASYN variable as well based on our previous findings.

Given that the two groups did not differ in their performance on measures of verbal ability, non-verbal reasoning and working memory, the enhanced performance of the ET group cannot be attributed to differences in the abilities measured. However, correlational analyses showed that across both groups of musicians, working memory abilities were a significant contributor to task performance. To assess whether group accounted for variance in task performance (ITI deviation) above and beyond individual working memory abilities, a hierarchical regression analysis was performed. These results showed that group was a significant predictor of task performance (ITI deviation), even when individual working memory abilities were considered. Previous findings have demonstrated an association between basic timing tasks and intelligence (Helmbold et al. 2007; Rammsayer and Brandler 2007). These studies have concluded that the relationship is not due to top-down processes such as working memory, but rather is associated with basic neural efficiency (Madison et al. 2009; Ullén et al. 2008). However, these studies do not consider musical training, and the tasks used are very basic and purposefully designed to require little involvement of working memory abilities (Helmbold et al. 2007; Rammsayer and Brandler 2007).

Previous findings indicated that musical training during childhood is associated with verbal abilities and non-verbal reasoning (e.g. MR) (Forgeard et al. 2008; Jentschke and Koelsch 2009; Schellenberg 2004, 2006). The current study does not support an association between musical training and verbal or non-verbal reasoning abilities within a group of highly trained adult musicians. It is important to distinguish between effects of musical training that may have short-term impact in childhood and those that last well into adulthood. It may be that music lessons trigger premature development of cognitive abilities, but some of these differences wash out as other children's cognitive abilities develop through other avenues of experience.

While the cognitive abilities of the two groups did not differ at the time of testing, an important question is whether this was true at the time of start of musical training. The cognitive tasks used in this study are subtests from the WAIS-III or the WASI. Overall, IQ scores are thought to be more or less stable across development and, in the absence of significant neurological disruption, demonstrate limited change from childhood to adulthood. If, however, the ET group had higher IQ scores as children, the LT group would have had to demonstrate a differential increase in IQ scores during their development, as the two groups do not differ currently. In light of the stability associated with IQ levels across the age span, the difference in task performance observed in these adult musicians is unlikely to be associated with potential group differences in IQ scores at an earlier time during childhood.

Although years of formal training and working memory scores were correlated with each other, they also accounted for unique portions of the variance in task performance. In other words, it was not the case that all individuals who performed well on the task had high working memory scores and many years of formal training. There were individuals with high working memory scores and few years of formal training that performed well and vice versa. This pattern of results suggests that components of formal music lessons, not general musical experience, are associated with better rhythm performance and enhanced auditory working memory abilities. Formal training may contribute to task performance in several ways. First, formal lessons emphasize explicit learning of a wide variety of complex rhythmic structures; potentially giving musicians with more formal training a better ability to parse the rhythms they were required to imitate (Chen et al. 2008). Second, formal lessons emphasize intensive and precise practice of rhythms, facilitating the development of motor skills required for precise timing and execution. Finally, formal lessons may emphasize tasks requiring, and thus enhancing working memory. An important distinction should be made in the literature between effects of formal music lessons and effects of playing music, as suggested by Schellenberg and Peretz (2008). Many aspects of music lessons are similar to scholastic requirements (e.g. attention, practice, self-discipline, memorization, reading, counting). Perhaps, formal lessons provide a scaffolding instructional approach for all skills involved in playing a musical instrument, including executive functions such as working memory (Schellenberg and Peretz 2008).

The present study shows convincing evidence for a possible sensitive period for musical training. However, it is possible that the musicians who began training at an early age differed in terms of pre-existing abilities, motivation and environment. Individual differences with respect to motor development, cognitive development or other genetic factors may play an important role in the group difference observed in this study. More specifically, children with innate enhanced sensorimotor skills might be those who begin earlier, and because of their better skills, get more out of their training. In addition, perhaps those who begin training at a younger age are inclined do so because of family influences, higher motivation levels, or other factors that were not evaluated in this study. Future studies should aim to evaluate these important areas to determine exactly which factors are underlying this observed performance difference.

In conclusion, these results provide evidence for a possible sensitive period for musical training before the age of seven as demonstrated by performance differences between ET and LT musicians on a rhythm synchronization task. These findings are consistent with neuroimaging findings that show differential effects of early training on brain structure. Group performance differences observed within this sample cannot be attributed to cognitive ability, as the two groups did not differ on measures of verbal and non-verbal reasoning or working memory abilities. Very interestingly, across both groups, working memory scores were associated with task performance, as were years of formal training. This suggests that formal training may be an important mediator of the effects of musical experience.

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