

Music training and working memory: An ERP study

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ABSTRACT

While previous research has suggested that music training is associated with improvements in various cognitive and linguistic skills, the mechanisms mediating or underlying these associations are mostly unknown. Here, we addressed the hypothesis that previous music training is related to improved working memory. Using event-related potentials (ERPs) and a standardized test of working memory, we investigated both neural and behavioral aspects of working memory in college-aged, non-professional musicians and non-musicians. Behaviorally, musicians outperformed non-musicians on standardized subtests of visual, phonological, and executive memory. ERPs were recorded in standard auditory and visual oddball paradigms (participants responded to infrequent deviant stimuli embedded in lists of standard stimuli). Electrophysiologically, musicians demonstrated faster updating of working memory (shorter latency P300s) in both the auditory and visual domains and musicians allocated more neural resources to auditory stimuli (larger amplitude P300), showing increased sensitivity to the auditory standard/deviant difference and less effortful updating of auditory working memory. These findings demonstrate that long-term music training is related to improvements in working memory, in both the auditory and visual domains and in terms of both behavioral and ERP measures.

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1. Introduction

A growing number of studies have reported correlations between music training and improvements on a variety of cognitive skills, including measures of nonverbal reasoning (e.g., Forgeard, Winner, Norton, & Schlaug, 2008), IQ (e.g., Schellenberg, 2004, 2006), verbal memory (e.g., Brandler & Rammsayer, 2003; Chan, Ho, & Cheung, 1998; Ho, Cheung, & Chan, 2003; Jakobson, Cuddy, & Kilgour, 2003; Jakobson, Lewycky, Kilgour, & Stoesz, 2008), arithmetic (e.g., Zafranas, 2004), speech processing (e.g., Moreno & Besson, 2006; Moreno et al., 2009), visual processing (e.g., Helmbold, Rammsayer, & Altenmüller, 2005; Jakobson et al., 2008; Zafranas, 2004), vocabulary (e.g., Forgeard et al., 2008), and reading skills (e.g., Moreno et al., 2009). The mechanisms mediating these associations are unknown. It has been suggested that working memory might play a role (e.g., Chen, Penhune, & Zatorre, 2008; Gunter, Schmidt, & Besson, 2003; Lee, Lu, & Ko, 2007; Williamon & Egner, 2004), but “there is little or no empirical evidence to support this hypothesis” that music training improves aspects of executive function (e.g., Hannon & Trainor, 2007; Schellenberg & Peretz, 2008, p. 46).

Working memory involves the temporary storage and manipulation of information, and functions to integrate incoming information with information in existing memory stores (e.g., Baddeley, 1992, 1998; Brumback, Low, Gratton, & Fabiani, 2005). Evidence from both lesion and neuroimaging studies supports Baddeley's (1992, 1998) model dividing the working memory system into modality based short-term stores (phonological/articulatory loop and visuospatial sketchpad, subsets of working memory with traces lasting only a few seconds without rehearsal) and a modality free, attention-controlling central executive associated with regulation of abilities necessary for goal-directed behavior (e.g., Baddeley, 1992, 2003; Baldo & Dronkers, 2006; Jonides et al., 1998; Koelsch et al., 2009; Postle & D'Esposito, 1999; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992). While some have argued for a tonal equivalent to the verbal phonological loop (e.g., Deutsch, 1970), evidence suggests that rehearsal and storage of both tonal and verbal information involves the phonological loop (e.g., Salamé & Baddeley, 1989; Semal, Demany, & Ueda, 1996) and activates overlapping neural networks (e.g., Koelsch et al., 2009; Schulze, Zysset, Mueller, Friederici, & Koelsch, in press). Here, we investigated if prior long-term music training was associated with improved working memory using both standardized behavioral measures and event-related potentials (ERPs).

1.1. Working memory and music training: behavioral studies

A handful of behavioral studies have explored which subsystems within the working memory system might be affected by

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music training, providing evidence of associations between working memory and music training. For example, children and adults who have received music training have been shown to outperform non-musician controls on measures of auditory and visual working memory such as forward and backward digit span (e.g., Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006; Lee et al., 2007; Parbery-Clark, Skoe, Lam, & Kraus, 2009), nonword span (e.g., Lee et al., 2007), operation span (e.g., Franklin, Moore, Yip, & Jonides, 2008; Lee et al., 2007), spatial span (e.g., Lee et al., 2007), and verbal working memory span (e.g., Franklin et al., 2008; Parbery-Clark et al., 2009) tasks. However, Lee et al. (2007) reported that musically trained adults scored higher than their control counterparts only on tasks related to phonological storage (forward digit and nonword span), while musically trained children scored higher than their control counterparts on these tasks as well as on tasks related to central executive functions (backward digit and operation span) and visuospatial storage (object and location span).

Consistent with this evidence for better phonological working memory in musically trained adults, Berti, Münzer, Schröger, and Pechmann (2006) reported that adult musicians outperformed non-musicians on a pitch comparison task, demonstrating advantages in storing auditory information that the authors suggested were due to improved working memory operations. Similarly, Pechmann and Mohr (1992) interpreted superior performance on their behavioral pitch discrimination task to improved working memory in musicians as compared to non-musicians. Williamson and colleagues have also reported differences in pitch memory for musicians and non-musicians, such that musical training was associated with use of multiple strategies for encoding pitch information (Williamson, Baddeley, & Hitch, 2010). Others have reported enhanced pitch processing in musically trained children and adults, as compared to their untrained counterparts, but have not directly connected this finding to changes in working memory with music training (e.g., Brattico et al., 2009; Fujioka et al., 2006; Hantz, Crummer, Wayman, Walton, & Frisina, 1992; Hantz, Kreilick, Braveman, & Swartz, 1995; Kishon-Rabin, Amir, Vexler, & Zaltz, 2001; Kuriki, Kanda, & Hirata, 2006; Lappe, Herholz, Trainor, & Pantev, 2008; Magne, Schön, & Besson, 2006; Marques, Moreno, Castro, & Besson, 2007; Moreno & Besson, 2006; Moreno et al., 2009; Nikjeh, Lister, & Frisch, 2008; Schneider et al., 2002; Schön, Magne, & Besson, 2004; Shahin, Bosnyak, Trainor, & Roberts, 2003; Shahin, Roberts, Pantev, Aziz, & Picton, 2007; Shahin, Roberts, & Trainor, 2004; Strait, Kraus, Parbery-Clark, & Ashley, 2010; Strait, Kraus, Skoe, & Ashley, 2009; Tervaniemi, Castaneda, Knoll, & Uther, 2006; Trainor, Desjardins, & Rockel, 1999; Wayman, Frisina, Walton, Hantz, & Crummer, 1992). While a recent study using a backward digit span task as a measure of auditory working memory failed to find differences between adult musicians and non-musicians, results from auditory attention and masking tasks were consistent with the interpretation that “musicians’ sensory enhancements result from strengthened cognitive modulation of auditory processing” (Strait et al., 2010, p. 26).

Others have reported similar findings in the visual domain: musically trained adults outperformed non-musicians on psychometric tasks requiring quick visual processing (Helmbold et al., 2005) and delayed visual recall and recognition (Jakobson et al., 2008), while children who received piano training for one year showed improvement on a visual short-term memory task (Zafranas, 2004). Musically trained adults also recalled sequentially visually presented note patterns better than non-musicians, particularly well-formed patterns, even when gestalt properties, verbal rehearsal, and familiarity were controlled (Kalakoski, 2007). Finally, older adults who took piano lessons showed gains on measures of visual working memory such as the Trail Making Test and Digit Symbol task, while controls who did not receive piano instruction did not (Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh,

2007). However, others have reported no advantages for musicians as compared to non-musicians on measures of visual memory or attention (Chan et al., 1998; Ho et al., 2003; Strait et al., 2010).

1.2. Working memory and music training: neuroscientific studies

1.2.1. fMRI studies

In addition to these behavioral findings, there is tenuous fMRI evidence suggesting a relation between music training and working memory at the neural level. In one study, Janata, Tillmann, and Bharucha (2002) found that attentive listening to one instrument in polyphonic music activated regions also involved in working memory processes, including the superior temporal gyrus, intraparietal sulcus, precentral sulcus, inferior frontal sulcus and gyrus, and the frontal operculum. However, this study only included trained musicians as participants and lacked a non-musician control group, precluding conclusions about the neural effects of music training. In another study, Chen et al. (2008) found that musicians behaviorally performed a rhythmic task better than non-musicians, and recruited the prefrontal cortex to a greater extent than non-musicians during performance of the task. They argued that the superior ability of musicians to organize and maintain a rhythm’s temporal structure was related to the greater involvement of the prefrontal cortex mediating working memory. Previously, Gaab and Schlaug (2003) reported that musicians relied more on short-term memory (with greater activation in right temporal cortex and supramarginal gyrus) than non-musicians (with greater right primary and left secondary auditory cortex activation) to perform a difficult pitch memory task, and Schulze et al. (in press) have reported recently differences in sensorimotor coding of verbal and tonal information in a working memory task in musicians as compared to non-musicians. Absent musical training or expertise, lesion and neuroimaging studies have associated specific neural regions with specific aspects of working memory (e.g., see Baddeley, 2003, for a review).

1.2.2. ERP studies: the P300 component

Given these disparate findings, further research targeting the subsystems of working memory at both the behavioral and neural levels is important to understanding a possible link between music training and working memory. In order to measure working memory processes at the neural level, particularly considering the relatively brief timing of processing within the short-term stores (e.g., Baddeley, 1998), it would be useful to employ a technique that allowed for real-time processing of information such as the recording of ERPs (e.g., Morgan, Klein, Boehm, Shapiro, & Linden, 2008, p. 989). There have been numerous studies investigating a link between the P300 ERP component and the working memory system (e.g., Brumback et al., 2005; Grune, Metz, Hagendorf, & Fischer, 1996; Guo, Lawson, Zhang, & Jiang, 2008; Kiss, Pazderka-Robinson, & Floden, 2001; Klein, Coles, & Donchin, 1984; Lefebvre, Marchand, Eskes, & Connolly, 2005; Morgan et al., 2008; Murphy & Segalowitz, 2004; Ruchkin et al., 1992; SanMiguel, Corral, & Escera, 2008; Talsma, Wijers, Klavier, & Mulder, 2001). The classic task used to measure working memory processing in a P300 paradigm is the traditional oddball task (e.g., Brumback et al., 2005; Croft, Gonsalvez, Gabriel, & Barry, 2003; Frisina, Walton, & Crummer, 1988; Klein et al., 1984; Murphy & Segalowitz, 2004; Polich, 1995, 2007). A two-stimulus oddball paradigm presents infrequent (deviant) target stimuli within a train of frequent (standard) stimuli, and the participant is asked to respond only to the deviant stimuli. The deviant stimuli in oddball tasks consistently elicit a marked P300 component in the ERP waveform (e.g., Brumback et al., 2005; Croft et al., 2003; Gonsalvez, Barry, Rushby, & Polich, 2007; Gonsalvez & Polich, 2002; Klein et al., 1984; Murphy & Segalowitz, 2004; Polich, 1995, 1997, 2007; SanMiguel et al., 2008), and this P300 is con-

sidered to be the manifestation of updating the working memory store (e.g., Donchin & Coles, 1988; Frisina et al., 1988; Klein et al., 1984; Polich, 2007). The P300 in an auditory oddball task is thought to index updating within the auditory sensory store (phonological/articulatory loop) while the visual P300 reflects updating within the visuospatial store (e.g., Bledowski et al., 2004; Grune et al., 1996; Johnson, 1989).

Both the amplitude and the latency of the P300 component elicited in oddball tasks have been related to working memory processes. The amplitude of the P300 is thought to reflect ease of performing the task: as task difficulty increases (in terms of distinguishing the deviants from the standards and updating the working memory store upon presentation of the deviants), P300 amplitude decreases (e.g., Hantz et al., 1992; Polich, 2007). Consistent with the finding that a larger P300 is associated with an “easier” task, larger P300 amplitude (in a 5-choice reaction time task) has been correlated with greater working memory capacity as measured by reading span (e.g., Nittono, Nageishi, Nakajima, & Ullsperger, 1999). The latency of the P300 is considered to be an indication of the timing and duration of stimulus evaluation, independent of any brain activity that mediates motor responses (e.g., Donchin & Coles, 1988; Polich, 2007). P300 latency is negatively correlated with working memory task (digit span) performance; that is, better performance on a digit span task is associated with earlier P300 latency (Polich, Howard, & Starr, 1983).

In the context of investigating the effects of music training, the P300 oddball task has been used primarily to study pitch and timbre processing in musicians as compared to non-musicians (e.g., Crummer, Walton, Wayman, Hantz, & Frisina, 1994; Hantz et al., 1992, 1995; Nikjeh et al., 2008; Trainor et al., 1999; Wayman et al., 1992). In such studies, musicians without perfect pitch typically show an earlier and larger P300 to pitch or timbre deviants than non-musicians (e.g., Besson & Fäita, 1995; Hantz et al., 1992, 1995; Nikjeh et al., 2008; Trainor et al., 1999). These findings generally have been interpreted in terms of musicians’ “superior auditory pitch discrimination” abilities (e.g., Nikjeh et al., 2008, p. 1004) but have not been discussed in terms of potential working memory implications. For example, this superior pitch processing in musicians may be related to faster (earlier P300) and more differentially sensitive (larger P300) processing within the sensory memory store indexed by the auditory oddball task. Comparative evidence from standardized behavioral measures of auditory working memory could contribute support to this hypothesis, but these studies included only the oddball task electrophysiological measure.

1.3. The present study

The present study was designed to investigate a possible association between music training and improvements in working memory at both the behavioral and neural levels. At the behavioral level, scores from standardized tests of phonological memory, visuospatial memory, and executive working memory (TOMAL-2, Reynolds & Voress, 2007) were compared between a group of musicians and a group of non-musicians. At the neural level, the amplitude and latency of the P300 component elicited in both auditory and visual oddball tasks were compared between the same two groups. In addition, correlations between the behavioral and neural measures were explored. Although previous studies, as reviewed above, have investigated various aspects of an association between music training and working memory, none to our knowledge has employed matching auditory and visual ERP paradigms designed to index working memory processing in combination with targeted standardized behavioral measures in the same groups of participants.

Given the auditory nature of their skill and the results of studies showing enhanced pitch processing in musicians (e.g., Brattico

et al., 2009; Fujioka et al., 2006; Hantz et al., 1992, 1995; Kuriki et al., 2006; Lappe et al., 2008; Marques et al., 2007; Moreno & Besson, 2006; Moreno et al., 2009; Nikjeh et al., 2008; Schneider et al., 2002; Shahin et al., 2003, 2007, 2004; Strait et al., 2009; Tervaniemi et al., 2006; Trainor et al., 1999; Wayman et al., 1992), we hypothesized that musicians would have a more efficient phonological loop for processing short-term auditory information. Thus we predicted that musicians would perform better on behavioral measures of phonological short-term memory (e.g., see Lee et al., 2007) and show a larger and earlier P300 to deviants in the auditory oddball task (e.g., see Crummer et al., 1994; Hantz et al., 1992; Wayman et al., 1992) in comparison to non-musicians. Given previous research suggesting stronger visuospatial working memory in musicians (e.g., Bugos et al., 2007; Helmbold et al., 2005; Jakobson et al., 2008; Zafranas, 2004), we further predicted that musicians would perform better on our behavioral measures of visuospatial short-term memory (cf. Chan et al., 1998; Lee et al., 2007; Strait et al., 2010), and perhaps show an earlier and larger P300 to deviants in the visual oddball task, although no previous research has addressed this. Finally, as both are considered to be measures of working memory processing, we expected that there would be significant positive correlations between the scores on the standardized behavioral tests and the amplitude and latency of the P300 elicited by deviants in each domain.

2. Methods

2.1. Participants

Participants were 32 undergraduate students (16 female), all of whom attended a highly selective college in the northeast. All were between the ages of 18 and 24 years old (mean 20; 2 years, *SD* 14.5 months). All participants were right-handed, monolingual English speakers (who learned English as a first language and did not self-report fluency in another language) with self-reported normal or corrected to normal vision and hearing, no history of neurological dysfunction, and were not taking any medication that affected neurological function. None were professional musicians. Participants were paid \$25 for their time. The Committee for the Protection of Human Subjects approved all study procedures and informed consent was obtained from each participant prior to inclusion in the study. Thus, the study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Participants were categorized as either musicians or non-musicians through pre-screening. Each group included 16 participants (8 females). Musicians met the following 4 criteria: they had studied music (instrumental) for at least 9 years (range 9–16 years, average 12.1, *SD* 2.0), they began playing prior to age 10 (range 5–10, average 7.4 years, *SD* 1.6), they had continuously studied on the same instrument up to the time of the experiment, and they reported still actively studying music (e.g., were involved in a campus music group, took lessons and/or self-reported practicing at least 3 h per week (average 6.3 h, *SD* 3.5)). Six were string players, 3 played piano, and 7 played brass/woodwind instruments. Non-musicians had either not studied music or had studied for fewer than 5 years prior to age 14 (average years of music study: 1.4 years, *SD* 1.6). These criteria are similar to those used in previous studies comparing musicians and non-musicians (e.g., Strait et al., 2010). Here, the musician group had significantly more years of training than the non-musician group ($t(30) = 16.53, p < .001$). Average age for the musician (20; 1 years, *SD* 14.4 months) and non-musician (20; 4 years, *SD* 15.0 months) groups was not significantly different ($t(30) = -.505, p = .617$).

2.2. Standardized behavioral testing

The phonological, visuospatial, and executive working memory subtests of the Test of Memory and Learning – Second Edition (TOMAL-2, Reynolds & Voress, 2007) were administered. Specifically, participants took the Digits Forward (DF) and Letters Forward (LF) subtests targeting phonological memory, the Abstract Visual Memory (AVM) and Memory for Location (MFL) subtests targeting visual memory, and the Digits Backward (DB) and Letters Backward (LB) subtests targeting executive working memory.

2.3. Electrophysiological (ERP) testing

Following administration of the TOMAL-2, participants were fitted with an elastic cap (Electro-Cap International) containing 29 tin electrodes to record electroencephalogram (EEG), as well as loose electrodes placed on the left and right mastoids (reference), at the external canthi of the left and right eyes (to record horizontal eye movements), and below the right eye (to record blinks). Scalp elec-



Fig. 1. Stimuli used in the visual oddball paradigm.

trode impedances were maintained below 3 Ω , mastoid electrodes below 2 Ω , and eye electrodes below 10 Ω . Following electrode preparation, EEG was recorded in an electrically shielded and sound-attenuating booth. The live EEG was amplified with SA Instrumentation bioamplifiers (bandpass 0.01–100 Hz) and digitized on-line (sampling rate 4 ms), referenced to the right mastoid electrode. The recordings were re-referenced to the averaged mastoids in the final data averaging.

Stimuli were presented in standard oddball paradigms using Presentation software (Neurobehavioral Systems). Four separate oddball paradigms, 2 auditory and 2 visual, were presented in counterbalanced order to each participant. In the auditory oddball paradigms, stimuli consisted of 800 Hz and 840 Hz tones. These frequencies do not correspond directly to musical notes, with 800 Hz falling between G and G# and 840 Hz falling between G# and A; thus, the tones could not be labeled in a familiar way. Each tone served as both a standard and a deviant between the two auditory paradigms (that is, the 800 Hz tone served as the standard and the 840 Hz tone served as the deviant in one auditory paradigm, while the reverse was the case in the other auditory paradigm). The auditory stimuli were presented as free-field sounds at an average loudness of 70 dB (A-weighted) from a speaker located about 66 in. directly in front of participants. Stimulus duration was 50 ms, with rise and fall times of 5 ms. The interstimulus interval (ISI) was 1450 ms, consistent with previous similar oddball studies (e.g., Brumback, Low, Gratton, & Fabiani, 2004; Brumback et al., 2005; Crummer et al., 1994; Hantz et al., 1992; Klein et al., 1984; Murphy & Segalowitz, 2004). A fixation cross at the center of a 19-in. monitor also located directly in front of participants was presented during the auditory paradigms. In the visual oddball paradigms, stimuli consisted of two abstract figures that were unfamiliar to the participants such that they had no labels or names (see Fig. 1). Between the two visual paradigms, each figure served as both a standard and a deviant. The visual stimuli were presented at the center of the 19-in. monitor, subtending 1.18° of horizontal visual angle and 1.86° of vertical visual angle. Visual stimulus duration was 50 ms and the ISI was 1450 ms, consistent with the auditory paradigm parameters.

Each paradigm began with the presentation of five consecutive standards in order to familiarize participants with the standard stimuli for that paradigm and establish a memory trace for the standards; ERPs to these stimuli were not included in analyses. Also within each paradigm, a “dummy” standard followed the presentation of each deviant and was not included in analyses. Stimuli were presented in four blocks of 565 stimuli (400 standards and 80 deviants, plus the 80 dummy standards following each deviant and the 5 standards beginning each list). Thus, within each paradigm, the deviant was presented 14.2% (80/565) of the time. The deviants were presented randomly throughout each block with the exception that one “dummy” standard and one standard stimulus followed each deviant, so that no deviant stimulus immediately followed another and there were no alternating deviant/standard/deviant stimulus presentations. Participants were asked to press a button on a response device whenever they heard or saw the deviant stimulus. Auditory and visual paradigms were interspersed and breaks occurred between paradigms. Gender, response hand, and order of paradigm presentation were counterbalanced across participants within each group and were equivalent between groups. The ERP recording portion of the experiment lasted about 1.5 h and the entire experiment took about 2.75 h.

2.4. Data analysis

Off-line, separate ERPs to standard and deviant trials within each domain were averaged for each subject at each electrode site in the time period from 100 ms before stimulus presentation to 1000 ms following stimulus onset. The peak amplitude and peak latency of the P300 were measured within the 250–550 ms time window in the auditory condition and the 300–750 epoch in the visual condition (time windows were determined by visual inspection of the individual subject waveforms and the grand average waveforms). The peak of the P300 was calculated as the most positive data point within the time window such that the three data points preceding and following were less positive. For purposes of analysis, data from the two auditory paradigms were collapsed, as were data from the two visual paradigms (separate analyses indicated no main effects of which stimulus served as the deviant for either the auditory or visual condition). Trials containing eye movements, muscular activity, or electrical noise were omitted from analyses, determined initially by use of

standard artifact rejection parameters and subsequently by individual inspection of data for artifact rejection.

Omnibus ANOVAs were used to analyze the peak amplitude and peak latency data separately within each domain. The between-subject factor was group (musician, non-musician), and within-subject factors included condition (standard, deviant), hemisphere (left, right), lateral/medial (lateral, medial), and anterior/posterior [6 levels: frontal (F7/8, F3/4), fronto-temporal (FT7/8, FC5/6), temporal (T3/4, C5/6), centro-temporal (CT5/6, C3/4), temporoparietal (T5/6, P3/4), and temporo-occipital (TO1/2, O1/2)]. Similar analyses were conducted at midline sites, with the between-subject factor group and within-subject factors condition and anterior/posterior [3 levels: frontal (Fz), central (Cz), and parietal (Pz)]. Significant interactions involving group and condition were followed up by planned ANOVAs focusing on deviants. The Greenhouse–Geisser correction was applied to all within-subject measures with more than one degree of freedom. Finally, Pearson correlations were conducted with the ERP measures of P300 peak amplitude and latency to deviant auditory and visual stimuli, the TOMAL-2 subtest scores, and years of music training. All results are significant at the .05 level unless otherwise noted.

3. Results

3.1. Standardized behavioral tests

Mean scaled scores on the TOMAL-2 subtests within each group are summarized in Table 1. An ANOVA with group (musician, non-musician) and subtest (Abstract Visual Memory, Memory for Location, Digits Forward, Letters Forward, Digits Backward, Letters Backward) was used to compare scaled subtest scores between groups. A main effect of group ($F(1, 30) = 8.62, p < .01$) indicated that musicians scored higher than non-musicians across subtests (subtest \times group, $p = .858$).

Supporting the hypothesis that music training is related to improvements in working memory (e.g., Chen et al., 2008; Franklin et al., 2008; Fujioka et al., 2006; Gunter et al., 2003; Lee et al., 2007; Parbery-Clark et al., 2009; Williamson & Egner, 2004), there were moderate positive correlations between years of music training across groups and average of visual memory task scaled scores ($r = .398, p < .05$), Digits Forward scores ($r = .365, p < .05$), Digits Backward scores ($r = .393, p < .05$), and the average of executive memory task scaled scores ($r = .371, p < .05$).

3.2. Behavioral responses in the ERP oddball task

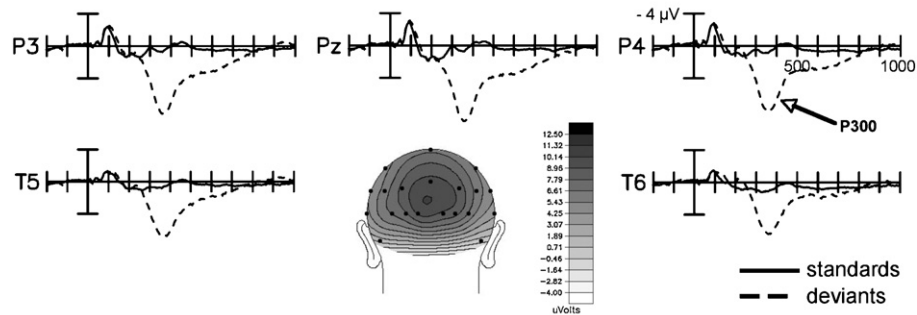
Overall, accuracy in responding to deviant stimuli was quite high in both the auditory (97.40%, SD 4.36%) and visual (96.80%, SD 3.96%) conditions. Accuracy in the musician group, on average, was 98.48% in the auditory condition and 97.31% in the visual condition. In the non-musician group, accuracy was 96.33% in the auditory condition and 96.29% in the visual condition. Accuracy scores appeared skewed, and a Shapiro–Wilk test confirmed that scores in both the auditory and visual conditions were not normally distributed (both $p = .001$). Thus, a Mann–Whitney’s U test was used to compare scores between groups, which showed that there was no significant difference in accuracy between groups in either the auditory ($z = -1.37, p = .170$) or visual ($z = -.533, p = .594$) domain.

There was also no significant difference between groups in reaction time to deviants in either the auditory ($t(30) = -1.029, p = .312$) or visual ($t(30) = -.627, p = .535$) condition. The musician group had a mean reaction time of 497.98 ms (SD 67.41 ms) in the auditory condition and 537.96 ms (SD 42.42 ms) in the visual condition. The non-musician group had a mean reaction time of 528.81 ms (SD 99.12 ms) in the auditory condition and 551.45 ms (SD 74.83 ms) in the visual condition.

3.3. ERPs: comparison of musicians and non-musicians

In the auditory condition (see Figs. 2A and 3A), an omnibus ANOVA with local peak amplitude measures

A Musicians: Auditory



B Musicians: Visual

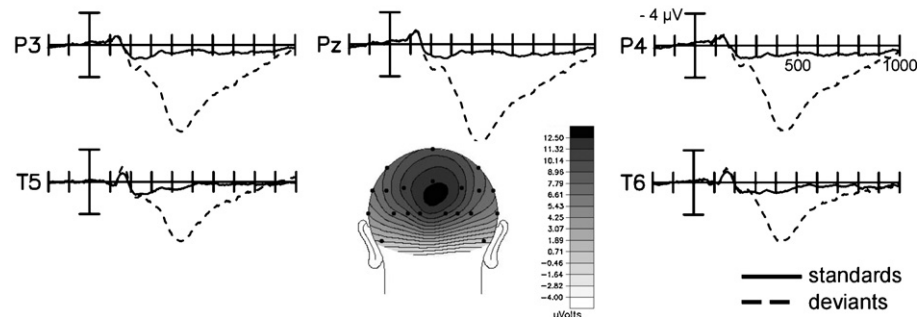
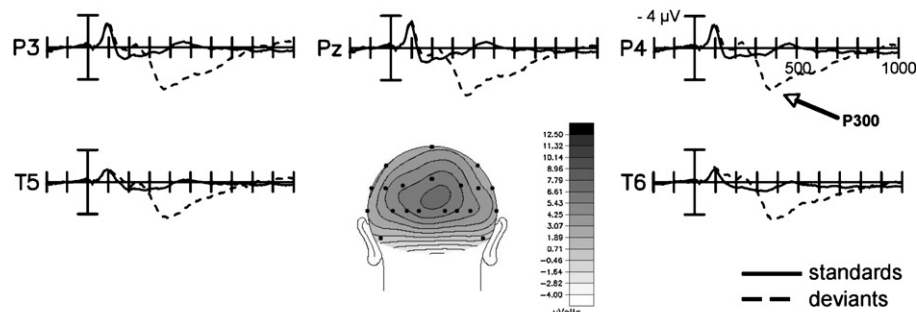


Fig. 2. Grand average ERP waveforms to standards (solid line) and deviants (dashed line) at temporoparietal sites for musicians in the (A) auditory and (B) visual conditions. The P300 elicited by deviants is labeled at site P4. Negative is plotted up, ticks mark 100 ms, stimulus onset was at time 0, and the calibration bar indicates 4 μ V. Pz is a midline site, P3/4 are medial sites, and T5/6 are lateral sites. The topographical voltage maps illustrate the distribution of the P300 to deviants across the scalp. A spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) was used to interpolate the potential on the surface of an idealized, spherical head based on the peak amplitude measures for the deviants at each electrode location.

A Non-musicians: Auditory



B Non-musicians: Visual

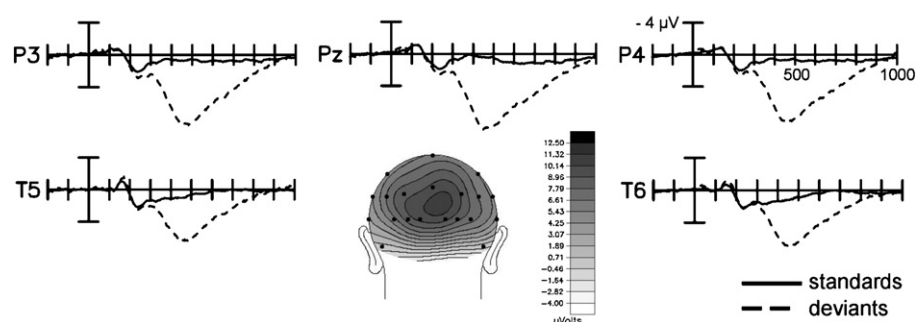


Fig. 3. Grand average ERP waveforms to standards (solid line) and deviants (dashed line) for non-musicians in the (A) auditory and (B) visual conditions. All else as in Fig. 2.

Table 1
Mean scaled scores (with SD) on the TOMAL-2 subtests for each group.

	AVM	MFL	AvgV	DF	LF	AvgP	DB	LB	AvgE
Musicians	12.25 (.86)	12.19 (1.87)	12.22 (1.03)	12.19 (1.28)	12.44 (2.10)	12.31 (1.50)	12.44 (2.13)	12.00 (2.92)	12.22 (2.29)
Non-musicians	11.56 (1.41)	10.81 (2.88)	11.19 (1.73)	11.19 (1.60)	10.88 (2.58)	11.03 (1.83)	10.71 (2.44)	10.94 (2.43)	10.84 (2.21)

Key: AVM, Abstract Visual Memory; MFL, Memory for Location; AvgV, average of visual short-term memory subtests AVM and MFL; DF, Digits Forward; LF, Letters Forward; AvgP, average of phonological short-term memory subtests DF and LF; DB, Digits Backward; LB, Letters Backward; AvgE, average of executive working memory subtests DB and LB.

taken at non-midline sites indicated that standards and deviants were processed differently across the scalp in musicians and non-musicians (group, $F(1, 30)=4.58, p<.05$; condition, $F(1, 30)=69.19, p<.001$; group \times condition, $F(1, 30)=4.52, p<.05$; group \times lateral/medial, $F(1, 30)=4.95, p<.05$; group \times condition \times lateral/medial, $F(1, 30)=5.07, p<.05$; group \times condition \times anterior/posterior \times lateral/medial, $F(5, 150)=3.93, p<.01$). A follow-up ANOVA focusing on deviants yielded a main effect of group ($F(1, 30)=4.83, p<.05$) such that the peak amplitude of the P300 elicited by auditory deviants was larger in musicians (mean $5.62 \mu V, SD 3.64$) than non-musicians (mean $3.49 \mu V, SD 4.32$), particularly at medial sites (group \times lateral/medial, $F(1, 30)=5.63, p<.05$; see Fig. 4). In similar analyses at midline sites, peak amplitude of the P300 to standards and deviants differed by group (group, $F(1, 30)=5.59, p<.05$; condition, $F(1, 30)=61.11, p<.001$; group \times condition, $F(1, 30)=7.$

$39, p<.05$). The follow-up analysis indicated that auditory deviants elicited a larger P300 in musicians (mean $7.10 \mu V, SD 4.05$) than non-musicians (mean $3.62 \mu V, SD 5.45$) at midline sites as well (group, $F(1, 30)=6.97, p<.05$) (Fig. 5).

Also in the auditory condition, the peak latency of the P300 to standards and deviants varied by group at non-midline sites (group \times condition, $F(1, 30)=6.69, p<.05$). Planned analyses indicated that auditory deviants elicited an earlier P300 in musicians (mean $362.23 \text{ ms}, SD 37.66$) as compared to non-musicians (mean $403.63 \text{ ms}, SD 70.67$; group, $F(1, 30)=7.21, p<.05$), particularly at posterior and medial sites (group \times anterior/posterior \times lateral/medial, $F(5, 150)=3.21, p<.05$). A similar pattern was apparent at midline sites, with differential processing of standards and deviants by group (condition \times group, $F(1, 30)=4.85, p<.05$) overall, driven by an earlier P300 to auditory deviants in musicians (mean $348.75 \text{ ms}, SD 29.80$)

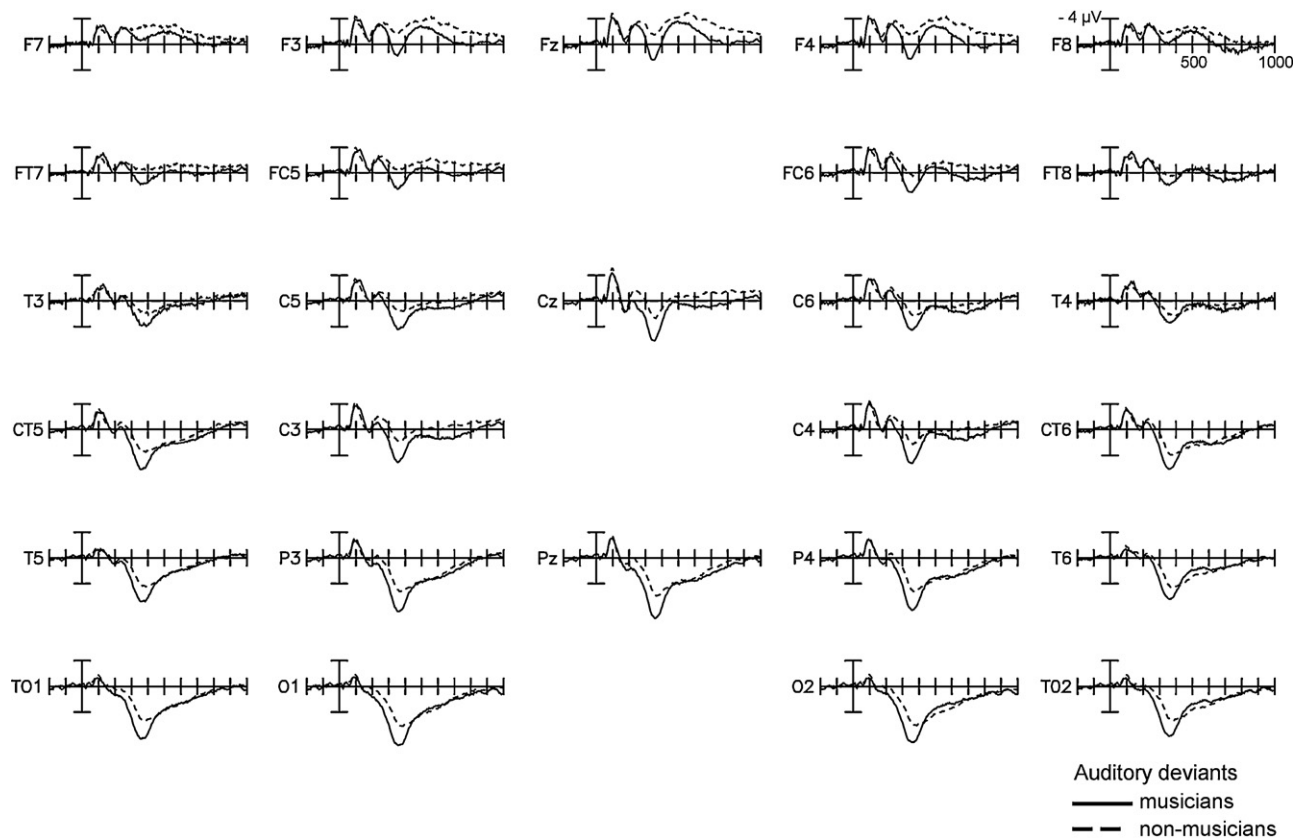


Fig. 4. Grand average ERPs to deviant stimuli across all electrode sites for musicians (solid line) and non-musicians (dashed line) in the auditory condition. More anterior sites are towards the top and more posterior sites are towards the bottom of the figure; midline sites are down the center, medial sites are towards the middle, and lateral sites are towards the edges of the figure. Negative is plotted up, ticks mark 100 ms, stimulus onset was at time 0, and the calibration bar indicates $4 \mu V$. Differences in both peak amplitude and peak latency of the P300 to auditory deviants were significant between groups.

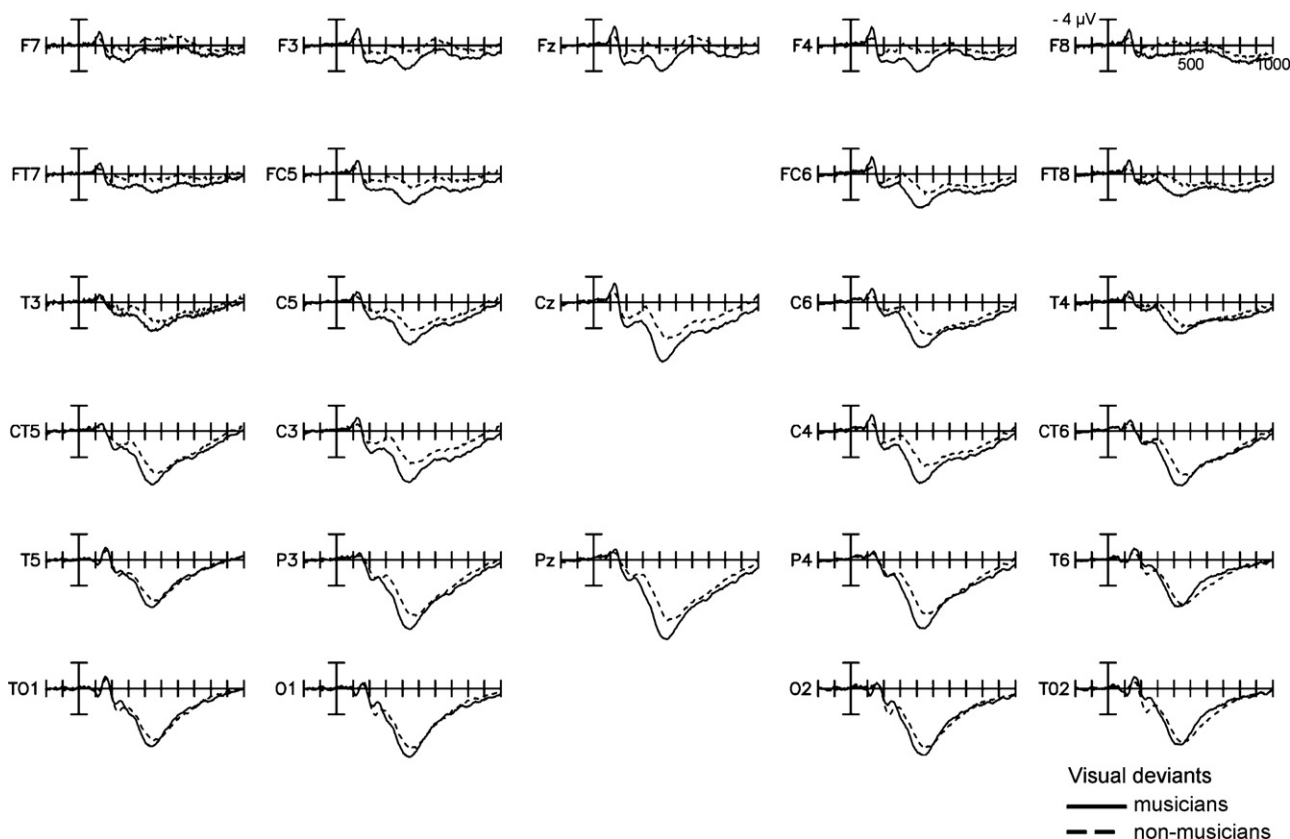


Fig. 5. Grand average ERPs to deviant stimuli across all electrode sites for musicians (solid line) and non-musicians (dashed line) in the visual condition. All else as in Fig. 4. Differences in peak amplitude of the P300 to visual deviants trended towards significance between groups, while differences in peak latency were significant between groups.

as compared to non-musicians (mean 390.58 ms, *SD* 71.06; group, $F(1, 30) = 5.82$, $p < .05$) (see Figs. 2b and 3B).

In the visual condition, the omnibus ANOVA with peak amplitude measures at non-midline sites indicated that standards and deviants were processed differently across the lateral/medial scalp by group (group \times condition \times lateral/medial, $F(1, 30) = 5.04$, $p < .05$). Follow-up analyses indicated a trend for visual deviants to elicit a larger P300 in musicians (mean 7.55 μ V, *SD* 3.79) than non-musicians (mean 6.11 μ V, *SD* 4.13), particularly at medial sites (group \times lateral/medial, $F(1, 30) = 3.82$, $p = .060$). Further follow-up ANOVAs at lateral (all effects involving group, $p > .172$) and medial (all effects involving group, $p > .109$) sites separately failed to indicate a significant group difference. A similar pattern was apparent at midline sites, with an interaction between group and condition overall ($F(1, 30) = 5.14$, $p < .05$) and a trend for visual deviants to elicit a larger P300 in musicians (mean 9.38 μ V, *SD* 4.97) than non-musicians (mean 6.79 μ V, *SD* 5.27) in follow-up analyses (group, $F(1, 30) = 3.78$, $p = .061$).

Also in the visual condition, the peak latency of the P300 to standards and deviants tended to differ across the scalp by group (group \times condition \times anterior/posterior \times lateral/medial, $F(5, 150) = 2.41$, $p = .051$). In follow-up analyses, visual deviants elicited an earlier P300 in musicians (mean 454.87 μ V, *SD* 85.56) than non-musicians (mean 513.17 μ V, *SD* 108.77; group, $F(1, 30) = 9.68$, $p < .01$), particularly at medial sites (group \times lateral/medial, $F(1, 30) = 5.67$, $p < .05$). In overall analyses at midline sites, no effects involving group were significant but the main effect of group showed a trend towards conventional significance levels ($p = .074$). Exploratory follow-up analyses of deviant processing only yielded a main effect of group ($F(1, 30) = 7.97$, $p < .01$) such that the P300

to visual deviants was earlier in musicians (mean 448.92 μ V, *SD* 83.67) than non-musicians (mean 510.92 μ V, *SD* 115.71).

3.4. Correlations between the ERP and behavioral data

Correlation analyses were conducted with the years of music training measure, the standardized subtest scaled scores, and average measures of P300 peak amplitude and latency taken at the posterior, medial sites at which the component was largest (average over P3/4, O1/2, and Pz). In the auditory domain, there were significant positive correlations between the peak amplitude of the P300 to auditory deviants averaged across the medial, posterior sites and performance on the TOMAL-2 Digits Forward ($r = .372$, $p < .05$) and Abstract Visual Memory ($r = .383$, $p < .05$) subtests. In addition, years of music training was moderately correlated with the peak amplitude of the auditory P300 ($r = .355$, $p < .05$). Similarly, there was a moderately strong negative correlation between peak latency of the P300 elicited by auditory deviants and years of music training ($r = -.434$, $p < .05$). In addition, P300 peak latency in the auditory condition was negatively correlated with performance on the Digits Forward task ($r = -.378$, $p < .05$).

In the visual domain, peak amplitude of the P300 to visual deviants was correlated with performance on the Abstract Visual Memory task ($r = .361$, $p < .05$). Years of music training was not correlated with P300 peak amplitude to visual deviants ($p = .21$). However, P300 peak latency to visual deviants was negatively correlated with years of music training ($r = -.470$, $p < .01$). In addition, peak latency of the visual P300 was negatively correlated with the average scaled scores for the visual memory tasks ($r = -.371$, $p < .05$).

4. Discussion

Analyses of both the ERP and behavioral test data revealed that previous long-term music training was associated with improvements in working memory in both the auditory and visual domains. Deviants in a classic oddball paradigm elicited significantly earlier P300s in musicians than non-musicians in both the auditory and visual conditions. Deviant tones also elicited a P300 with a larger peak amplitude in musicians than non-musicians, with a similar trend for deviant pictures in the visual oddball condition. Further, musicians outperformed their non-musician counterparts on all of the visual, phonological, and executive memory subtests administered from the TOMAL-2 (Reynolds & Voress, 2007). To our knowledge, this is the first study to use both standardized behavioral tests and matched ERP auditory and visual paradigms focused on working memory processing, consistent with current models of working memory (e.g., Baddeley, 2003), in the same subjects in order to compare musically untrained participants and musically trained nonprofessionals. Overall, the results indicate that some aspects of working memory do differ in musicians and non-musicians, providing empirical evidence to support the hypothesis that music training improves aspects of executive function (e.g., Hannon & Trainor, 2007; Schellenberg & Peretz, 2008).

4.1. P300 latency: auditory and visual paradigms

As predicted, a marked P300 component, widespread across the scalp but maximal at temporoparietal sites, was elicited by the deviant stimuli in both the auditory and visual oddball paradigms (e.g., see Polich, 2007). In both the auditory and visual conditions, deviant stimuli elicited an earlier P300 in musicians than in non-musicians, indexing faster stimulus evaluation and updating of both auditory and visual working memory in musicians (e.g., Donchin & Coles, 1988; Guo et al., 2008; Polich, 2007). This is consistent with previous findings showing that musicians were faster than non-musicians at classifying linguistic pitch stimuli (Marques et al., 2007; Schön et al., 2004), and previous reports of shorter-latency late positive components to auditory stimuli in musicians (e.g., Besson & Faïta, 1995; Schön et al., 2004). Interestingly, the latencies of the P300 to deviant stimuli in both conditions were correlated moderately with extent of music training (years of music training and auditory P300 latency, $r = -.434$; and visual P300 latency, $r = -.470$), such that the peak latency of the P300 decreased as years of music training increased, consistent with the suggestion that the observed latency differences between groups are related to music training.

Further, replicating a previous finding with adults (Polich et al., 1983), P300 latency in the auditory condition was negatively correlated ($r = -.368$) with performance on the Digits Forward task (Reynolds & Voress, 2007), showing that speed of processing the auditory deviant stimuli is associated with enhanced phonological working memory as measured by a specific standardized test. It is somewhat curious that a similar correlation was not observed with performance on the Letters Forward task, given that both are putative measures of phonological short-term memory. For both groups, there was greater variability on the Letters task, but while musicians scored slightly better with Letters than Numbers, non-musicians scored slightly worse. The lack of correlation is more likely due to a lack of power than to an indication that digit and letter recall rely on different phonological memory systems. In the visual condition, P300 latency was negatively correlated with not only scores on the Memory for Location task ($r = -.355$), showing a similar association between speed of processing visual deviants and visual working memory, but also scores on the Digits Forward ($r = -.359$) and Letters Backward ($r = -.353$) tasks (Reynolds & Voress, 2007). These subtests are thought to measure phono-

logical and executive aspects of working memory, respectively, suggesting that the visual ERP effect may be less specific to visual working memory. Skilled musicians are required to attend to and integrate auditory and visual information simultaneously on the order of milliseconds; it is possible that training that involves development of such an integration ability is reflected in the P300 latency differences observed here. Speculatively, these latency differences between groups may not be constrained to processing within the phonological loop or visuospatial sketchpad sensory stores, but extend to processing differences within the central executive related to controlling and allocating attention to incoming auditory and visual sensory information; we revisit this speculation below.

4.2. P300 amplitude: auditory paradigm

Deviant tones in the auditory oddball condition also elicited a significantly larger amplitude P300 in musicians than in non-musicians, consistent with previous ERP findings and reports of enhanced pitch processing in musicians as reviewed above (e.g., Brattico et al., 2009; Crummer et al., 1994; Fujioka et al., 2006; Hantz et al., 1992, 1995; Kuriki et al., 2006; Lappe et al., 2008; Marques et al., 2007; Moreno & Besson, 2006; Moreno et al., 2009; Münte, Nager, Beiss, Schroeder, & Altenmüller, 2003; Nikjeh et al., 2008; Schneider et al., 2002; Shahin et al., 2003, 2007, 2004; Strait et al., 2009; Tervaniemi et al., 2006; Trainor et al., 1999; Wayman et al., 1992). This larger P300 may be an indication of easier discrimination of auditory stimuli for musicians as compared to non-musicians; that is, the musicians may have been more sensitive to the differences between the auditory deviants and standards than the non-musicians (e.g., see Guo et al., 2008). Because P300 amplitude decreases with increasing task difficulty (e.g., Hantz et al., 1992; Polich, 2007), the current pattern of findings suggests that distinguishing the auditory deviants from the standards and updating the working memory store upon presentation of the deviants were more difficult or less efficient for the non-musicians. This is consistent generally with a conceptualization of working memory as dependent on individual or group differences (Pechmann & Mohr, 1992, p. 319) and more specifically with behavioral findings from an interference paradigm suggesting that “musicians use processes or strategies to maintain [auditory information]... within the context of working memory, which are not at the disposal of subjects with no special musical training or experience” (Berti et al., 2006, p. 115). Thus, it appears that auditory sensory memory mechanisms can be modulated by training (e.g., Koelsch, Schröger, & Tervaniemi, 1999, p. 1309) and that music training, in particular, may result in changes in memory for tones such that musicians are less “vulnerable to a manipulation of acoustic similarity” (Williamson et al., 2010, p. 172). It is important to note that there were no significant differences between groups in reaction time or button-press accuracy in the auditory (or visual) oddball task, so the observed electrophysiological differences are not due to differences in the ability (as measured by task performance) to distinguish the deviant and standard stimuli. Rather, the differences would appear to be due to the neural process of updating auditory working memory – processing within the phonological loop (e.g., Baddeley, 2003) – in the context of the oddball paradigm.

Consistent with this interpretation and previous work indicating that larger P300 amplitude is correlated with greater working memory capacity as measured by simple span tasks (Nittono et al., 1999), musicians also scored higher than non-musicians on the phonological memory subtests of the TOMAL-2 (Reynolds & Voress, 2007). Further, there was a moderate positive correlation ($r = .378$) between peak amplitude of the P300 to auditory deviants and performance on the Digits Forward task, speculatively suggesting that

the auditory oddball task and the auditory forward digit span task might draw upon similar phonological working memory resources. In addition, extent of music training was moderately correlated with peak amplitude of the auditory P300 ($r=.355$). Overall, the differences between groups in P300 peak amplitude and latency in the auditory oddball paradigm suggest that musicians more efficiently draw upon neural working memory resources to process auditory deviant stimuli.

4.3. P300 amplitude: visual paradigm

In contrast, the findings from the visual oddball paradigm are more ambiguous. While the P300 to visual deviants was markedly earlier in musicians than non-musicians as discussed above, P300 peak amplitude showed only strong trends towards being larger in musicians than non-musicians at medial and midline sites (follow-up statistics could not further clarify these trends). One possibility for this pattern of findings might be more variability in one group or the other with respect to peak amplitude of the P300; however, the mean peak amplitude of the P300 to visual deviants at non-midline sites in the musicians was $7.55 \mu\text{V}$ ($SD\ 3.79$) and in the non-musicians was $6.11 \mu\text{V}$ ($SD\ 4.13$), suggesting only a slight difference in variability. Another possibility is that differences between groups in updating visual working memory are subtler than differences in updating auditory working memory, and our design with sixteen participants per group did not have the power to unambiguously statistically document those differences. This would be consistent with the primarily auditory nature of a musician's skill, and previous behavioral findings in adults showing between-group differences only in the auditory domain (e.g., Chan et al., 1998; Lee et al., 2007; Parbery-Clark et al., 2009). Perhaps related, years of music training was not correlated with peak amplitude of the P300 to visual deviants; however, there was a moderate positive correlation ($r=.359$) between P300 peak amplitude to visual deviants and performance on the Abstract Visual Memory task (Reynolds & Voress, 2007), suggesting the possibility of overlapping visual working memory resources used in the performance of these tasks.

As noted above, overall, the literature on visual working memory in relation to music training in children and adults is mixed, with some studies reporting improved visual processing in musicians in comparison to non-musicians (e.g., Bugos et al., 2007; Helmbold et al., 2005; Jakobson et al., 2008; Kalakoski, 2007; Zafran, 2004) and others reporting no effect of music training on visual memory or attention (e.g., Chan et al., 1998; Ho et al., 2003; Strait et al., 2010). These contradictory findings may in part be due to the varied tasks that have been used as measures of visual memory – from the Trail Making Test to design recall. Here, the ERP visual memory task was matched as closely as possible to the ERP auditory memory task in order to provide a controlled comparison between domains. Although our findings do not speak to why music training might be associated with improved visual working memory, speculatively, it may be that training in reading music, in combination with playing an instrument, affects visual memory and attention (e.g., Bugos et al., 2007). Improvements in central executive attention with music training may also play a role, a possibility discussed at more length below.

It may be important to note in this context that the college student participants in the present study were skilled and active musicians, but not professional or expert musicians. It may be the case that the trend for neural differences in updating visual working memory observed here would have been stronger in professional musicians (cf. Lee et al., 2007, but see Lotze, Scheler, Tan, Braun, & Birbaumer, 2003 and Tervaniemi et al., 2006, for differences between amateurs and professionals, amateurs

and non-musicians). Consistent with this interpretation, studies of expert musicians with conservatory training have reported improvements in quick visual processing (Helmbold et al., 2005) and delayed visual recall (Jakobson et al., 2008). Overall though, the strong statistical trends, if not the correlation data, do suggest that distinguishing the visual deviants from the standards and updating the visual working memory store upon presentation of the deviants tended to be more difficult or less efficient for the non-musicians, implying visual working memory differences – differences in processing within the visuospatial sketchpad (e.g., Baddeley, 2003) – between groups.

4.4. Standardized tests of working memory

Consistent with this interpretation, the musician group outperformed the non-musician group on standardized subtests of the TOMAL-2 (Reynolds & Voress, 2007) indexing all three components of Baddeley's (1992, 1998) model of working memory: phonological, visual, and executive. In addition, there were positive correlations between years of music training and average visual memory scores, phonological memory task scores (Digits Forward), and executive memory (Digits Backward) and average executive memory task scores, such that as music training increased, performance on these TOMAL-2 measures increased. Thus, the results from the behavioral measures provide further support for the hypothesis that music training is related to improvements in multiple aspects of working memory (e.g., Besson, Schön, Moreno, Santos, & Magne, 2007; Lee et al., 2007; Williamon & Egner, 2004). Such working memory span tasks are thought to index a "fundamental capacity that underpins complex as well as elementary cognitive processes" (Lépine, Barrouillet, & Camos, 2005, p. 165), and so in turn may at least in part underlie the transfer effects observed with music training.

4.5. Accuracy and reaction time in the oddball tasks

In contrast to the standardized tests of memory, behavioral measures of accuracy and reaction time in the oddball tasks, as noted above, did not differ significantly between the musician and non-musician groups. Previous studies have reported higher accuracy in musicians as compared to non-musicians on behavioral measures of pitch discrimination; however, these studies employed more difficult and varied discrimination tasks than used here (e.g., Berti et al., 2006; Hantz et al., 1992, 1995; Marques et al., 2007; Moreno & Besson, 2006; Moreno et al., 2009). Replicating the pattern observed here, others have also reported differences in pitch discrimination at the neural level unaccompanied by performance differences in accuracy and reaction time (e.g., Brattico et al., 2009; Fujioka et al., 2006; Kuriki et al., 2006; Schneider et al., 2002; Shahin et al., 2003, 2004, 2007; Wayman et al., 1992). Here, the performance-matched accuracy and reaction time measures allow for an interpretation of the observed P300 amplitude and latency differences in terms of the process of updating working memory without the confounds of performance differences and the motor response (Donchin & Coles, 1988; Polich, 2007). With the functional ability to correctly identify deviant stimuli held constant, the P300 amplitude and latency differences are even more clearly interpretable in terms of "task difficulty" (Hantz et al., 1992; Polich, 2007) and the neural ease and efficiency with which working memory is updated.

4.6. Training-related or intrinsic?

Overall, both the ERP and TOMAL-2 data from the current study are consistent with the hypothesis that music training is associated with improved working memory. However, it could be argued

that, because this was not a longitudinal study with random assignment of participants, a causal relationship cannot be inferred: music training may induce brain plasticity or music training may build on pre-existing neural differences in participants. Existing literature does support a causal inference. A number of previous music training studies with children reporting a link between music training and enhancements in a variety of cognitive abilities, such as verbal memory, reading skills, and speech, have used random assignment (e.g., Besson et al., 2007; Moreno & Besson, 2006; Moreno et al., 2009). This experimental control of experience is a strong argument for training-induced brain plasticity (e.g., Kraus & Banai, 2007; Kraus & Chandrasekaran, 2010; Lappe et al., 2008).

Evidence from imaging studies also supports this interpretation (for a review, see Münte, Altenmüller, & Jäncke, 2002). For example, in a recent MRI study, there were no differences between the brains of children who were starting music lessons and those who were planning on taking lessons (Norton et al., 2005); this suggests that neural differences between musicians and non-musicians are reflective of training-induced plasticity, not inherent differences between groups. Structurally, in expert musicians, there are positive correlations between gray matter volume in specific regions and level of musical expertise, amount of practice, and level of musicianship (e.g., Amunts et al., 1997; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Gaser & Schlaug, 2003; Habib & Besson, 2009; Pantev et al., 1998). Moreover, neuroanatomical and functional adaptations with music training appear to be specific to the instrument played (e.g., Bangert & Schlaug, 2006; Peretz & Zatorre, 2005; Shahin et al., 2004). Further, functionally, a recent fMRI report indicated that processing in the hippocampus related to auditory temporal novelty was enhanced in students studying music, and longitudinal analyses indicated that the hippocampal effects were due to training rather than predisposition (Herdender et al., 2010). (Interestingly, there is some evidence that the P300 may be generated in limbic regions (Halgren et al., 1980).) Finally, Gaab and Schlaug (2003) reported that musicians activated brain regions specialized in short-term memory while non-musicians relied on regions involved in pitch discrimination during an fMRI pitch memory task; because the groups' task performance was matched (as is the case in the present study), the authors concluded that the results indicated processing differences between groups related to music training. Taken together, these findings strongly suggest that neuroanatomical and functional differences seen in the brains of musicians as compared to non-musicians, such as the differences in working memory processing observed here, are training-related and not intrinsic to those individuals (see also, e.g., Hyde et al., 2009).

4.7. Caveats

Another potential criticism of the present study might be that our interpretation of the results focuses primarily on working memory. An alternative, and not mutually exclusive, interpretation is that the results reflect increased ability to focus attention in musicians as compared to non-musicians. Indeed, musicians outperformed non-musicians on all of the subtests of the TOMAL-2 and there was ERP evidence for more efficient processing of deviants in musicians in both the auditory and visual conditions; surely this summative pattern of findings could suggest a general attention effect. We have focused on a working memory interpretation because the P300 in the oddball paradigm is related specifically to updating working memory (e.g., Donchin & Coles, 1988) and because the behavioral tests were specifically tests of memory (Reynolds & Voress, 2007). However, to the extent that memory and attention can be differentiated in such measures and paradigms, we would speculate that improved

attention skills in musicians were likely to have contributed to our findings. Thus, in terms of the Baddeley's (1992, 1998, 2003) model, we might contend that there is some evidence here for an association between music training and improvements in phonological/articulatory loop, visuospatial sketchpad, and central executive processing.

A further criticism might be that still other differences between the two groups could have contributed to the observed working memory differences; musical experience may not be the only explanation for the better performance of the musician group as compared to the non-musician group. For example, the musician and non-musician groups might have differed in terms of IQ. Indeed, previous findings with children have indicated that music training enhances full-scale IQ, for which one of the component measures is digit span – a traditional test of working memory (e.g., Schellenberg, 2004). However, another study investigating associations between music training and verbal and visual memory found that between-group differences in memory remained even after controlling for IQ (Jakobson et al., 2008). In addition, others have reported no differences in full-scale IQ between musicians and non-musicians (e.g., Brandler & Rammsayer, 2003; Franklin et al., 2008; Helmbold et al., 2005). Typically, perhaps because of such findings, most extant studies of the effects of musical training on memory have not considered the possible influence of IQ (e.g., Chan et al., 1998; Forgeard et al., 2008; Ho et al., 2003).

Given the close relation between working memory and IQ (e.g., Conway, Kane, & Rangle, 2003), the possibility of IQ differences between groups contributing to the observed effects in the present context could be seen to lead to a somewhat circular argument. Recent ERP data do not help to clarify this conundrum. For example, in one study using five subtests of the Wechsler Intelligence Scale for Children, only scores on the Digits Forward subtest – a measure of working memory – were correlated with P300 latency in an auditory oddball paradigm (as found here, shorter latency was associated with longer span, Boucher et al., 2010). In another study of fluid intelligence as measured by Raven Progressive Matrices scores, women with higher scores showed larger and earlier P300s in an auditory oddball paradigm with backward masking, leading the authors to conclude that “a substantial portion of the variance in general intelligence is attributable to the speed and efficiency with which” working memory is updated (De Pascalis, Varriale, & Matteoli, 2008, pp. 45, 44). Such evidence for a complex and overlapping relation between working memory and IQ suggests that IQ might be involved in the association between working memory and music training observed here, but does not necessarily suggest that IQ is the driving force. Indeed, yet another variable might be influencing both previously observed IQ changes (e.g., Schellenberg, 2004) and the presently observed working memory changes with music training. Although further research is needed to clarify these relations, overall, in evaluation of the hypothesis that music training improves aspects of executive function (e.g., Hannon & Trainor, 2007; Schellenberg & Peretz, 2008), the differences in working memory observed here at both the behavioral and electrophysiological levels provide positive support. That other factors may also be in play does not invalidate this conclusion, especially considering that the current study was designed specifically to address this hypothesis.

4.8. Summary

In summary, the findings of this study demonstrate that long-term music training in non-professional musicians is associated with improvements in working memory, in both the auditory and visual domains and on both behavioral and ERP measures, and perhaps with improvements in attention. Musicians outperformed non-musicians on standardized subtests of visual, phonological,

and executive memory. In addition, musicians demonstrated faster updating of auditory and visual working memory representations and more efficiently drew upon working memory resources to process auditory deviant stimuli. To our knowledge, this is the first study to use both behavioral and electrophysiological measures to address directly the hypothesis that music training improves aspects of executive function (e.g., Schellenberg & Peretz, 2008) in both auditory and visual domains; our positive findings can serve as a foundation for further research investigating the mechanisms mediating the association between music training and improvements on a variety of skills.

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