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Tuning the mind: Exploring the connections between musical ability and executive functions

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ABSTRACT

A growing body of research suggests that musical experience and ability are related to a variety of cognitive abilities, including executive functioning (EF). However, it is not yet clear if these relationships are limited to specific components of EF, limited to auditory tasks, or reflect very general cognitive advantages. This study investigated the existence and generality of the relationship between musical ability and EFs by evaluating the musical experience and ability of a large group of participants and investigating whether this predicts individual differences on three different components of EF – inhibition, updating, and switching – in both auditory and visual modalities. Musical ability predicted better performance on both auditory and visual updating tasks, even when controlling for a variety of potential confounds (age, handedness, bilingualism, and socio-economic status). However, musical ability was not clearly related to inhibitory control and was unrelated to switching performance. These data thus show that cognitive advantages associated with musical ability are not limited to auditory processes, but are limited to specific aspects of EF. This supports a process-specific (but modality-general) relationship between musical ability and non-musical aspects of cognition.

1. Introduction

The ability to control and regulate our thoughts and behavior, termed *executive function* (EF; also *executive control* or *cognitive control*), plays a critical role in nearly every aspect of cognition (Engle, 2002). It is often argued that there are three core EFs (e.g., Diamond, 2013; Logue & Gould, 2013; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000): *inhibition* refers to the ability to control attention, behavior, and thoughts, especially in the face of conflicting responses; *updating* refers to the ability to continuously monitor information and to rapidly add and remove information from working memory; and *switching* refers to flexibly switching between tasks or mental sets. These processes are closely related but separable; for example, individual differences in EF components relate differentially to complex "frontal lobe" tasks (Miyake et al., 2000) and to general intelligence (Friedman et al., 2006).

Among the complex activities that rely on EFs are the perception and production of music. Active music listening involves building complex cognitive representations of musical structure (e.g., Koelsch, Rohrmeier, Torrecuso, & Jentschke, 2013; Lerdahl & Jackendoff, 1983; Patel, 2008), generating musical expectancies (e.g., Huron, 2006; Margulis, 2005; Meyer, 1956; Rohrmeier & Koelsch, 2012), and detecting and resolving musical ambiguities (e.g., Jackendoff, 1991; Slevc & Okada, 2015); all processes that plausibly draw on EFs. Producing and learning music likely involves even greater EF demands. For example, music is most often played in coordination with others (Palmer, 2013), which requires *switching* between multiple auditory streams (Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013) and adjusting to other performers (e.g., Loehr & Palmer, 2011; Moore & Chen, 2010). Thus music performance may be associated with relatively general switching advantages, and musicians have indeed been found to outperform non-musicians on switching tasks (Hanna-Pladdy & MacKay, 2011; Moradzadeh, Blumenthal, & Wiseheart, 2014; see also Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh, 2007; Zuk, Benjamin, Kenyon, & Gaab, 2014).

Playing music with other performers not only requires shifting attention, but also exercising *inhibitory control* to monitor for conflict and to make corresponding adjustments to one's own performance (Jentzsch, Mkrtchian, & Kansal, 2014; Palmer, 2013). Processing complex polyrhythms (e.g., tapping a main meter with one hand and a counter meter with another) also requires

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inhibitory control (Vuust, Roepstorff, Wallentin, Mouridsen, & Østergaard, 2006; Vuust, Wallentin, Mouridsen, Østergaard, & Roepstorff, 2011). Musical experience might therefore lead to general inhibitory control advantages (Moreno & Farzan, 2015). In fact, adult musicians show faster responses than non-musician controls in conflict conditions of both a pitch-based auditory Stroop task and in a visual "Simon Arrows" task (Bialystok & DePape, 2009), musicians outperform non-musicians on a stop-signal task (Strait, Kraus, Parbery-Clark, & Ashley, 2010; see also Moreno, Wodniecka, Tays, Alain, & Bialystok, 2014), and professional musicians show smaller color/word Stroop interference effects than amateur musicians (Travis, Harung, & Lagrosen, 2011). These findings are not limited to college-aged participants: five-year-old children assigned to a four-week intensive computerized musical training improved more than a visual art training control group on a go/no-go task (and showed corresponding changes in electrophysiological responses; Moreno et al., 2011). Similarly, older adults showed reduced Stroop interference following four months of piano training, unlike an age-matched group pursuing other leisure activities (Seinfeld, Figueroa, Ortiz-Gil, & Sanchez-Vives, 2013). Older adult musicians have also been found to outperform age matched non-musicians on a composite measure of typical cognitive control tasks (Amer, Kalender, Hasher, Trehub, & Wong, 2013).

Finally, sight-reading music involves playing while simultaneously looking ahead in the score, thus sight-readers are constantly *updating* which notes have been played and which are yet-to-be-played. Skilled sight-readers fixate several notes ahead of where they are playing (Furneaux & Land, 1999; cf. Drake & Palmer, 2000) and, accordingly, sight-reading ability is related to non-musical measures of memory control (Kopiez & Lee, 2008; Meinz & Hambrick, 2010). Furthermore, primary school students in a 1.5-year music-training program improved more than a control group (natural science training) on tasks of working memory updating (counting span and complex span; Roden, Grube, Bongard, & Kreutz, 2014). Finally, there is evidence that musicians outperform non-musicians on *n-back* tasks (Oechslin, Van De Ville, Lazeyras, Hauert, & James, 2013; see also Pallesen et al., 2010).

In sum, there is a range of evidence that musical experience and ability predicts performance on tasks tapping switching, inhibition, and updating. Nonetheless, this evidence is somewhat mixed overall (e.g., Schellenberg, 2011; cf. Elpus, 2013) and our understanding of these mixed results remains limited for at least three reasons. First, past studies have typically discussed EFs only generally without systematically differentiating between various aspects of EF. To our knowledge, only two studies have systematically investigated multiple components of EF: one found that duration of music lessons in children correlated with performance on multiple EF tasks (Degé, Kubicek, & Schwarzer, 2011) but another found no such relationships (Schellenberg, 2011). Relatedly, the modality-specificity or generality of these effects remains unclear. While some work suggests that musician advantages in EF (and other cognitive abilities) may be limited to auditory tasks (e.g., Hansen, Wallentin, & Vuust, 2013; Strait, O'Connell, Parbery-Clark, & Kraus, 2014; Strait et al., 2010; cf. Carey et al., 2015), other studies find effects in the visual modality as well (e.g., Bialystok & DePape, 2009; Oechslin et al., 2013), but there have been few investigations using comparable auditory and visual EF tasks. Second, relevant studies have targeted a variety of populations (ranging from primary school children to elderly adults), have used a variety of experimental tasks, and have used a wide variety of criteria to distinguish musicians from non-musicians. It is thus difficult to compare results across studies and unclear whether discrepant results reflect differences in tasks, populations, or group criteria. Third, potential confounds have rarely been assessed, so observed relationships might actually reflect some other difference between those who do and do not pursue musical training. For example, socio-economic status (SES) predicts both engagement in music (e.g., Corrigall, Schellenberg, & Misura, 2013; Norton et al., 2005) and EF abilities (Hackman & Farah, 2009), yet has only rarely been considered in these correlational studies. This combination of various populations, various measures, and potential confounds make it difficult to assess the overall relationship between musical experience and EF processes.

The goal of the current study was to address these three issues by investigating multiple components of EF (inhibition, updating, and switching) using both auditory and non-auditory tasks, and to examine how individual differences in these component functions relate to a continuous measure of musical ability. Furthermore, we included a set of covariates (including SES) in order to reach a more comprehensive understanding of the specific relationships between musical ability and EF.

2. Method

2.1. Participants

Ninety-six participants (49 women) were recruited from the University of Maryland community via flyers and email lists, and received $10/h for their participation in two 1¼-h experimental sessions. To ensure a wide spread of musical experience, recruitment targeted 48 participants with less than two years of formal musical training and 48 participants with at least five years of formal musical training. Although participants were recruited as two distinct groups, musical experience and ability are unlikely to reflect underlying dichotomous factors; therefore we rely on continuous measures of musical experience and ability as detailed below.[1] (Details on participants' musical experience are presented in supplemental materials online.)

Two participants who did not report having normal hearing were excluded from all analyses, as was one additional participant who scored more than 3.5 standard deviations away from the mean on two of the six EF tasks. One other participant did not correctly perform the visual switching task and so was excluded from analyses involving that task. Although all participants reported using English as their primary/dominant language, five participants did report speaking a language other than English as their first. Excluding these five participants did not change the overall pattern of results and they are therefore included in the analyses reported below. Thirty-eight participants (42%) spoke more than one language with at least adequate proficiency (as assessed by the LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007; see below for details) and an additional 19 (20%) reported minimal proficiency in a language other than English. Eight participants were left-handed (i.e., had negative scores on the Edinburgh Handedness Inventory; Oldfield, 1971), although laterality indices were somewhat variable overall (see Table 1).

2.2. Materials

The critical tasks and measures are summarized in Table 1 and described below. We analyzed logarithmically transformed RTs for all tasks involving response time (RT) measures, but note that analyses of trimmed raw RTs after excluding all responses farther than 2.5 standard deviations from each participant's mean RT yielded the same pattern of statistical results.

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[1] One additional reason not to rely on group assignment is that our participants did not appear to have been overly concerned about meeting group criteria; e.g., eleven participants who responded to the 'musician' recruitment ads later reported having had between 0–5 years of music lessons. This may simply reflect the specific way musical experience was assessed; see note *e* of Table 1, below.

Table 1
Dependent measures and descriptive statistics for the tasks and questionnaires used in this study across all participants.

Task (& dependent measure)	Mean (SD)	Range	Reliability[a]
Executive functions			
Inhibition (response time in ms)[b]			
Auditory Stroop task			
Incongruent	618 (139)	374–991	
Congruent	543 (122)	351–886	
Difference (inhibition effect)	75 (35)	−4 to 164	0.70
Visual Simon task			
Incongruent	420 (49)	320–576	
Congruent	395 (53)	292–575	
Difference (inhibition effect)	25 (20)	−21 to 83	0.76
Updating (accuracy: proportion hits minus proportion false alarms)			
Auditory pitch-back task			
2-back	0.53 (0.29)	−0.23 to 1.00	
3-back	0.24 (0.26)	−0.31 to 0.84	
4-back	0.19 (0.22)	−0.33 to 0.65	
Combined	0.32 (0.22)	−0.15 to 0.73	0.92
Visual letter-back task			
2-back	0.75 (0.27)	−0.44 to 1.00	
3-back	0.46 (0.32)	−0.81 to 1.00	
4-back	0.36 (0.27)	−0.58 to 0.94	
Combined	0.52 (0.25)	−0.52 to 0.97	0.95
Switching (response time in ms)[c]			
Auditory switching task			
Switch RT	1152 (287)	601–1919	
Stay RT	943 (215)	507–1505	
Difference (switching cost)	209 (1 2 2)	−18 to 654	0.82
Visual switching task[d]			
Switch RT	1140 (347)	598–2180	
Stay RT	688 (127)	505–1208	
Difference (switching cost)	452 (268)	−72 to 1290	0.97
Musical ability			
Ollen Musical Sophistication Index (OMSI)			
Years of musical training[e]	4.36 (5.49)	0–22	
Years of regular practice	5.22 (6.01)	0–23	
Combined OMSI score	310.92 (274.83)	17–992	
Musical Ear Test (MET; accuracy: proportion hits minus proportion false alarms)			
Melody subtest	0.46 (0.23)	−0.08 to 0.88	
Rhythm subtest	0.41 (0.23)	−0.12 to 0.85	
Combined MET score	0.44 (0.21)	0.02–0.85	0.88
Other measures			
Age	20.84 (3.29)	18–32	
Socioeconomic Status (MacArthur scale of subjective social status; 1 = lowest, 10 = highest)[f]			
Community Ladder	6.23 (1.72)	1.5–10	
US Ladder	6.40 (1.68)	2.0–9.5	
Combined Ladder Scores	6.32 (1.38)	3.5–9.5	
L2 proficiency (self-ratings: 0 = none and 10 = perfect)			
Speaking	3.21 (3.20)	0–10	
Understanding	3.59 (3.45)	0–10	
Reading	3.22 (3.34)	0–10	
Average L2 proficiency rating	3.34 (3.22)	0–10	
Handedness (−100 = strongly left handed; +100 = strongly right handed)			
Edinburgh Index	62.10 (47.73)	−95 to 100	

Note: N = 93.

[a] Split-half correlations adjusted by the Spearman-Brown prophecy formula.

[b] Response times from correct trials only. Accuracy rates were high overall and showed the same pattern: higher accuracy on congruent than incongruent trials for both auditory (97.6% vs. 93.0%; $t(92) = -8.36$) and visual (98.5% vs. 94.2%; $t(92) = -9.19$) inhibition tasks.

[c] Response times from correct trials only. Accuracy rates showed the same pattern, with higher accuracy on switch than stay trials for both auditory (89.2% vs. 86.7%, $t(92) = -7.16$) and visual (94.3% vs. 90.7%, $t(91) = -9.90$) switching tasks.

[d] One participant who did not switch between visual tasks was excluded from these measures, thus N = 92 for the visual switching task.

[e] One might expect the average years of musical training to be at least five, given that half of the participants were recruited as having "at least five years of formal musical training." The lower average value here likely reflects a difference between our recruitment criteria (of "formal musical training") and how musical training is assessed in the OMSI, which asks, "How many years of *private* music lessons have you received?" (italics added).

[f] One participant did not complete the SES scales, so N = 92 for this measure.

2.2.1. Measures of executive functions

Three different subcomponents of EFs–inhibition, updating, and switching (Diamond, 2013; Miyake et al., 2000)–were assessed both in auditory and non-auditory modalities.

2.2.1.1. Inhibition. Individual differences in inhibitory control ability were assessed with auditory and visual tasks based on the specific implementations used by Bialystok and DePape (2009). In the *auditory Stroop task* (Hamers & Lambert, 1972), participants heard the words "high" or "low" on either a high pitch (D4) or a low pitch (D2), and were instructed to categorize the pitch of each stimulus as quickly and accurately as possible by pressing the right mouse button for high pitches or the left mouse button for low pitches.[2] In the *visual Simon arrows task* (Simon & Rudell, 1967), participants saw left- or right-pointing arrows on either the left or right side of the screen, and were instructed to indicate the direction the arrow was pointing as quickly and accurately as possible by pressing the mouse button corresponding to the arrow direction.

In both tasks, participants first performed a block of 96 categorization trials (preceded by 10 practice trials) for only the task-relevant aspect of the stimuli to ensure familiarity with both aspects of the task (i.e., categorized the pitch of neutral syllables ("ahh") and categorized the arrow direction for arrows presented in the center of the screen). Participants then completed a critical block of 192 trials (preceded by 20 practice trials) presented in a random order with equal representation of each possible stimulus, thus half of the stimuli were congruent and half incongruent. Performance was evaluated as the difference between response times in the congruent and the incongruent conditions, so that higher scores indicate better inhibitory control.

2.2.1.2. Updating. Individual differences in memory updating ability were assessed with auditory and visual *n-back* tasks (Jonides et al., 1997; Kirchner, 1958), often used as measures of working memory (e.g., Owen, McMillan, Laird, & Bullmore, 2005). In the *auditory pitch-back task,* participants heard a series of 500 ms long sinewave tones drawn from a single C-major scale (i.e., there were eight discrete pitches) and were instructed to respond when hearing a pitch matching the pitch heard n tones previously. In the *visual letter-back task,* participants saw a series of single letters drawn from a set of eight letters (chosen to be visually distinct: C, D, G, K, P, Q, T, V) presented for 500 ms each, and were instructed to respond when seeing a letter matching the letter seen n letters previously. In both task versions, the interstimulus-interval was set to 2500 ms.[3]

For both updating tasks, participants first practiced 1, 2, 3, and 4 back trials (one block of each), then performed three blocks of 2-back trials, three blocks of 3-back trials, and three blocks of 4-back trials in that order. Each block consisted of $20 + n$ stimuli, of which the last 20 stimuli included 6 targets (i.e. items that matched the stimulus presented n items previously). The dependent variable was represented by the proportion of hits minus the proportion of false alarms across the three load levels (Jaeggi, Buschkuehl, Perrig, & Meier, 2010; Jaeggi, Studer-Luethi et al., 2010), thus higher scores indicate more accurate working memory updating performance.

2.2.1.3. Switching. Individual differences in switching ability were assessed with cued alternating runs switching paradigms (Rogers & Monsell, 1995) where participants heard or saw bivalent stimuli and had to switch between responding to one of the two stimulus dimensions in a predictable, cued pattern. In the *auditory switching task*, participants heard a series of 500 ms long tones and switched every two trials between categorizing the pitch (high or low) when the tone played in the right ear and the timbre (string or wind instrument) when the tone played in the left ear. Pitches and timbres were chosen to be easily distinguishable: High and low pitches were separated by at least three octaves (A5 and C6 were the high pitches and A2 and F#2 were the low pitches) and timbres were flute and tuba for the wind instruments and cello and viola for the strings. In the *visual switching task*, participants saw a series of letter-number pairs and switched (every two trials) between categorizing the number when the stimulus appeared on the right side of the screen (odd or even; from the set 4, 5, 8, or 9), or the letter when the stimulus appeared on the left side of the screen (consonant or vowel; from the set of A, I, G, and K).

For both switching tasks, stimuli were preceded by a 250 ms fixation cross and trials were separated by 150 ms after a correct response or by 1500 ms after an erroneous response (following Rogers & Monsell, 1995). Participants first practiced each task separately (four blocks where participants performed 24 trials of task 1 and then 24 trials of task 2). In these practice blocks, tasks were always presented with the appropriate location cue used to cue the task in the following switching blocks – i.e., pitch categorization was always played to the left ear and timbre categorization was always played to the right ear; number categorization was always on the left side of the screen and letter categorization was always on the right. In the visual task, practice trials were paired with a neutral stimulus (#, ?, *, or %) instead of the alternate task stimulus (e.g., a practice number trial might be "#4" and a practice letter trial might be "A%"). Participants then practiced 24 trials of the switching task, then performed five critical blocks of 64 trials each. Performance was evaluated as the difference between response time on stay (no-switch) trials and response time on switch trials, so that higher scores indicate better switching performance.

2.2.2. Measures of musical experience and ability

We assessed individual differences in musical experience and ability with two measures: one self-report measure primarily evaluating musical experience and one behavioral measure evaluating ability to process musically-relevant stimuli. The relationship between musical *aptitude* and musical *experience* is somewhat controversial (see Schellenberg & Weiss, 2013, for discussion) and it is unlikely that musical aptitude and experience can be distinguished in this sort of cross-sectional design. Thus we use the term "musical ability" broadly, assuming that individual differences on both measures reflect some degree of underlying musical aptitude as well as effects of training and experience.

2.2.2.1. Ollen Musical Sophistication Index (OMSI). Musical experience was assessed with the Ollen Musical Sophistication Index (OMSI; Ollen, 2006),[4] consisting of ten self-report questions assessing musical training and experience. These include questions commonly used in previous research investigating effects of musical training, including years of musical training and age of onset of musical training, however the OMSI also provides a composite score that indicates the probability that a music expert would categorize the participant as musically sophisticated (i.e., the test battery was developed using expert ratings as a criterion variable, such that the questionnaire accurately predicts experts' classifications). This

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[2] Unlike Bialystok and DePape (2009), we did not include the reverse task (categorizing words in the face of congruent or incongruent pitch) both because Bialystok and DePape (2009) found effects of musical training only on the pitch categorization task and for reasons of time.

[3] It was found after data collection that the software presented the auditory stimuli with a slight delay (on average, 95 ms), which resulted in an effective interstimulus-interval of about 2,595 ms for the auditory updating task.

[4] The OMSI is also available online: http://marcs-survey.uws.edu.au/OMSI/.

score ranges from zero to 1000, with higher scores indicating higher levels of musical sophistication, and produces better classification than many other commonly used measures (e.g., years of training; Ollen, 2006).

2.2.2.2. Musical Ear Test (MET). Musical ability was assessed with the Musical Ear Test (MET; Wallentin, Nielsen, Friis-Olivarius, Vuust, & Vuust, 2010), which requires participants to judge whether two short musical stimuli are the same or different. In the *melody subtest* (MET-M), participants hear 52 sets of two melodies that do or do not include a note differing in pitch (with half of these pitch deviations also causing a difference in melodic contour). In the *rhythm subtest* (MET-R), participants hear 52 sets of two short rhythms (in wood-block beats) where the second rhythm does or does not contain one rhythmic change. The MET is similar to other commonly used tests of musical ability such as the Advanced Measures of Musical Audiation (AMMA; Gordon, 2007), however the MET offers the practical advantage of taking less time to administer (approximately 20 min) while still having good psychometric properties (Wallentin et al., 2010).

2.2.3. Other background and demographic measures

We focused on four potential confounding factors: age, SES, handedness, and bilingualism. SES, which is related both to engagement in music (Corrigall et al., 2013; Norton et al., 2005) and to EF abilities (Calvo & Bialystok, 2014; Hackman & Farah, 2009), was evaluated with the MacArthur Scale of Subjective Social Status (Adler & Stewart, 2007). On this measure, participants mark the rungs, on two ten-step pictorial ladders, corresponding to their perceived standing relative to their community and to the US. The combined rating on these ladders can predict health-related outcomes as well as, or better than, other more objective measures of SES (e.g., Singh-Manoux, Marmot, & Adler, 2005). Given evidence (albeit mixed) for a greater prevalence of left-handedness in musicians (Aggleton, Kentridge, & Good, 1994), handedness effects on musical ability (e.g., Jäncke, Schlaug, & Steinmetz, 1997; Kopiez, Galley, & Lee, 2006), and handedness effects on cognitive tasks (also with somewhat mixed findings; e.g., Beratis, Rabavilas, Kyprianou, Papadimitriou, & Papageorgiou, 2013; Nettle, 2003; Powell, Kemp, & García-Finaña, 2012), we administered the Edinburgh handedness inventory (Oldfield, 1971). Finally, bilingualism has been found to predict aspects of EF (e.g., Bialystok, Craik, Green, & Gollan, 2009), so we administered the Language Experience and Proficiency Questionnaire (LEAP-Q; Marian et al., 2007): participants were considered bilingual if they reported speaking a second language with a mean self-rated proficiency of at least 5 on a 1–10 scale (where 5 is defined as "adequate"), averaged across ratings of ability in second language speaking, understanding, and reading.

2.3. Procedure

Tasks were administered across two separate 1¼-h sessions, separated by at least one day. The EF tasks were counterbalanced across sessions, but constrained such that visual and auditory versions of the same EF component never occurred in the same session and such that an individual session never involved all auditory or all visual EF tasks. This resulted in six possible orders for the EF tasks that were administered equally often across participants. The questionnaires were always administered at the end of session one and the Musical Ear Task at the end of session two.

3. Results & discussion

Analyses were conducted in the R statistical platform (version 3.1.2). Table 1 presents descriptive statistics for each measure and zero-order correlations are reported in the Appendix.

3.1. Relationships among DVs: diversity of EFs across domains

Pearson's correlations between the separate EF tasks (Table 2; shown with inhibition and switching tasks scored such that higher scores indicate better performance) suggest that, while these components are related, there is considerable diversity in the abilities captured by these tasks (cf. Miyake & Friedman, 2012; Miyake et al., 2000). Correlations between the auditory and visual versions of individual EF subcomponents were fairly high, except between the auditory and visual inhibition tasks. This suggests a distinction between inhibition of auditory and visual/verbal material, but might also reflect the relatively lower reliabilities of these tasks (see Table 1). Negative correlations between task switching performance and performance on (visual) inhibitory control fit with the suggestion that sustained inhibitory control makes it more difficult to flexibly shift between tasks, and thus there may be a tradeoff between cognitive control and cognitive flexibility (Goschke, 2000; Miyake & Friedman, 2012).

3.2. Relationships among IVs: commonality of musical measures

The melody and rhythm subtests of the MET were well correlated, and were also highly correlated with measures of musical experience and training (see Table 3). Therefore, a composite measure of musical ability was constructed by combining standardized z-scores on the two MET subtests (melody and rhythm) with the composite OMSI score.

3.3. Musical experience, ability, and domains of EF

The zero-order correlations between the measures of EF and musical ability in Table 4 suggest that musical ability may, in fact, be related to some aspects of EF. In particular, musical ability predicts better performance on both auditory and visual working memory updating tasks. In contrast, higher levels of musical ability actually predicted somewhat worse performance on the auditory switching task. For both updating and switching, performance was more strongly correlated with musical discrimination tests (the MET) than with measures of musical experience (from the

Table 2
Zero-order correlations between executive functioning measures.

	Inhibition		Updating		Switching	
	Auditory	Visual	Auditory	Visual	Auditory	Visual[1]
Inhibition						
Auditory	–					
Visual	0.01	–				
Updating						
Auditory	0.17	−0.04	–			
Visual	0.08	0.05	0.54***	–		
Switching						
Auditory	0.00	−0.23*	0.16	0.06	–	
Visual[a]	−0.02	−0.29**	0.23*	0.21*	0.36***	–

Note: N = 93. Inhibition and switching measures are reversed (i.e., congruent-minus-incongruent RTs and stay-minus-switch RTs) so that higher values indicate better performance for all tasks.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

[a] One participant who did not switch between tasks was excluded, so $N = 92$ for correlations involving the visual switching task.

Table 3
Zero-order correlations between musical ability measures.

	Musical ear test (MET)			Musical experience		
	Combined	Melody	Rhythm	OMSI	Lessons	Practice
MET-combined	–					
Melody subtest	0.90^{***}	–				
Rhythm subtest	0.90^{***}	0.61^{***}	–			
OMSI	0.45^{***}	0.47^{***}	0.34^{**}	–		
Years lessons	0.57^{***}	0.60^{***}	0.42^{***}	0.67^{***}	–	
Years practice	0.60^{***}	0.65^{***}	0.42^{***}	0.78^{***}	0.87^{***}	–

Note: N = 93. MET = Musical Ear Task (Wallentin et al., 2010); OMSI = Ollen Musical Sophistication Index (Ollen, 2006).
[*] $p < 0.05$.
[**] $p < 0.01$.
[***] $p < 0.001$.

Table 4
Zero-order correlations between executive functioning tasks and musical ability measures.

	Inhibition[a]		Updating		Switching[a]	
	Auditory	Visual	Auditory	Visual	Auditory	Visual
Musical composite	−0.18	0.11	0.62^{***}	0.38^{**}	$-0.17^{\dagger}$	−0.05
MET-combined	−0.12	0.08	0.62^{***}	0.41^{***}	−0.18	−0.08
Melody subtest	−0.12	0.12	0.58^{***}	0.34^{***}	-0.23^{*}	−0.08
Rhythm subtest	−0.10	0.03	0.53^{***}	0.40^{***}	−0.08	−0.06
OMSI	$-0.20^{\dagger}$	0.11	0.37^{***}	$0.17^{\dagger}$	−0.09	0.02
Years lessons	−0.13	0.17	0.47^{***}	0.18	−0.09	−0.03
Years practice	−0.15	0.18	0.41^{***}	0.15	−0.11	0.00

Note: N = 93; MET = Musical Ear Task (Wallentin et al., 2010); OMSI = Ollen Musical Sophistication Index (Ollen, 2006).
[a] Inhibition and switching tasks were scored such that higher scores indicate better performance (i.e., congruent-minus-incongruent RTs and stay-minus-switch RTs).
[*] $p < 0.05$.
[**] $p < 0.01$.
[***] $p < 0.001$.
[†] $p < .10$.

OMSI questionnaire). However, because these musical measures are highly correlated and theoretically interrelated (i.e., performance on musical tasks presumably reflects, to some extent, effects of training, and likelihood of engaging in musical training presumably relates, to some extent, to musical processing ability; cf. Table 3), we rely on the composite musical ability score in the analyses below.

These zero-order correlations might be confounded with a variety of other factors, including age, handedness, SES, and bilingualism. Indeed, age was associated with higher scores on the composite musical ability measure ($r = 0.29$, $p < 0.01$), perhaps reflecting higher levels of musical experience over time. Handedness was correlated with auditory updating performance ($r = -0.21$, $p < 0.05$), reflecting a disadvantage for more strongly right-handed individuals. In contrast, handedness was mostly unrelated to musical ability measures, fitting with other work finding little relationship between handedness and musicianship (Hering, Catarci, & Steiner, 1995; Oldfield, 1969; Piro & Ortiz, 2010). In these data, SES was not correlated with any measure of EF or with musical ability. This is somewhat surprising given robust effects demonstrated elsewhere (e.g., Skoe, Kirzman, & Kraus, 2013), however it may simply reflect the relatively limited variability of SES in our college-student sample (see Table 1).

Although this study did not specifically recruit participants with differing linguistic backgrounds, the sample did include bilingual participants. There is reason to expect bilingualism to correlate with performance on at least some types of EF tasks (e.g., Bialystok et al., 2009; Kroll & Bialystok, 2013), however, bilingual and monolingual participants in this sample did not differ on any EF scores (all $|t|\text{s} < 1$).[5] Bilinguals have sometimes been shown to outperform monolinguals on both incongruent *and* congruent trials on inhibitory tasks (thus showing no advantage in inhibition difference scores; e.g., Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009), however bilinguals in this sample performed no differently from monolinguals on either incongruent or congruent trials in the auditory or visual inhibition tasks (all $|t|\text{s} < 1.34$). Note, however, that few of these participants were balanced bilinguals, and this restricted range of L2 proficiency could account for the lack of effect. Bilinguals did report slightly higher levels of musical experience than monolinguals, with an average of two years more of formal training, although this difference reached only marginal significance ($t(78.87) = 1.74$, $p < 0.10$). There was no difference between bilinguals' and monolinguals' performance on other measures of musical experience or on the MET.

3.4. Multiple regression analyses

To determine whether musical ability can predict *unique* variance in individuals' EF task performance, we first conducted a multivariate multiple regression on the six dependent measures (i.e., the six EF tasks: auditory and visual versions of inhibition, updating, and switching) after controlling for age, SES,[6] handedness, and bilingualism. Although we did not observe significant zero-order correlations between EF measures and either SES or bilingualism, we deemed it important to control for these factors nonetheless given other evidence that EFs are related to both SES (Calvo & Bialystok, 2014; Skoe et al., 2013) and bilingualism (e.g., Kroll & Bialystok, 2013). This multivariate analysis revealed a significant main effect for musical ability ($V = 0.41$, $F_{(6,80)} = 9.40$, $p < 0.001$), showing that performance on EF tasks is indeed related to musical

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[5] Tests between bilinguals and monolinguals were conducted with Welch's t test, assuming unequal variances.

[6] One participant did not answer questions related to SES, thus these regression analyses are based on 92 participants.

ability (no other effects reached significance). To examine the specificity or generality of this relationship, we conducted via a series of follow-up univariate multiple regression analyses to determine whether musical ability relates to each individual EF task (again after controlling for age, SES, handedness, and bilingualism). The results of these analyses are reported in Table 5 and the relationship between musical ability and each EF task is represented graphically in Fig. 1.

As can be seen in Fig. 1 and Table 5, results from the regression analyses parallel the correlational findings presented above: musical ability was robustly related to working memory updating in both auditory and visual modalities, even after controlling for age, SES, handedness, and bilingualism. In contrast, musical ability was unrelated to inhibition or to switching performance in either auditory or visual tasks.[7]

A potential concern is that part of the musical ability measure–the Musical Ear Test–requires same/different judgments of sequentially presented musical excerpts, and so might be considered a type of short-term memory task. If so, the relationship between memory updating and musical ability might reflect the memory-based aspects of this musical ability measure rather than musical ability *per se*. Although musical memory may be a critical part of musical ability, we nonetheless conducted a similar set of regression analyses that treated musicianship as a dichotomous factor, contrasting the 47 participants who were recruited as "musicians" (defined as having had 5 or more years of musical training) with the 46 recruited as "non-musicians" (defined as having had 2 or fewer years of musical training), while controlling for age, SES, handedness, and bilingualism.

As can be seen in Fig. 2, this group factor (musician/non-musician) also predicted unique variance in auditory *n*-back accuracy ($b = -1.01$, $CI = \pm 0.36$, $t = -5.60$, $p < 0.001$) and, although the effect was only marginally significant, in visual *n*-back performance as well ($b = -0.39$, $CI = \pm 0.42$, $t = -1.86$, $p < 0.07$). Somewhat surprisingly, the musician group performed significantly *worse* than the non-musician group on the auditory Stroop task ($b = -0.52$, $CI = \pm 0.43$, $t = -2.43$, $p < 0.05$) and (marginally significantly) better on the Simon arrows task ($b = 0.42$, $CI = \pm 0.42$, $t = 1.99$, $p < 0.06$), although neither of these effects were evident when treating musical ability as a continuous measure (above). As with the continuous musical ability measure presented above, the group factor was not a significant predictor of either auditory or visual switching performance.

4. General discussion

There is growing interest in the possible relationships between musical ability and executive functioning. However, our understanding of this relationship is limited because most previous studies have examined only individual components of EF and have examined relatively small groups of participants. In addition, the only two relatively large studies that examined how musical experience relates to multiple aspects of EF (in children) yielded inconsistent findings (Degé et al., 2011; Schellenberg, 2011). Drawing conclusions from this past work is difficult not only because of the variety of EF components examined, but also the variety of tasks used to measure EF and the variety of criteria used to categorize participants as "musicians" or "non-musicians". In addition, it is not yet clear if musicians show advantages only in the auditory modality (e.g., Hansen et al., 2013; Strait et al., 2010; cf. Carey et al., 2015) or if musical ability is related to performance on non-auditory EF tasks as well (e.g., Bialystok & DePape, 2009; Oechslin et al., 2013).

To address these issues, this study investigated the relationship between musical ability and both auditory and visual versions of three types of commonly used EF tasks, tapping inhibition, updating, and switching (Diamond, 2013; Miyake et al., 2000). Rather than targeting separate groups of musicians and non-musicians (e.g., by using some arbitrary cutoff for musical experience), we tested a relatively large group of participants and relied on both self-report measures of musical experience and on behavioral performance on musical tasks to create a continuous measure of musical ability.[8]

Individual differences in musical ability did predict performance on working memory updating tasks (specifically, auditory and visual *n*-back tasks), but showed little relationship to inhibitory control abilities (as assessed with auditory and spatial Stroop tasks) or to cognitive flexibility (assessed with auditory and visual task switching tasks). Contrasting with suggestions that cognitive advantages in musicians are limited to auditory tasks (perhaps arising from enhanced sensory/cognitive connectivity; e.g., Strait & Kraus, 2014), this pattern was not limited to auditory tasks. Instead, musical ability was similarly related (or unrelated) to both auditory and visual versions of tasks tapping specific EF subcomponents. Musical ability thus does not appear to be associated with EF advantages across the board nor only with advantages in the auditory modality, but rather is related selectively to working memory updating abilities.

This relationship between musical ability and memory updating fits with other work showing that musicians have advantages in memory maintenance and control (George & Coch, 2011; Meinz & Hambrick, 2010; Oechslin et al., 2013; Pallesen et al., 2010) as well as with longitudinal findings of improved working memory updating abilities following a musical training program (Roden et al., 2014). One hypothesized link between working memory updating and musical experience is based on the demands of musical sight-reading (Meinz & Hambrick, 2010), however sight reading experience is unlikely to completely account for the effects found here as even those participants who self-identified as non-musicians (and so who presumably do not have experience sight reading music) showed a significant relationship between musical ability and performance on both auditory ($r(44) = 0.45$) and visual updating tasks ($r(44) = 0.39$). Instead, this relationship likely reflects other ways in which musical processing places relatively strong demands on working memory updating. Such demands are plausible; the memory of serial order is critical to the representation and production of musical sequences (e.g., Palmer & Pfordresher, 2003), and so musical processing might draw particularly heavily on the ability to maintain and update representations involving serial order. Note that music might be even more demanding on working memory updating than language, for example. Listening to speech involves quickly abstracting away from "surface" form toward meaning (and thus comprehenders show relatively poor memory for surface form; e.g., Potter & Lombardi, 1998), but there is likely

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[7] For completeness, we also tested whether the relationships between musical ability and updating were significantly different from the (non)relationships between musical ability and inhibition or switching tasks by conducting a set of tests for differences between non-independent correlations (i.e., comparing the correlations between the different EF residual scores and musical ability, as shown in Fig. 1), controlling for multiple comparisons with the Holm-Bonferroni method. The correlation between musical ability and residual auditory updating scores ($r = .57$) was significantly greater than the correlations between musical ability and residual scores for each of the four inhibition and switching tasks (all $ts \geq 3.46$). The correlation between musical ability and residual visual updating scores ($r = .33$) was significantly greater than the correlation between musical ability and residual visual inhibition ($t = 3.1$) and visual switching scores ($t = 2.35$) but did not differ significantly from the correlations between musical ability and residual scores for the auditory inhibition and switching tasks.

[8] Note, however, that a more typical approach of comparing participants who self-identified as "musicians" with those who identified as "non-musicians" yielded a similar pattern of results overall, leading to the relatively unsurprising conclusion that self-identification as a musician is related to our measures of musical ability.

Table 5
Summary of univariate regression analyses. Outcome variables were scored such that higher values correspond to better performance. Continuous variables were standardized (*z*-scored), and bilingualism was coded as +0.5 for bilingual and −0.5 for monolingual participants.

Predictors	Inhibition (RT difference scores: congruent minus incongruent RTs)			
	Auditory		Visual	
	B (*CI*)	*t*	*B* (*CI*)	*t*
(Intercept)	0.00 (−0.21 to 0.22)	0.03	−0.02 (−0.23 to 0.19)	−0.19
Age	0.04 (−0.18 to 0.26)	0.39	0.05 (−0.17 to 0.27)	0.42
SES	−0.13 (−0.35 to 0.08)	−1.23	−0.00 (−0.22 to 0.21)	−0.04
Handedness	−0.07 (−0.29 to 0.14)	−0.69	0.18 (−0.03 to 0.39)	1.68
Bilingualism	0.00 (−0.43 to 0.43)	0.01	−0.11 (−0.54 to 0.32)	−0.52
Musical ability	−0.20 (−0.43 to 0.02)	−1.81	0.11 (−0.12 to 0.33)	0.95
R^2/adj. R^2	0.053/−0.002		0.056/0.001	
Predictors	Updating (Pr scores: proportion hits minus proportion false alarms)			
	Auditory		Visual	
	B (*CI*)	*t*	*B* (*CI*)	*t*
(Intercept)	−0.01 (−0.17 to 0.15)	−0.11	−0.01 (−0.21 to 0.18)	−0.14
Age	0.03 (−0.14 to 0.20)	0.40	0.07 (−0.13 to 0.28)	0.71
SES	−0.03 (−0.20 to 0.13)	−0.42	−0.07 (−0.27 to 0.12)	−0.75
Handedness	−0.24 (−0.40 to −0.07)	−2.89†	−0.22 (−0.42 to −0.03)	−2.30†
Bilingualism	−0.06 (−0.39 to 0.28)	−0.34	−0.12 (−0.52 to 0.27)	−0.61
Musical Ability	0.62 (0.45–0.79)	7.08*	0.36 (0.16–0.57)	3.49*
R^2/adj. R^2	0.43/0.40		0.20/0.15	
Predictors	Switching (RT difference scores: stay minus switch RTs)			
	Auditory		Visual	
	B (*CI*)	*t*	*B* (*CI*)	*t*
(Intercept)	0.01 (−0.20 to 0.22)	0.12	−0.02 (−0.19 to 0.23)	0.19
Age	−0.13 (−0.35 to 0.08)	−1.22	−0.16 (−0.38 to 0.06)	−1.45
SES	0.13 (−0.09 to 0.34)	1.19	0.14 (−0.07 to 0.36)	1.34
Handedness	−0.02 (−0.23 to 0.19)	−0.18	0.05 (−0.16 to 0.26)	0.46
Bilingualism	0.04 (−0.39 to 0.47)	0.19	−0.02 (−0.44 to 0.41)	−0.08
Musical Ability	−0.13 (−0.36 to 0.09)	−1.20	−0.03 (−0.25 to 0.19)	−0.26
R^2/adj. R^2	0.066/0.011		0.048/−0.008	

Note: $N = 92$ (*d.f.* = 5,86) except for the visual switching task, where $N = 91$ (*d.f.* = 5,85).
[*] $p < 0.05$, corrected for multiple comparisons (Bonferroni adjusted $p < 0.008$ [0.05/6]).
[†] $p < 0.05$, uncorrected.

no such conceptual abstraction in music (cf. Schellenberg, Stalinsky, & Marks, 2014).

Given the demands music places on working memory updating, the relationship between musical ability and updating observed here might be a result of sustained engagement in music (i.e., regular memory engagement via musical experience might have *improved* updating abilities). There is at least one longitudinal (quasi)experimental study that supports this conclusion (Roden et al., 2014), although there have been few experimental longitudinal studies of musical experience and cognitive abilities so far (review: Okada & Slevc, in press). However, it is likely that individuals who can more successfully or more easily accomplish musical tasks, for example, by being better able to look ahead in sight reading and better able to maintain and update serial order in musical sequences, might also be more likely to pursue musical experiences (cf. Corrigall et al., 2013; Zatorre, 2013). That is, the association between musical ability and working memory updating most likely reflects both pre-existing differences that influence the likelihood of pursuing musical experience as well as experience-based affects of musical engagement (cf. Schellenberg, 2015).

Although correlational studies such as this cannot disentangle effects of musical experience from pre-existing differences between those who do or do not pursue musical training, the specificity of the relationships observed here – where musical ability is related selectively to working memory updating and not to inhibition or switching performance – suggests that the measure of musical ability is not simply acting as a proxy for task engagement or serving only as a reflection of advantages in general intelligence (e.g., Schellenberg, 2011). However, this selectivity is surprising in light of other work finding that musicians show advantages on inhibitory control (e.g., Amer et al., 2013; Moreno et al., 2011; Strait et al., 2010). Similarly, these findings contrast with other work finding musician advantages in task switching (Hanna-Pladdy & MacKay, 2011; Moradzadeh et al., 2014).

The exact reason for these discrepant findings is not entirely clear, although they may at least partially reflect a difference in focus: most previous work has examined effects of musical *training* rather than musical ability, as is used here to encompass both musical experience and aptitude. While groups defined based on musical training are also likely to differ in skills that might predispose engagement in musical activities (e.g., Corrigall & Schellenberg, 2015; Corrigall et al., 2013), some of these predispositions may apply somewhat less to non-training-based measures of musical ability. Discrepancies between these data and previous findings may also reflect methodological issues. Most previous studies have investigated separate groups of musicians and non-musicians (typically defined as having more or less then some specific number of years of musical training), whereas the present study relied on continuous measures of musical ability. Although group comparisons of musicians and non-musicians are reasonable

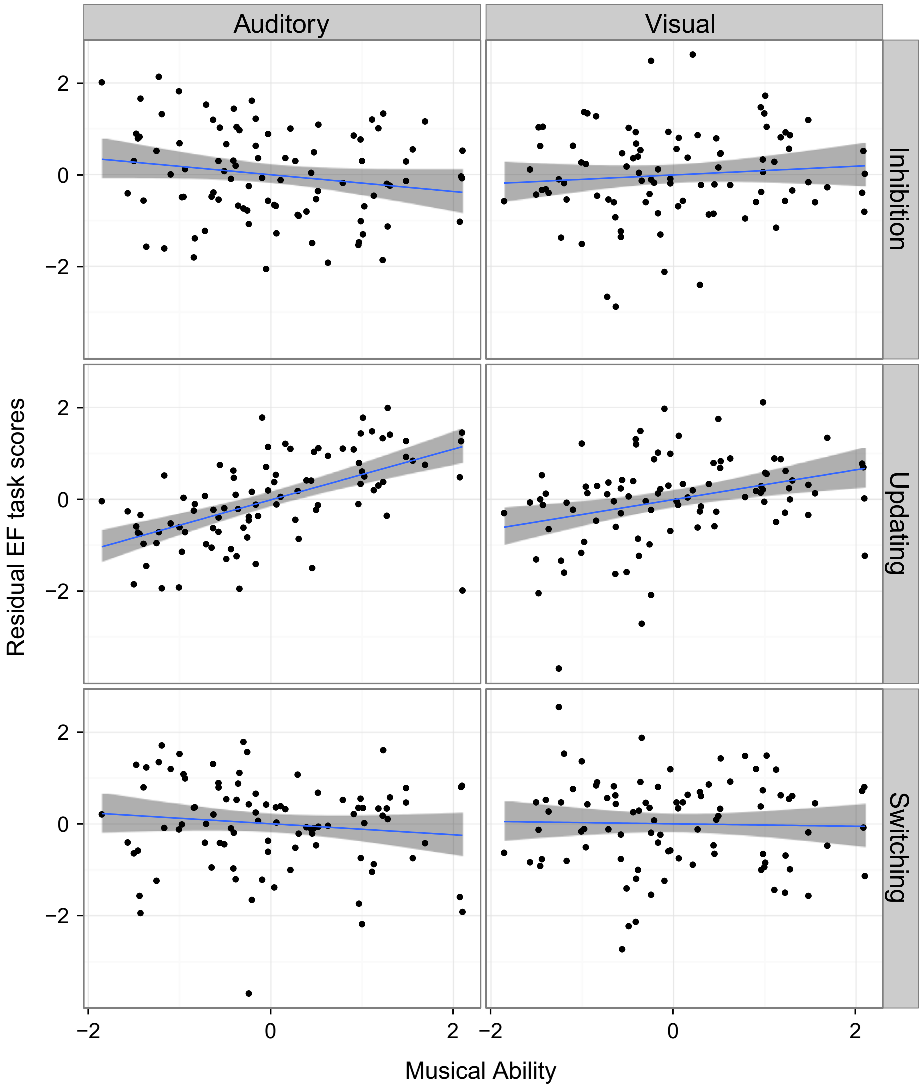

Fig. 1. Residual variance on inhibition tasks (standardized difference scores: congruent minus incongruent RTs), updating tasks (standardized accuracy scores: proportion hits minus proportion false alarms), and switching tasks (standardized difference scores: stay minus switch RTs) after regressing on age, SES, handedness, and bilingualism, as a function of musical ability (standardized composite score).

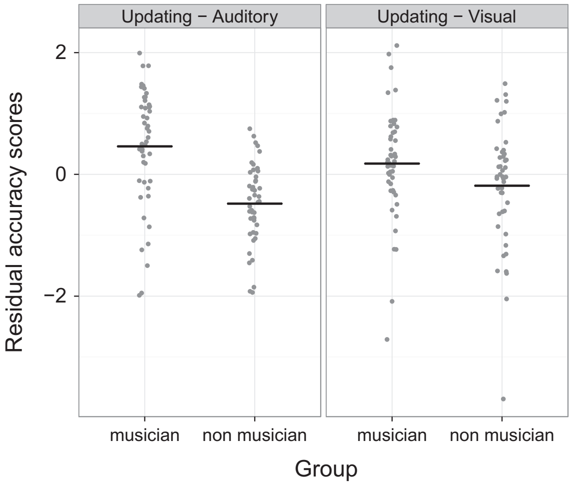

Fig. 2. Residual variance on working memory updating tasks (standardized accuracy scores: proportion hits minus proportion false alarms), after regressing on age, SES, handedness, and bilingualism, as a function of group (musician or non-musician). Lines indicate group means and dots represent individual participants.

in some cases, musical ability is unlikely to be a dichotomous variable and the specific way in which groups are defined may influence what patterns emerge. Relatedly, it is possible that group studies of musicians/non-musicians are susceptible to a type of Hawthorne effect – i.e., that those participants recruited as "musicians" may be differently motivated or engaged than those recruited as "non-musician" controls (cf. Boot, Simons, Stothart, & Stutts, 2013). This is unlikely to explain the results reported here, however, because the observed relationships between musical ability and EFs were specific to one component (updating) and because this relationship was apparent even in non-musician participants.

Discrepancies with other findings may also reflect choices of tasks and measures. For example, it is possible that the updating tasks are relatively more difficult than the inhibition or switching tasks (although performance was quite variable for all tasks); if so, differential relationships with musical ability could, at least in part, reflect differences in difficulty across tasks. In addition, several previous studies showing musician advantages in inhibitory control have examined both behavioral and electrophysiological measures of performance on stop signal tasks (e.g., Moreno et al., 2011, 2014), which might differ in important ways from the auditory and visual Stroop tasks used here. Electrophysiological indices might be more sensitive to subtle group differences than behavioral measures (e.g. Schön & François, 2011; see also Zhang, Peng, Chen, & Hu, 2015) and performance on stop-signal and Stroop tasks are not necessarily correlated and have been argued to reflect different underlying processes (e.g., Khng & Lee, 2014; MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). In fact, a previous study showing musician advantages on Stroop-type tasks (Bialystok & DePape, 2009) did not actually report smaller interference effects for musicians, but rather faster responses to both incongruent *and* congruent stimuli in a conflict context. Our data are actually consistent with those findings: while we found no relationship between musical ability and Stroop effects for auditory or visual tasks, musical ability did significantly predict response time overall (on both congruent and incongruent trials) for both auditory ($b = -0.064$, $SE = 0.022$, $t_{(86)} = -2.42$, $p < 0.05$) and visual ($b = -0.032$, $SE = 0.012$, $t_{(86)} = -3.17$, $p < 0.01$) Stroop tasks.[9] There is thus a need for finer-grained empirical and theoretical work addressing the relationship of musical ability/experience to different components of inhibition and inhibitory control.

In addition, some previous work has relied on tasks with relatively poor construct validity (as pointed out by Moradzadeh et al., 2014) and typically has not attempted to control for potential confounding variables such as SES. In these data, the relationship between musical ability and working memory updating persisted even when controlling for SES, bilingualism, age, and handedness. In general, however, these potential confounding factors were unrelated or only weakly related to EFs and musical ability. For example, SES did not predict EFs or musical ability in these data, which is surprising given other evidence for a link between SES and EFs (Calvo & Bialystok, 2014; Hackman & Farah, 2009) and between SES and musical experience (Corrigall et al., 2013; Norton et al., 2005). Similarly, EFs and musical ability were not related to bilingualism, contrasting with evidence for a bilingual advantage in EF abilities (e.g., Bialystok et al., 2009; Kroll & Bialystok, 2013; but see, e.g., Paap & Greenberg, 2013). Although these non-relationships are somewhat surprising, they may simply reflect a limited variability of SES and of language experience in this mostly college-student sample (see Table 1).

Some other effects did emerge: increasing age was associated with greater levels of musical ability, likely driven by an increase in musical experience over age. In addition, a higher degree of right-handedness was associated with somewhat worse performance on the updating tasks, fitting with other evidence that left- or mixed-handedness is associated with better EF performance (e.g., Beratis et al., 2013; Gunstad, Spitznagel, Luyster, Cohen, & Paul, 2007). Although there is some evidence for similar effects of handedness on aspects of musical ability (e.g., Jäncke et al., 1997; Kopiez et al., 2006), handedness was unrelated to measures of musical ability in these data.

Our findings do come with some caveats. For one, we assessed only a few of many potential confounds that could be related to EF and musical ability and so it remains possible that some other factors underlie the relationships observed here, such as general intelligence (Schellenberg, 2004), attention (Strait et al., 2010), or personality traits (Corrigall et al., 2013). This is an inevitable concern in correlational studies such as this, however this concern is lessened somewhat given that musical ability was not indiscriminately related to performance on all EF tasks, but was related selectively to working memory updating. This concern highlights, however, the need for experimental studies of the relationship between musical ability and specific domains of executive functioning. There is a small body of longitudinal studies of this sort (e.g., Moreno et al., 2011; Roden et al., 2014), but so far these approaches have not investigated multiple domains of EF and have yielded somewhat mixed results (e.g., Mehr, Schachner, Katz, & Spelke, 2013; Rickard, Bambrick, & Gill, 2012; see Okada & Slevc, in press, for a review), and so more work is clearly needed. In particular, the present findings suggest the utility of investigating memory updating in longitudinal designs.

A second caveat is that, while we did have a wide range (and a relatively normal distribution) of musical experience in our participant group, few of our participants were professional musicians or had extremely high levels of training (see supplemental materials). It therefore remains possible that a different pattern of relationships with EF might emerge among people with very advanced levels of musical accomplishment. Relatedly, while we did assess multiple aspects of musical ability and experience, these are likely only a few of the skills that make up musical ability. In particular, our assessment of musical experience did not assess different *types* of musical experience, which may show differential relationships to cognitive abilities (Beaty, Smeekens, Silva, Hodges, & Kane, 2013; Carey et al., 2015; Merrett, Peretz, & Wilson, 2013). In addition, our processing tasks measured only melodic and rhythmic discrimination and did not assess musical production, sensitivity to timbre, or any number of other aspects of musical ability. These limitations were necessary given time constraints, however the development of more comprehensive measures of musical ability (e.g., Law & Zentner, 2012; Müllensiefen, Gingras, Musil, & Stewart, 2014) will be of great benefit to future work on the relationships between musical and non-musical abilities.

5. Conclusions

These data show that musical ability – assessed by both performance on musical discrimination tasks and by measures of musical experience – is associated (perhaps uniquely) with working memory updating abilities. This not only points to an important role of memory updating in musical ability, but also lends some correlational support to the idea that musical experience could influence working memory abilities outside of the musical domain. However, these data also show that musical ability is not related to cognitive abilities across the board, underscoring the need for a more detailed understanding of the relationships between specific aspects of musical experience and specific aspects of cognitive functioning (see also Merrett et al., 2013). Of course, the primary value of musical education is not its potential to lead to cognitive benefits; there are a wide variety of beneficial effects of musical experience, including its emotional (e.g., Chanda & Levitin, 2013; Laukka, 2007) and social effects (e.g., Kirschner & Tomasello, 2010), not to mention the intrinsic value of musical experiences and musical skill. Nevertheless, a better understanding of music's relationship to other cognitive abilities moves us toward a better understanding of the complex perceptual and cognitive processes underlying our love for, and impressive abilities in, music.

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[9] Based on repeated measures regressions predicting log-transformed response time as a function of musical ability, after controlling for congruency, age, SES, handedness, and bilingualism.

Appendix A. Zero-order Pearson's correlations for all measures used in this study.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Aud. inhibition	–															
2. Vis. inhibition	0.01	–														
3. Aud. updating	−0.17	0.04	–													
4. Vis. updating	−0.08	−0.05	0.54***	–												
5. Aud. switching	0.00	−0.23*	−0.16	−0.06	–											
6. Vis. switching	−0.02	−0.29**	−0.23*	−0.21*	0.36***	–										
7. MET melody	−0.12	0.12	0.58***	0.34***	−0.23*	−0.08	–									
8. MET rhythm	−0.10	0.03	0.53***	0.40***	−0.08	−0.06	0.61***	–								
9. MET combined	−0.12	0.08	0.62***	0.41***	−0.18	−0.08	0.90***	0.90***	–							
10. OMSI	−0.20	0.11	0.37***	0.17	−0.09	0.02	0.47***	0.34**	0.45***	–						
11. Yrs lessons	−0.13	0.17	0.47***	0.18	−0.09	−0.03	0.60***	0.42***	0.57***	0.67***	–					
12. Yrs practice	−0.15	0.18	0.41***	0.15	−0.11	0.00	0.65***	0.42***	0.60***	0.78***	0.87***	–				
13. MusicAbility	−0.18	0.11	0.62***	0.38***	−0.17	−0.05	0.86***	0.80***	0.93***	0.75***	0.70***	0.77***	–			
14. Age	−0.03	0.09	0.20	0.16	−0.16	−0.15	0.19	0.19	0.21*	0.31**	0.20	0.23*	0.29**	–		
15. SES	−0.10	−0.04	−0.08	−0.09	0.13	0.13	−0.07	−0.07	−0.08	−0.12	−0.08	−0.13	−0.11	0.09	–	
16. Handedness	−0.07	0.40	−0.21*	−0.20	−0.05	0.01	−0.07	0.05	−0.01	0.09	0.05	0.10	0.03	0.05	−0.09	–

Note: N = 93 except for all correlations involving SES, for which N = 92. All cognitive tasks were scored such that higher scores indicate better performance. *Aud.* = Auditory; *Vis.* = Visual; *MET* = Musical Ear Task (Wallentin et al., 2010); *OMSI* = Ollen Musical Sophistication Index (Ollen, 2006); *SES* = socio-economic status (Adler and Stewart, 2007).

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.03.017.

References

Adler, N., & Stewart, J. (2007). *The MacArthur scale of subjective social status*. . Retrieved fromhttp://www.macses.ucsf.edu/research/psychosocial/subjective.php.

Aggleton, J. P., Kentridge, R. W., & Good, J. M. M. (1994). Handedness and musical ability: A study of professional orchestral players, composers, and choir members. *Psychology of Music, 22*(2), 148–156. http://dx.doi.org/10.1177/0305735694222004.

Amer, T., Kalender, B., Hasher, L., Trehub, S. E., & Wong, Y. (2013). Do older professional musicians have cognitive advantages? *PLoS ONE, 8*(8), 1–8. http://dx.doi.org/10.1371/journal.pone.0071630.

Beaty, R. E., Smeekens, B. A., Silvia, P. J., Hodges, D. A., & Kane, M. J. (2013). A first look at the role of domain-general cognitive and creative abilities in Jazz improvisation. *Psychomusicology: Music, Mind & Brain, 23*(4), 262–268. http://dx.doi.org/10.1037/a0034968.

Beratis, I. N., Rabavilas, A. D., Kyprianou, M., Papadimitriou, G. N., & Papageorgiou, C. (2013). Investigation of the link between higher order cognitive functions and handedness. *Journal of Clinical and Experimental Neuropsychology, 35*(4), 393–403. http://dx.doi.org/10.1080/13803395.2013.778231.

Bialystok, E., Craik, F., Green, D., & Gollan, T. (2009). Bilingual minds. *Psychological Science in the Public Interest, 10*(3), 89–129. http://dx.doi.org/10.1177/1529100610387084.

Bialystok, E., & DePape, A.-M. (2009). Musical expertise, bilingualism, and executive functioning. *Journal of Experimental Psychology: Human Perception and Performance, 35*(2), 565–574. http://dx.doi.org/10.1037/a0012735.

Boot, W. R., Simons, D. J., Stothart, C., & Stutts, C. (2013). The pervasive problem with placebos in psychology: Why active control groups are not sufficient to rule out placebo effects. *Perspectives on Psychological Science, 8*(4), 445–454. http://dx.doi.org/10.1177/1745691613491271.

Bugos, J., Perlstein, W., McCrae, C., Brophy, T., & Bedenbaugh, P. (2007). Individualized piano instruction enhances executive functioning and working memory in older adults. *Aging & Mental Health, 11*(4), 464–471. http://dx.doi.org/10.1080/13607860601086504.

Calvo, A., & Bialystok, E. (2014). Independent effects of bilingualism and socioeconomic status on language ability and executive functioning. *Cognition, 130*(3), 278–288. http://dx.doi.org/10.1016/j.cognition.2013.11.015.

Carey, D., Rosen, S., Krishnan, S., Pearce, M. T., Shepherd, A., Aydelott, J., & Dick, F. (2015). Generality and specificity in the effects of musical expertise on perception and cognition. *Cognition, 137*, 81–105. http://dx.doi.org/10.1016/j.cognition.2014.12.005.

Chanda, M. L., & Levitin, D. J. (2013). The neurochemistry of music. *Trends in Cognitive Sciences, 17*(4), 179–193. http://dx.doi.org/10.1016/j.tics.2013.02.007.

Corrigall, K. A., & Schellenberg, E. G. (2015). Predicting who takes music lessons: Parent and child characteristics. *Frontiers in Psychology, 6*, 1–8. http://dx.doi.org/10.3389/fpsyg.2015.00282.

Corrigall, K. A., Schellenberg, E. G., & Misura, N. M. (2013). Music training, cognition, and personality. *Frontiers in Psychology, 4*, 222. http://dx.doi.org/10.3389/fpsyg.2013.00222.

Costa, A., Hernández, M., Costa-Faidella, J., & Sebastián-Gallés, N. (2009). On the bilingual advantage in conflict processing: Now you see it, now you don't. *Cognition, 113*(2), 135–149. http://dx.doi.org/10.1016/j.cognition.2009.08.001.

Degé, F., Kubicek, C., & Schwarzer, G. (2011). Music lessons and intelligence: A relation mediated by Executive Functions. *Music Perception, 29*(2), 195–201.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. http://dx.doi.org/10.1146/annurev-psych-113011-143750.

Drake, C., & Palmer, C. (2000). Skill acquisition in music performance: Relations between planning and temporal control. *Cognition, 74*(1), 1–32.

Elpus, K. (2013). is it the music or is it selection bias? A nationwide analysis of music and non-music students' SAT scores. *Journal of Research in Music Education, 61*(2), 175–194. http://dx.doi.org/10.1177/0022429413485601.

Engle, R. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*(1), 19–23.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., Defries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science, 17*(2), 172–179. http://dx.doi.org/10.1111/j.1467-9280.2006.01681.x.

Furneaux, S., & Land, M. F. (1999). The effects of skill on the eye-hand span during musical sight-reading. *Proceedings of the Royal Society B, 266*(1436), 2435–2440. http://dx.doi.org/10.1098/rspb.1999.0943.

George, E. M., & Coch, D. (2011). Music training and working memory: An ERP study. *Neuropsychologia, 49*(5), 1083–1094. http://dx.doi.org/10.1016/j.neuropsychologia.2011.02.001.

Gordon, E. (2007). *Learning sequences in music: A contemporary music learning theory*. Chicago, IL: GIA Publications.

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task set switching. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes* (pp. 331–355). Cambridge, MA: MIT Press. http://doi.org/10.2337/db11-0571.

Gunstad, J., Spitznagel, M. B., Luyster, F., Cohen, R. A., & Paul, R. H. (2007). Handedness and cognition across the healthy lifespan. *The International Journal of Neuroscience, 117*(4), 477–485. http://dx.doi.org/10.1080/00207450600773483.

Hackman, D. A., & Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends in Cognitive Sciences, 13*(2), 65–73. http://dx.doi.org/10.1016/j.tics.2008.11.003.

Hamers, J. F., & Lambert, W. E. (1972). Bilingual interdependencies in auditory perception. *Journal of Verbal Learning and Verbal Behavior, 11*(3), 303–310. http://dx.doi.org/10.1016/S0022-5371(72)80091-4.

Hanna-Pladdy, B., & MacKay, A. (2011). The relation between instrumental musical activity and cognitive aging. *Neuropsychology, 25*(3), 378–386. http://dx.doi.org/10.1037/a0021895.

Hansen, M., Wallentin, M., & Vuust, P. (2013). Working memory and musical competence of musicians and non-musicians. *Psychology of Music, 41*(3), 779–793. http://dx.doi.org/10.1177/0305735612452186.

Hering, R., Catarci, T., & Steiner, T. (1995). Handedness in musicians. *Functional Neurology, 10*(1), 23–26. http://dx.doi.org/10.1111/j.2044-8295.1969.tb01181.x.

Huron, D. B. (2006). *Sweet anticipation: Music and the psychology of expectation*. Cambridge, MA: MIT Press.

Jackendoff, R. (1991). Musical parsing and musical affect. *Music Perception, 9*(2), 199–229.

Jaeggi, S. M., Buschkuehl, M., Perrig, W. J., & Meier, B. (2010). The concurrent validity of the N-back task as a working memory measure. *Memory, 18*(4), 394–412. http://dx.doi.org/10.1080/09658211003702171.

Jaeggi, S. M., Studer-Luethi, B., Buschkuehl, M., Su, Y.-F., Jonides, J., & Perrig, W. J. (2010). The relationship between n-back performance and matrix reasoning – Implications for training and transfer. *Intelligence, 38*(6), 625–635. http://dx.doi.org/10.1016/j.intell.2010.09.001.

Jäncke, L., Schlaug, G., & Steinmetz, H. (1997). Hand skill asymmetry in professional musicians. *Brain and Cognition, 34*(3), 424–432. http://dx.doi.org/10.1006/brcg.1997.0922.

Jentzsch, I., Mkrtchian, A., & Kansal, N. (2014). Improved effectiveness of performance monitoring in amateur instrumental musicians. *Neuropsychologia, 52*, 117–124. http://dx.doi.org/10.1016/j.neuropsychologia.2013.09.025.

Jonides, J., Schumacher, E. H., Smith, E. E., Lauber, E. J., Awh, E., Minoshima, S., & Koeppe, R. A. (1997). Verbal working memory load affects regional brain activation as measured by PET. *Journal of Cognitive Neuroscience, 9*(4), 462–475. http://dx.doi.org/10.1162/jocn.1997.9.4.462.

Khng, K. H., & Lee, K. (2014). The relationship between stroop and stop-signal measures of inhibition in adolescents: Influences from variations in context and measure estimation. *PLoS ONE, 9*(7), e101356. http://dx.doi.org/10.1371/journal.pone.0101356.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352–358.

Kirschner, S., & Tomasello, M. (2010). Joint music making promotes prosocial behavior in 4-year-old children. *Evolution and Human Behavior, 31*(5), 354–364. http://dx.doi.org/10.1016/j.evolhumbehav.2010.04.004.

Koelsch, S., Rohrmeier, M., Torrecuso, R., & Jentschke, S. (2013). Processing of hierarchical syntactic structure in music. *Proceedings of the National Academy of Sciences, 110*(38), 15443–15448. http://dx.doi.org/10.1073/pnas.1300272110.

Kopiez, R., Galley, N., & Lee, J. I. (2006). The advantage of a decreasing right-hand superiority: The influence of laterality on a selected musical skill (sight reading achievement). *Neuropsychologia, 44*(7), 1079–1087. http://dx.doi.org/10.1016/j.neuropsychologia.2005.10.023.

Kopiez, R., & Lee, J. I. (2008). Towards a general model of skills involved in sight reading music. *Music Education Research, 10*(1), 41–62. http://dx.doi.org/10.1080/14613800701871363.

Kroll, J. F., & Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology, 25*(5), 497–514. http://dx.doi.org/10.1080/20445911.2013.799170.

Laukka, P. (2007). Uses of music and psychological well-being among the elderly. *Journal of Happiness Studies, 8*, 215–241. http://dx.doi.org/10.1007/s10902-006-9024-3.

Law, L. N. C., & Zentner, M. (2012). Assessing musical abilities objectively: Construction and validation of the profile of music perception skills. *PLoS ONE, 7*(12), e52508. http://dx.doi.org/10.1371/journal.pone.0052508.

Lerdahl, F., & Jackendoff, R. (1983). *A generative theory of tonal music*.Cambridge, MA: MIT Press.

Loehr, J. D., Kourtis, D., Vesper, C., Sebanz, N., & Knoblich, G. (2013). Monitoring individual and joint action outcomes in duet music performance. *Journal of Cognitive Neuroscience, 25*(7), 1049–1061. http://dx.doi.org/10.1162/jocn_a_00388.

Loehr, J. D., & Palmer, C. (2011). Temporal coordination between performing musicians. *Quarterly Journal of Experimental Psychology, 64*(11), 2153–2167. http://dx.doi.org/10.1080/17470218.2011.603427.

Logue, S. F., & Gould, T. J. (2013). The neural and genetic basis of executive function: Attention, cognitive flexibility, and response inhibition. *Pharmacology, Biochemistry, and Behavior, 123*, 45–54. http://dx.doi.org/10.1016/j.pbb.2013.08.007.

MacLeod, C. M., Dodd, M. D., Sheard, E. D., Wilson, D. E., & Bibi, U. (2003). In opposition to inhibition. In B. H. Ross (Ed.), *The psychology of learning and motivation* (pp. 163–214). New York, NY: Elsevier.

Margulis, E. H. (2005). A model of melodic expectation. *Music Perception, 22*(4), 663–714. http://dx.doi.org/10.1525/mp.2005.22.4.663.

Marian, V., Blumenfeld, H. K., & Kaushanskaya, M. (2007). The language experience and proficiency questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech Language and Hearing Research, 50*, 940–967.

Mehr, S. A., Schachner, A., Katz, R. C., & Spelke, E. S. (2013). Two randomized trials provide no consistent evidence for nonmusical cognitive benefits of brief preschool music enrichment. *PLoS ONE, 8*(12), e82007. http://dx.doi.org/10.1371/journal.pone.0082007.

Meinz, E. J., & Hambrick, D. Z. (2010). Deliberate practice is necessary but not sufficient to explain individual differences in piano sight-reading skill: The role of working memory capacity. *Psychological Science, 21*(7), 914–919. http://dx.doi.org/10.1177/0956797610373933.

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

Meyer, L. B. (1956). *Emotion and meaning in music*.Chicago, IL: University of Chicago Press.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science, 21*(1), 8–14. http://dx.doi.org/10.1177/0963721411429458.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. http://dx.doi.org/10.1006/cogp.1999.0734.

Moore, G. P., & Chen, J. (2010). Timings and interactions of skilled musicians. *Biological Cybernetics, 103*(5), 401–414. http://dx.doi.org/10.1007/s00422-010-0407-5.

Moradzadeh, L., Blumenthal, G., & Wiseheart, M. (2014). Musical training, bilingualism, and executive function: A closer look at task switching and dual-task performance. *Cognitive Science*, n/a–n/a. http://dx.doi.org/10.1111/cogs.12183.

Moreno, S., Bialystok, E., Barac, R., Schellenberg, E. G., Cepeda, N. J., & Chau, T. (2011). Short-term music training enhances verbal intelligence and executive function. *Psychological Science, 22*(11), 1425–1433. http://dx.doi.org/10.1177/0956797611416999.

Moreno, S., & Farzan, F. (2015). Music training and inhibitory control: A multidimensional model. *Annals of the New York Academy of Sciences, 1337*(1), 147–152. http://dx.doi.org/10.1111/nyas.12674.

Moreno, S., Wodniecka, Z., Tays, W., Alain, C., & Bialystok, E. (2014). Inhibitory control in bilinguals and musicians: Event related potential (ERP) evidence for experience-specific effects. *PLoS ONE, 9*(4), e94169. http://dx.doi.org/10.1371/journal.pone.0094169.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The musicality of non-musicians: An index for assessing musical sophistication in the general population. *PLoS ONE, 9*(2), e89642. http://dx.doi.org/10.1371/journal.pone.0089642.

Nettle, D. (2003). Hand laterality and cognitive ability: A multiple regression approach. *Brain and Cognition, 52*(3), 390–398. http://dx.doi.org/10.1016/S0278-2626(03)00187-8.

Norton, A., Winner, E., Cronin, K., Overy, K., Lee, D. J., & Schlaug, G. (2005). Are there pre-existing neural, cognitive, or motoric markers for musical ability? *Brain & Cognition, 59*(2), 124–134. http://dx.doi.org/10.1016/j.bandc.2005.05.009.

Oechslin, M. S., Van De Ville, D., Lazeyras, F., Hauert, C.-A., & James, C. E. (2013). Degree of musical expertise modulates higher order brain functioning. *Cerebral Cortex, 23*(9), 2213–2224. http://dx.doi.org/10.1093/cercor/bhs206.

Okada, B. M., & Slevc, L. R. (in press). Music training: Contributions to executive function. In M. F. Bunting, J. M. Novick, M. R. Dougherty, & R. W. Engle (Eds.), *An integrative approach to cognitive and working memory training: Perspectives from psychology, neuroscience, and human development*. New York, NY: Oxford University Press (in press).

Oldfield, R. C. (1969). Handedness in musicians. *British Journal of Psychology, 60*(1), 91–99. http://dx.doi.org/10.1111/j.2044-8295.1969.tb01181.x.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113. http://dx.doi.org/10.1016/0028-3932(71)90067-4.

Ollen, J. (2006). *A criterion-related validity test of selected indicators of musical sophistication using expert ratings* (Doctoral dissertation). Ohio State University. Retrieved fromhttps://etd.ohiolink.edu/.

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping, 25*(1), 46–59.

Paap, K. R., & Greenberg, Z. I. (2013). There is no coherent evidence for a bilingual advantage in executive processing. *Cognitive Psychology, 66*(2), 232–258. http://dx.doi.org/10.1016/j.cogpsych.2012.12.002.

Pallesen, K. J., Brattico, E., Bailey, C. J., Korvenoja, A., Koivisto, J., Gjedde, A., & Carlson, S. (2010). Cognitive control in auditory working memory is enhanced in musicians. *PLoS ONE, 5*(6), e11120. http://dx.doi.org/10.1371/journal.pone.0011120.

Palmer, C. (2013). Music performance: Movement and coordination. In D. Deutsch (Ed.), *The psychology of music* (3rd ed., pp. 405–422). Academic Press.

Palmer, C., & Pfordresher, P. Q. (2003). Incremental planning in sequence production. *Psychological Review, 110*(4), 683–712. http://dx.doi.org/10.1037/0033-295X.110.4.683.

Patel, A. D. (2008). *Music, language, and the brain*.New York, NY: Oxford University Press.

Piro, J., & Ortiz, C. (2010). No association between music ability and hand preference in children. *Journal of Motor Behavior, 42*(5), 269–275. http://dx.doi.org/10.1080/00222895.2010.502550.

Potter, M. C., & Lombardi, L. (1998). Syntactic priming in immediate recall of sentences. *Journal of Memory and Language, 38*(3), 265–282. http://dx.doi.org/10.1006/jmla.1997.2546.

Powell, J. L., Kemp, G. J., & García-Finaña, M. (2012). Association between language and spatial laterality and cognitive ability: An fMRI study. *NeuroImage, 59*(2), 1818–1829. http://dx.doi.org/10.1016/j.neuroimage.2011.08.040.

Rickard, N. S., Bambrick, C. J., & Gill, A. (2012). Absence of widespread psychosocial and cognitive effects of school-based music instruction in 10–13-year-old students. *International Journal of Music Education, 30*(1), 57–78. http://dx.doi.org/10.1177/0255761411431399.

Roden, I., Grube, D., Bongard, S., & Kreutz, G. (2014). Does music training enhance working memory performance? Findings from a quasi-experimental longitudinal study. *Psychology of Music, 42*(2), 284–298. http://dx.doi.org/10.1177/0305735612471239.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*(2), 207–231. http://dx.doi.org/10.1037/0096-3445.124.2.207.

Rohrmeier, M. A., & Koelsch, S. (2012). Predictive information processing in music cognition. A critical review. *International Journal of Psychophysiology, 83*(2), 164–175. http://dx.doi.org/10.1016/j.ijpsycho.2011.12.010.

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychological Science, 15*(8), 511–514. http://dx.doi.org/10.1111/j.0956-7976.2004.00711.x.

Schellenberg, E. G. (2011). Examining the association between music lessons and intelligence. *British Journal of Psychology, 102*(3), 283–302. http://dx.doi.org/10.1111/j.2044-8295.2010.02000.x.

Schellenberg, E. G. (2015). Music training and speech perception: A gene–environment interaction. *Annals of the New York Academy of Sciences, 1337*, 170–177. http://dx.doi.org/10.1111/nyas.12627.

Schellenberg, E. G., Stalinski, S. M., & Marks, B. M. (2014). Memory for surface features of unfamiliar melodies: Independent effects of changes in pitch and tempo. *Psychological Research Psychologische Forschung, 78*(1), 84–95. http://dx.doi.org/10.1007/s00426-013-0483-y.

Schellenberg, E. G., & Weiss, M. W. (2013). Music and cognitive abilities. In D. Deutsch (Ed.). *The psychology of music* (3rd ed.) (Vol. 14, pp. 499–550). San Diego, CA: Elsevier.

Schön, D., & François, C. (2011). Musical expertise and statistical learning of musical and linguistic structures. *Frontiers in Psychology, 2*, 167. http://dx.doi.org/10.3389/fpsyg.2011.00167.

Seinfeld, S., Figueroa, H., Ortiz-Gil, J., & Sanchez-Vives, M. V. (2013). Effects of music learning and piano practice on cognitive function, mood and quality of life in older adults. *Frontiers in Psychology, 4*, 1–13. http://dx.doi.org/10.3389/fpsyg.2013.00810.

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology, 51*, 300–304.

Singh-Manoux, A., Marmot, M. G., & Adler, N. E. (2005). Does subjective social status predict health and change in health status better than objective status? *Psychosomatic Medicine, 67*(6), 855–861. http://dx.doi.org/10.1097/01.psy.0000188434.52941.a0.

Skoe, E., Krizman, J., & Kraus, N. (2013). The impoverished brain: Disparities in maternal education affect the neural response to sound. *The Journal of Neuroscience, 33*(44), 17221–17231. http://dx.doi.org/10.1523/JNEUROSCI.2102-13.2013.

Slevc, L. R., & Okada, B. M. (2015). Processing structure in language and music: A case for shared reliance on cognitive control. *Psychonomic Bulletin & Review, 22*, 637–652. http://dx.doi.org/10.3758/s13423-014-0712-4.

Strait, D. L., & Kraus, N. (2014). Biological impact of auditory expertise across the life span: Musicians as a model of auditory learning. *Hearing Research, 308*, 109–121. http://dx.doi.org/10.1016/j.heares.2013.08.004.

Strait, D. L., Kraus, N., Parbery-Clark, A., & Ashley, R. (2010). Musical experience shapes top-down auditory mechanisms: Evidence from masking and auditory attention performance. *Hearing Research, 261*(1–2), 22–29. http://dx.doi.org/10.1016/j.heares.2009.12.021.

Strait, D. L., O'Connell, S., Parbery-Clark, A., & Kraus, N. (2014). Musicians' enhanced neural differentiation of speech sounds arises early in life: Developmental evidence from ages 3 to 30. *Cerebral Cortex, 24*(9), 2512–2521. http://dx.doi.org/10.1093/cercor/bht103.

Travis, F., Harung, H. S., & Lagrosen, Y. (2011). Moral development, executive functioning, peak experiences and brain patterns in professional and amateur classical musicians: Interpreted in light of a Unified Theory of Performance. *Consciousness and Cognition, 20*(4), 1256–1264. http://dx.doi.org/10.1016/j.concog.2011.03.020.

Vuust, P., Roepstorff, A., Wallentin, M., Mouridsen, K., & Østergaard, L. (2006). It don't mean a thing. Keeping the rhythm during polyrhythmic tension, activates language areas (BA47). *NeuroImage, 31*(2), 832–841. http://dx.doi.org/10.1016/j.neuroimage.2005.12.037.

Vuust, P., Wallentin, M., Mouridsen, K., Ostergaard, L., & Roepstorff, A. (2011). Tapping polyrhythms in music activates language areas. *Neuroscience Letters, 494*(3), 211–216. http://dx.doi.org/10.1016/j.neulet.2011.03.015.

Wallentin, M., Nielsen, A. H., Friis-Olivarius, M., Vuust, C., & Vuust, P. (2010). The Musical Ear Test, a new reliable test for measuring musical competence. *Learning and Individual Differences, 20*(3), 188–196. http://dx.doi.org/10.1016/j.lindif.2010.02.004.

Zatorre, R. J. (2013). Predispositions and plasticity in music and speech learning: Neural correlates and implications. *Science, 342*, 585–589. http://dx.doi.org/10.1126/science.1238414.

Zhang, L., Peng, W., Chen, J., & Hu, L. (2015). Electrophysiological evidences demonstrating differences in brain functions between nonmusicians and musicians. *Scientific Reports, 5*, 13796. http://dx.doi.org/10.1038/srep13796.

Zuk, J., Benjamin, C., Kenyon, A., & Gaab, N. (2014). Behavioral and neural correlates of executive functioning in musicians and non-musicians. *PLoS ONE, 9*(6), e99868. http://dx.doi.org/10.1371/journal.pone.0099868.