COGNITIVE SCIENCE
A Multidisciplinary Journal

Cognitive Science 39 (2015) 992–1020

ISSN: 0364-0213 print / 1551-6709 online
DOI: 10.1111/cogs.12183

Musical Training, Bilingualism, and Executive Function: A Closer Look at Task Switching and Dual-Task Performance

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Received 16 April 2013; received in revised form 17 March 2014; accepted 2 April 2014

Abstract

This study investigated whether musical training and bilingualism are associated with enhancements in specific components of executive function, namely, task switching and dual-task performance. Participants (n = 153) belonging to one of four groups (monolingual musician, bilingual musician, bilingual non-musician, or monolingual non-musician) were matched on age and socioeconomic status and administered task switching and dual-task paradigms. Results demonstrated reduced global and local switch costs in musicians compared with non-musicians, suggesting that musical training can contribute to increased efficiency in the ability to shift flexibly between mental sets. On dual-task performance, musicians also outperformed non-musicians. There was neither a cognitive advantage for bilinguals relative to monolinguals, nor an interaction between music and language to suggest additive effects of both types of experience. These findings demonstrate that long-term musical training is associated with improvements in task switching and dual-task performance.

Keywords: Task switching; Dual-task performance; Transfer of training; Bilingualism; Musical training; Executive function

1. Introduction

Research over the past few decades has shown that our experiences not only alter behavior (Feng, Spence, & Pratt, 2007; Thorell, Lindqvist, Bergman-Nutley, Bohlin, & Klingberg, 2009) but also lead to benefits in areas of cognition that are distant from the skill being developed (Colcombe & Kramer, 2003), a concept known as far transfer. Far

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transfer effects of skill training or experience on cognition have been demonstrated in areas such as physical exercise (Colcombe & Kramer, 2003), video game playing (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Feng et al., 2007; Green & Bavelier, 2003), bilingualism (Bialystok, Craik, Klein, & Viswanathan, 2004), and musical training (Moreno et al., 2011).

Despite the growing body of literature demonstrating training-induced changes in cognitive function, some areas of cognition have received more attention than others. For example, in the musical training literature, areas such as working memory (Lee, Lu, & Ko, 2007), verbal memory (Franklin et al., 2008), verbal intelligence (Moreno et al., 2011), linguistic processing (Moreno et al., 2009), and auditory–visual perception (Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006) have received the greatest attention, while task switching and dual-task performance have been largely ignored, irrespective of the fact that these constructs play an important role in musical training. A different trend occurs in the bilingualism literature. While there has been adequate focus on bilingualism and task switching, particularly as it relates to cognitive control, the overall pattern of findings is equivocal (Barac & Bialystok, 2012; Paap & Greenberg, 2013). Moreover, little attention has been given to bilingualism and dual-task performance. As for the combined effects of musical training and bilingualism, only recently studies have begun to assess the link between music and language processing (Bidelman, Hutka, & Moreno, 2013; Cooper & Wang, 2012; Lee & Lee, 2010; Lee, Lee, & Shr, 2011; Patel, 2003). However, no studies to date have assessed the additive effects of bilingualism and musical training on task switching or dual-task performance.

The goals of this study were to (a) determine the extent to which musical training is associated with cognitive advantages in task switching and dual-task performance, (b) contribute to the existing literature on bilingualism and task switching and dual-task performance by examining these associations using theoretically motivated paradigms while controlling for critical variables such as socioeconomic status (SES), and (c) explore the possibility of additive effects of musical training and bilingualism on task switching and dual-task performance.

1.1. Musical training and task switching

1.1.1. Musical training

Musical training involves complex motor, auditory, and cognitive processing of information, such as translating symbols to sound and keeping the rhythm and tempo of a musical piece in memory, while simultaneously monitoring one's motor movements. At the cognitive level, musical training involves learning to (a) switch attention between groups of notes, rhythm, tempo, and stylistic elements of a musical piece, (b) simultaneously translate and combine, in real time, visual and auditory stimuli, such as notes on a score and sounds from an instrument, (c) maintain multiple components of the musical piece in working memory, such as notes and variations in tone and rhythm, and (d) ignore or inhibit interference from competing stimuli, such as alternate melodic or harmonic lines generated by other musicians. This list is not exhaustive, however, and additional processes likely are involved in musical training and performance.

Expert musicians spend at least 10,000 hours practicing and performing music requiring this wide range of cognitive skill sets by the age of 21 (Ericsson, Krampe, & Tesch-Romer, 1993). Thus, playing a musical instrument on a regular basis not only might improve performance on specific and directly related skills, such as low-level auditory pitch and rhythm processing, but also could extend its effects to improving higher cognitive processes, which are exercised continuously during musical learning and practice (Schlaug, Norton, Overy, & Winner, 2005). In fact, evidence for far transfer effects of musical training has been observed in relation to general intelligence (Schellenberg, 2006), interference control (Bialystok & DePape, 2009), verbal memory (Ho, Cheung, & Chan, 2003), and working memory (Lee et al., 2007). In contrast, there are few studies that have directly explored the relationship between musical training and task switching or musical training and dual-task performance.

1.1.2. *Task switching*

Task switching is the ability to switch between tasks or mental sets (Jersild, 1927) and may reflect cognitive flexibility (Meiran, 2010). Studies have consistently found that switching or alternating between tasks results in higher reaction times (or switch costs) compared to repeatedly performing the same task (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). Two types of switch cost can be measured in a task-switching paradigm. Local switch cost (also referred to as specific or switching cost) can be defined as the reaction time difference between a switch trial and a non-switch trial within a mixed-task block (i.e., a block that contains both switch and non-switch trials), while global switch cost (also referred to as general or mixing cost) can be defined as the difference in reaction time between non-switch trials within a single-task block (i.e., a block that contains a single, repeated task) and non-switch trials in a mixed-task block (Braver, Reynolds, & Donaldson, 2003; Mayr, Diedrichsen, Ivry, & Keele, 2006; Philipp, Kalinich, Koch, & Schubotz, 2008). These two types of switch cost are associated with separate cognitive processes (Philipp et al., 2008; Prior & MacWhinney, 2010; Rubin & Meiran, 2005). Local switch cost is thought to reflect the cognitive effort required to shift from one mental set to another (Verhaeghen & Basak, 2005), while global switch cost is thought to reflect the ability to maintain and activate two or more competing task sets in memory (Braver et al., 2003; Dibbets & Jolles, 2006).

The few studies that have examined musical training and task switching have looked at this relationship indirectly and used paradigms with poor construct validity. For example, Hanna-Pladdy and MacKay (2011) administered a neuropsychological battery to a sample of older adults varying in musical ability. The battery included the Trail Making Test, a task requiring participants to draw a line connecting letters and numbers in numerical and alphabetical sequence as quickly as possible (Reitan & Wolfson, 1993). They reported musician benefits on the Trail Making Test, especially in high-activity musicians. Similarly, Bugos, Perlstein, McCrae, Brophy, and Bedenbaugh (2007) used the Trail Making Test as a measure of cognitive flexibility with a sample of older adults who received piano training for 6 months compared with controls. Results demonstrated that older adults who had received musical training performed better on the Trail Making Test and Digit Symbol paradigms compared with healthy controls. Finally, Bialystok and DePape (2009) used the Trail Making Test as part of a larger battery in their investigation of executive function in musicians, bilinguals, and monolinguals. Although they reported musician benefits on other executive function tasks, such as Simon and auditory Stroop, they did not find any musician or bilingual advantages on the Trail Making Test. The Trail Making Test is generally used as a diagnostic tool in clinical settings to measure impairment in executive function, and it appears to tap working memory ability to a greater extent than task-switching ability (Salthouse, 2011; Sanchez-Cubillo et al., 2009). Moreover, this paradigm only consists of univalent stimuli (in which the stimuli are associated with a single task), which, unlike bivalent stimuli (in which the stimuli are associated with two tasks), typically do not produce switch costs (Finkbeiner, Almeida, Janssen, & Caramazza, 2006).

Taken together, examining shifting ability using the Trail Making Test has produced mixed results. Moreover, evidence suggests that this paradigm measures more than just task-switching ability and may primarily tap working memory ability. To effectively assess the relationship between musical training and task-switching ability, valid paradigms are needed that allow for more accurate measurement of this construct. This study aimed to study task switching using a contemporary, theoretically motivated paradigm.

1.2. Bilingualism and task switching

1.2.1. Bilingualism

Bilingualism, or the ability to communicate in two languages, is a type of skill that has been suggested to offer metalinguistic advantages (i.e., benefits that extend beyond language; Bialystok, 2009). The effects of bilingualism on executive function have been extensively investigated over the past several decades, and according to this literature, bilinguals appear to have certain cognitive advantages compared to monolinguals, such as improved selective attention and cognitive flexibility resulting from the experience of having to coordinate the cognitive demands of two or more languages (Bialystok et al., 2004; Bialystok & Shapero, 2005). This process could involve, but is not limited to, (a) inhibiting the non-target language to speak the target language fluently, (b) maintaining information from both languages in working memory, (c) switching from one language to another, and (d) simultaneously accessing and manipulating multiple language components, such as grammar, pronunciation, and meaning. Evidence for a bilingual advantage has been observed in constructs such as inhibitory control (Green, 1998), task switching (Prior & MacWhinney, 2010), selective attention (Costa, 2005), and working memory (Just & Carpenter, 1992). Moreover, the bilingual advantage has been observed in various cultures (Bialystok & Martin, 2004; Costa, 2005) and across the life span (Bialystok et al., 2004).

1.2.2. Task switching

Bilinguals often need to switch between two or more languages (called language or code switching; Meuter & Allport, 1999), which can produce switch costs. A dominant theory of language switching involves the role of inhibition. According to the inhibitory account, an individual's first language (L1) needs to be suppressed in order for the second language (L2) to become activated (Meuter & Allport, 1999). Moreover, if L1 is the dominant language, it might be more difficult to suppress this language, and higher switch costs would be incurred when switching back to L1, presumably because it is difficult to overcome the high degree of inhibition initially used to suppress the dominant L1 (Meuter & Allport, 1999). This description is consistent with Allport's task set inertia theory (Allport et al., 1994).

Several studies have investigated the role of task-switching ability in bilingualism, with some demonstrating bilingual advantages. Bialystok and Martin (2004), for example, demonstrated bilingual advantages on the dimensional change card sort task (Zelazo, Reznick, & Pinon, 1995) in preschool children. At the simplest level, this paradigm involves shifting from one dimension to another, such as color to shape or vice versa, and requires activation of the current sorting rule, inhibition of the previous criterion, and the ability to switch mental sets. Bialystok and Martin, however, also included conditions such as color object (e.g., red flowers and blue rabbits), which involved identifying objects rather than geometrical shapes, and function–location, where stimuli represented a function (e.g., things to wear) or location (e.g., things to wear inside or outside the house). Data showed that bilingual children were able to perform better on the color-shape and color-object conditions, which required sorting based on perceptual features, compared to monolingual children. However, performance between the two groups did not differ in the function–location condition, where sorting was based on a semantic dimension.

Prior and MacWhinney (2010) demonstrated a bilingual advantage in task switching in a study of 88 young adults attending university. These participants were tested on a non-linguistic task-switching paradigm that required them to respond to shapes or colors on a computer screen. Results showed that bilinguals had a smaller local switch cost compared to monolinguals on this task, even after controlling for working memory and Scholastic Aptitude Test (SAT) performance. However, SES was poorly controlled in this study despite research showing that it is an important confounding factor in bilingualism research (Morton & Harper, 2007).

Barac and Bialystok (2012) provide further evidence of a bilingual advantage in task-switching ability. In this study, three separate bilingual groups (Chinese–English, French–English, and Spanish–English bilingual children) were compared to SES-matched monolingual children on a task-switching paradigm. Results showed that all three bilingual groups had smaller global switch costs than monolinguals, and no differences were found between the groups on local switch cost.

Taken as a literature, investigations of task-switching benefits in bilinguals versus monolinguals have produced inconsistent results. Moreover, it is not clear which aspect of task switching produces bilingual benefits. Some studies support task-switching benefits in local switch cost (e.g., Prior & MacWhinney, 2010), and others provide support for benefits in global switch cost (e.g., Barac & Bialystok, 2012), despite using similar color-shape tasks with non-verbal task cues. The current research aims to shed more light on the relationship between task switching and bilingualism while addressing some of the limitations in previous research using paradigms with appropriate task difficulty and controlling for SES.

1.3. Bilingualism and dual-task performance

Dual-task performance is another component of executive function, and it refers to the ability to perform two or more tasks concurrently (Pashler, 1994). Performing two or more tasks simultaneously can be challenging because one task can interfere with the performance of the other (e.g., talking on a cell phone and driving). Like task switching, the literature identifying the exact cognitive mechanisms involved in dual-task performance is complex, and conflicting views surrounding the contribution of activation and/or interference to performance costs also extend to dual-task performance.

Bilingualism involves the use of a multitude of interrelated executive processes (Garbin et al., 2010; Meuter & Allport, 1999). Dual-task performance (or multitasking) is one of these cognitive processes, and it appears to play an important role in language production. Whether an individual is translating text or speech in mind, he or she must simultaneously attend to and manipulate many components of language (we can call these modules) within working memory, including phonology (e.g., rules of pronunciation), syntax (e.g., rules of grammar), and semantics (i.e., meaning). In the case of bilinguals, as the individual switches from one language to another, he or she will need to access these modules more frequently and in a more complex manner as compared to someone who is only using one language. This process may, therefore, strengthen the cognitive (i.e., dual-tasking) system required to produce or access these modules. Moreover, the individual likely will need to inhibit one set of modules for L1 to access another set of modules for L2, and the challenge of switching between modules might serve to further strengthen dual-task performance in bilinguals. Although switching is involved in this process as a person alternates between languages, an important dimension is dual-task performance since an individual must simultaneously access and discriminate between multiple language components to produce the correct language outputs. However, task switching and dual-task performance are not entirely discrete constructs. Some research suggests that dual-task performance consists of multiple and rapid task switches; thus, at the core of dual-task performance is task switching (Rubenstein, Meyer, & Evans, 2001).

There is scant research examining the role of dual-task performance in bilingualism. Some research suggests a dual-task advantage for bimodal bilinguals, who use sign language alongside a spoken language (Emmorey, Borinstein, Thompson, & Gollan, 2010). Little research has investigated dual-task performance in unimodal bilinguals, who speak two spoken languages. Preliminary reports indicate dual-task performance benefits in unimodal bilinguals compared with monolinguals in a driving simulation task where individuals are required to drive and simultaneously speak on a cell phone (Telner, Wiesenthal, Bialystok, & York, 2008). In another study by Bialystok, Craik, and Ruocco (2006), unimodal bilinguals outperformed monolinguals on a dual-task paradigm consisting of concurrently classifying visual images and auditory information, but the bilingual benefit was only found using relatively simple letter and number stimuli, and more complex animal and music stimuli failed to show a language group effect. Taken together, evidence for a bilingualism benefit in dual-task performance is equivocal.

1.4. Musical training, bilingualism, and executive function

A central goal of this study was to explore the potential interaction between musical training and bilingualism with respect to task switching and dual-task performance. Music and language processing appear to involve overlapping cortical networks (Patel, 2003; Patel & Iversen, 2007). However, music and language processing also are known to activate non-overlapping neural regions (Rogalsky, Rong, Saberi, & Hickok, 2011). To the extent that different regions or networks process music and language (Rogalsky et al., 2011), and to the extent that these regions are used during executive function task performance and thus music and/or language experience have strengthened associations between neurons that are relevant to executive function task performance (Posner & Patoine, 2009), we predict that music and language experience should confer differing, additive benefits during executive function task performance. We were interested in exploring this possibility as it extends to higher level cognition using behavioral measures.

1.5. The present study

There were several predictions for this study. First, we expected musicians to outperform non-musicians on task-switching ability and dual-task performance. In terms of task-switching performance, we expected musicians to show smaller global switch costs compared with non-musicians due to the high working memory demands involved in musical training and the association between the ability to maintain and activate competing task sets in memory and global switch cost (Braver et al., 2003). We expected musicians to show smaller local switch costs compared with non-musicians. Musician advantages have been found on tasks that require continual switching between task sets (e.g., Hanna-Pladdy & MacKay, 2011), and studies have shown better interference control among musicians compared to controls (e.g., Bialystok & DePape, 2009). We expected musicians to perform better than non-musicians on response incompatible trials, in which the same stimuli are associated with a different response for each task, because musical training involves learning to efficiently decode symbols and attend to multiple cues. We had no reason to expect musical training to have an effect on response compatible trials, in which no interference is involved. Finally, we expected musicians to have better accuracy on dual-task paradigms compared with non-musicians, given the need for continuous multitasking during musical performance.

Second, we expected bilinguals to outperform monolinguals on task-switching ability and dual-task performance. The literature on bilingualism and task switching demonstrates local switch cost benefits in some cases and global switch cost benefits in other cases. While we expected benefits, it should be noted that bilingualism benefits are inconsistent even with similar paradigms, so we made this prediction hesitantly. We expected bilinguals to outperform monolinguals on response incompatible trials, and bilinguals and monolinguals to perform similarly on response compatible trials, based on previous work showing interference control benefits in bilinguals. Evidence supporting a bilingualism benefit at dual-task performance is equivocal; thus, we hesitantly predicted a bilingualism benefit.

Finally, we were interested in examining whether there would be additive effects of musical training and bilingualism on task switching and dual-task performance. Some research suggests that music and language access overlapping neural regions, while other studies point to non-overlapping regions. Here, we explored the possibility that being both musically trained and bilingual may confer additive benefits compared to having only one skill set.

2. Method

2.1. Participants

Participants consisted of 153 university students ranging from 18 to 31 years of age ($M = 22.01$, $SD = 2.86$). There were four experimental groups consisting of monolingual musicians ($n = 45$), monolingual non-musicians ($n = 36$), bilingual musicians ($n = 36$), and bilingual non-musicians ($n = 36$). Bilinguals were fluent in English plus at least one other language (Arabic, Armenian, Bulgarian, Cantonese, Farsi, French, German, Ghanian, Greek, Gujarati, Hebrew, Hindi, Italian, Indonesian, Japanese, Kachi, Korean, Mandarin, Portuguese, Punjabi, Romanian, Russian, Serbian, Sinhalese, Spanish, Tibetan, Turkmen, Twi, Urdu, Vietnamese, Yoruba, and Zulu). Among bilinguals, who were asked to describe their bilingualism on a 5-point scale (i.e., 1 = speak only one language, 2 = weak bilingual, 3 = unbalanced bilingual, 4 = practical bilingual, and 5 = fluent bilingual), 55% described themselves as fluent bilinguals (i.e., they are able to converse fluently, and they actively use two languages every day), 37% described themselves as practical bilinguals (i.e., they can carry out conversation fluently but do not use their second language daily), and 8% considered themselves unbalanced bilinguals (i.e., they are able to carry out basic conversation with minor grammatical errors, without the speaker repeating the sentence, but are not fully fluent). Musicians had an average of 12 years of formal musical training (range 6–22 years). Moreover, 90% had music theory training, 83% had ear training, and on average musicians rated themselves 3.25 or having “good” sight-reading ability on a 5-point scale where 1 = “beginner” and 5 = “expert.” Musicians consisted of instrumentalists (88.4%) who played at least one of 17 instruments (bass, cello, clarinet, drums, flute, guitar, keyboard, organ, piano, saxophone, shamisen, steel drum, trombone, trumpet, ukulele, viola, and violin) and vocalists (11.6%). Participants were recruited using posters disseminated at Toronto universities and by word of mouth, and they were paid $30 for their time.

Participants were not significantly different in age, $F(3, 148) = 1.63$, $p = .185$, or SES (as measured by mother's education), $F(3, 149) = 2.24$, $p = .086$ (Table 1). As an additional check of SES matching, non-verbal IQ did not differ between groups, $F(3, 148) = 0.255$, $p = .857$. Receptive vocabulary score was significantly higher in musicians compared to non-musicians, $t(70) = 2.88$, $p < .005$, $d = 0.68$, a finding that is consistent with previous literature demonstrating a link between musical training and verbal ability (Moreno et al., 2011; Schellenberg, 2006). In addition, receptive vocabulary was higher among monolinguals compared to bilinguals, $t(70) = 3.47$, $p < .001$, $d = 0.82$, a trend that has been demonstrated regularly in these groups (Ben Zeev, 1977; Bialystok & Craik, 2010). Within the musician group, there were no significant differences in mean years of musical experience between monolingual and bilingual musicians, $t(80) = 0.33$, $p = .740$, or mean age at which monolingual and bilingual musicians began training, $t(79) = 0.26$, $p = .797$. However, monolingual musicians spent significantly more hours per week practicing music at the time of participating in this study, compared to bilingual musicians, $t(76) = 2.52$, $p = .014$, $d = 0.57$.

2.2. Tasks

2.2.1. Language and musical background questionnaires

Participants completed a self-report questionnaire regarding their musical, language, and demographic background prior to completing the experimental tasks. The musical background questionnaire included questions regarding the age at which participants began taking music lessons and the duration of their training, the frequency and duration at which they practiced music on a weekly basis, and the level of sight-reading, ear training, and music theory achieved. The language background questionnaire included questions regarding what languages the participant could speak and understand, the frequency of language use, and the context and proportion of use of the languages spoken (i.e., percentage of time spent talking, listening, and reading, and the language(s) used at home

Table 1
Participant characteristics, mean (*SD*)

	Musician		Non-Musician	
Variable	Monolingual	Bilingual	Monolingual	Bilingual
Age (years)	21.5 (3.1)	22.5 (3.2)	22.6 (2.6)	21.5 (2.3)
SES (mother's education)	3.4 (1.1)	3.4 (1.4)	2.7 (1.3)	3.4 (1.3)
K-BIT-2 Vocabulary (raw)	51.0 (3.4)	49.2 (3.6)	49.7 (4.4)	45.0 (4.4)
K-BIT-2 Matrices (normed)	102.8 (22.3)	104.6 (14.7)	103.7 (15.2)	101.2 (12.5)
Musical Training (years)	12.0 (4.7)	12.4 (5.6)	—	—
Age Started Musical Training (years)	7.7 (2.9)	7.9 (3.5)	—	—
Weekly Musical Practice (hours)	9.8 (7.0)	5.7 (7.3)	—	—

Note. SES = socioeconomic status; K-BIT-2 = Kaufman Brief Intelligence Test 2. Mother's education ranged from 0 to 5 (0 = high school not completed, 1 = high school diploma, 2 = some college, 3 = college diploma, 4 = bachelor's degree, 5 = graduate or professional degree).

and work/school). Finally, demographic questions inquired about the level of education completed by the participant and the participant's parents, their family income, the participant's daily use of computer or video games, involvement in sports and other physical activities, and general health.

2.2.2. *Intelligence and vocabulary*

Vocabulary and non-verbal intelligence were assessed using the Kaufman Brief Intelligence Test 2 (K-BIT-2; Kaufman & Kaufman, 2004). The Matrices subtest of the K-BIT-2 is a standardized measure of non-verbal fluid intelligence. In this task, a series of abstract images were presented, and participants were required to complete visual analogies by indicating the relationship between images. The Verbal Knowledge subtest of the K-BIT-2 was used to examine receptive vocabulary. In this task, participants were presented with a word or phrase, and they were required to choose a picture that corresponded to that word or phrase. This task required no reading or spelling on the part of the participant. Both the Matrices and Verbal Knowledge subtests were administered and scored according to the K-BIT-2 manual, and standardized Matrices scores were obtained for participants. We did not administer the Riddles subtest, so Verbal Knowledge scores are raw, not standardized.

2.2.3. *Task-switching paradigm*

Task-switching performance was assessed using the Quantity/Identity task, which was also used in Cepeda, Cepeda, and Kramer (2000; Exp. 1). The task consisted of three separate blocks. In the first block, participants were required to indicate (when prompted by a cue) how many numbers (i.e., the quantity) were presented on the screen, and the correct response included one of two answer choices (either 1 or 3). In the second block, participants indicated that the value of the digit(s) or what number (i.e., identity) was presented on the screen, and they selected the value from two answer choices (either 1 or 3). During the third block, participants switched between indicating the quantity and identity of the numbers on the screen predictably every third trial, and similar to blocks 1 and 2, the correct response included one of two answer choices (either 1 or 3). Across all three blocks, the trials consisted of both response incompatible and response compatible stimuli. A response incompatible trial occurred when stimuli required different responses for each task (i.e., 3 and 111). In contrast, in a response compatible trial both tasks required the same response for a given stimulus (i.e., 1 and 333). The first two blocks of this task contained 24 trials and the third block contained 72 trials, with eight practice trials per block, and the response-stimulus interval randomly varied between 300 and 600 ms. Cue-stimulus interval was 0 ms, meaning that the cue was displayed simultaneously with the stimulus. Trials were self-paced; a participant's response on one trial instigated the next trial. The task took ~10 min to complete.

2.2.4. *Dual-task paradigms*

Dual-task performance was assessed using two tasks. First, participants completed the Krantz paradigm (Krantz, 2007), a rapid serial visual presentation task combined with a motor tracking task. In this task, participants were required to track a moving white dot (4 pixels in diameter, moving at a speed of 8 pixels per update and varying in degree of angle from 0 to 360°) with a target box (size = 16 pixels), which was controlled using the mouse. At the same time, they attended to single capitalized serif letters (font size = 24 pt) flashing one at a time in the center of the computer screen (duration of letter stimuli was 150 ms; average time between letters was 500 ms). Participants were required to click the mouse button whenever they saw the target letter X. After two practice trials, participants completed 10 experimental trials. Each trial lasted 20 s and the task took about 4 min to complete. The tasks produced three measures of accuracy, namely, average tracking error (i.e., average distance of the target box from the moving dot), the proportion of target responses (i.e., hits) in response to letter X, and the proportion of non-target responses (i.e., false alarms) in response to letter X. False alarms can be characterized as when a participant inaccurately reports the presence of letter X when another letter is present.

Second, participants completed a dual n-back task (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008), specifically, Brain Workshop (http://brainworkshop.sourceforge.net/). The task contained two main sections: 1-back and 2-back. Each main section contained three subsections: position single task, audio single task, and dual task. First, participants were required to remember the position of blue squares as they were presented one-by-one on a grid. They were required to press “A” on the keyboard every time a blue square appeared in the same position as the blue square just before it (“1-back position”). Second, participants heard letters (played through speakers), and they had to press “L” every time the letter they heard was the same as the letter that came just before it (“1-back audio”). Third, participants were required to perform the first and second parts at the same time (“dual 1-back”). Following the 1-back section, the procedure was repeated, however, participants were required to remember items presented the time before the previous item, or 2-back. The 1-back and 2-back conditions focus on measuring working memory while dual 1-back and dual 2-back focus on measuring attentional control and dual-task performance. Cards showing “A = position” and “L = audio” were placed on top of the keyboard to remind the participant which key corresponded to a particular response. Each of the six subsections had 56 trials, and each trial lasted 2.6 s. The task took about 15 min to complete.

2.3. Procedure

It is noteworthy that the Quantity/Identity and Krantz paradigms were a part of a larger battery consisting of 11 tasks that measured seven different cognitive constructs. It took approximately 2 h for participants to complete this battery of tasks, including a 10- to 15-min break in the middle. The order of tasks was kept consistent, beginning with informed consent by participants, followed by musical, language, and demographic questionnaires, the task battery, and lastly, debriefing of participants. The dual n-back paradigm was not a part of the original test battery. Participants were contacted 1 year after the initial testing session to return for a follow-up session where additional cognitive tasks were administered, including the dual n-back paradigm. Of the 153 participants who were contacted at year 2, 54 participants agreed to partake in the follow-up session, and of those, 48 participants had usable data. Of this subset, all participants had partaken in the first testing session and demographic variables for this group were consistent with the initial 153 participants. All of the tasks were presented using a Microsoft Windows XP computer with Core i5 CPU and were displayed on a 15-in (1,280 × 1,024 pixels) LCD monitor.

3. Results

3.1. Task switching

3.1.1. Global switch cost

Global switch cost was calculated as the difference in mean reaction times (RTs) between non-switch trials from the single-task blocks (i.e., average of block 1 and 2 means) and non-switch trials in the mixed-task block. To explore how different levels of switch block type and response compatibility interact with music and language, a 2 × 2 × 2 × 2 (switch block type [non-switch trials in switch blocks, non-switch trials in non-switch blocks] × response compatibility [compatible, incompatible] × musician status [musician, non-musician] × language status [bilingual, monolingual]) repeated-measures ANOVA was run. Results (Table 2) showed a main effect of switch block type, $F(1, 146) = 733.96$, $p < .001$, $\eta_p^2 = .834$, with faster RTs on non-switch trials in single-task blocks ($M = 444$, $SE = 8$) versus non-switch trials in mixed-task ($M = 865$, $SE = 17$) blocks. A main effect of response compatibility, $F(1, 146) = 72.91$, $p < .001$, $\eta_p^2 = .333$, was also demonstrated, with faster RTs on compatible ($M = 630$, $SE = 11$) versus incompatible ($M = 679$, $SE = 11$) trials. Moreover, a significant interaction between musician status and switch block type was demonstrated, $F(1, 146) = 13.15$, $p < .001$, $\eta_p^2 = .083$ (Fig. 1). Follow-up *t*-tests revealed faster RTs for musicians versus non-musicians on non-switch trials in both mixed task, $t(148) = -4.48$, $p < .001$, [$M_{\text{mus}} = 788$, $SD = 192$ vs. $M_{\text{n-mus}} = 940$, $SD = 224$], and single task, $t(148) = -2.27$, $p = .025$, [$M_{\text{mus}} = 427$, $SD = 75$ vs. $M_{\text{n-mus}} = 463$, $SD = 112$], blocks. Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = 0.025$).

In addition, a significant interaction was demonstrated between switch block type and response compatibility, $F(1, 146) = 16.83$, $p < .001$, $\eta_p^2 = .103$. Follow-up paired samples *t*-tests revealed faster performance on non-switch versus switch blocks for both compatible, $t(149) = 23.45$, $p < .001$, [$M_{\text{switch}} = 823$, $SD = 226$ vs. $M_{\text{n-switch}} = 431$, $SD = 92$], and incompatible trials, $t(149) = 25.19$, $p < .001$, [$M_{\text{switch}} = 893$, $SD = 234$ vs. $M_{\text{n-switch}} = 456$, $SD = 102$]. Moreover, participants displayed faster performance for compatible versus incompatible trials for both switch, $t(149) = -6.62$, $p < .001$, [$M_{\text{comp}} = 823$, $SD = 226$ vs. $M_{\text{incomp}} = 893$, $SD = 234$], and non-switch blocks, $t(149) = -7.44$, $p < .001$, [$M_{\text{comp}} = 431$, $SD = 92$ vs. $M_{\text{incomp}} = 456$, $SD = 102$]. Post-hoc analyses were based on an adjusted Bonferroni alpha level (0.0125).

Table 2
Mean scores (*SD*) for switch task measures by participant group

Trial/Block Type	Non-Switch Trial in Non-Switch Block	Switch Trial in Switch Block	Non-Switch Trial in Switch Block
Compatible			
Musician			
Monolingual	429 (77)	835 (207)	747 (206)
Bilingual	403 (71)	903 (214)	764 (198)
Non-musician			
Monolingual	442 (111)	829 (179)	891 (255)
Bilingual	451 (105)	926 (193)	916 (196)
Incompatible			
Musician			
Monolingual	450 (83)	915 (234)	805 (215)
Bilingual	417 (71)	1,007 (263)	843 (193)
Non-musician			
Monolingual	477 (118)	940 (199)	962 (258)
Bilingual	481 (124)	1,043 (189)	993 (216)

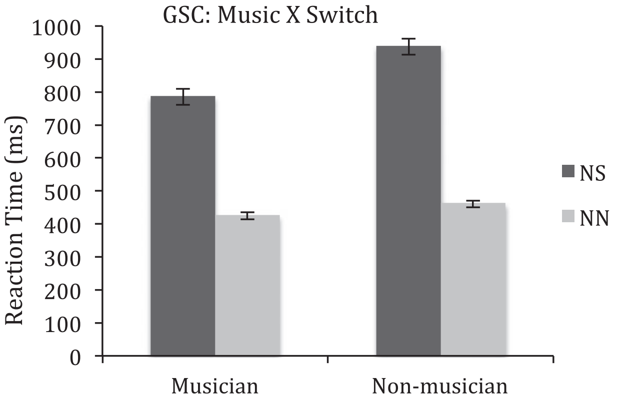

Fig. 1. Music by switch interaction in global switch cost. *Note.* NN = non-switch trial in non-switch (single-task) block; NS = non-switch trial in switch (mixed-task) block.

In terms of bilingualism, the results did not reveal any significant interactions between language status and other variables such as switch, compatibility, or musician status ($ps > .21$), and no main effects of language status were demonstrated ($p = .70$).

3.1.2. Local switch cost

Local switch cost was calculated as the difference in mean RTs between switch and non-switch trials in mixed-task blocks. To explore how different levels of switch status and response compatibility interact with musician status and language status, a 2 × 2 × 2 × 2 (switch status [switch trials in switch blocks, non-switch trials in switch blocks] × response compatibility [compatible, incompatible] × musician status [musician, non-musician] × language status [bilingual, monolingual] repeated-measures ANOVA was run. Results (Fig. 2) showed a main effect for switch status, $F(1, 146) = 44.49$, $p < .001$, $\eta_p^2 = .234$, with faster RTs on non-switch ($M = 865$, $SE = 17$) versus switch ($M = 924$, $SE = 17$) trials in a mixed-task block, and a main effect of response compatibility, $F(1, 146) = 119.03$, $p < .001$, $\eta_p^2 = .449$, with faster RTs on compatible ($M = 851$, $SE = 16$) versus incompatible ($M = 939$, $SE = 17$) trials. Findings also demonstrated a significant interaction between musician status and switch status, $F(1, 146) = 11.64$, $p = .001$, $\eta_p^2 = .074$. Follow-up *t*-tests revealed significantly faster RTs for musicians versus non-musicians on switch, $t(148) = -2.72$, $p = .007$, [$M_{\text{mus}} = 879$, $SD = 196$ vs. $M_{\text{n-mus}} = 969$, $SD = 207$], and non-switch trials, $t(148) = -4.43$, $p < .001$, [$M_{\text{mus}} = 788$, $SD = 192$ vs. $M_{\text{n-mus}} = 940$, $SD = 224$], in mixed-task blocks. Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = .025$). However, the size of local switch cost (difference between switch and non-switch trials in mixed-task blocks) was larger for musicians than non-musicians. Thus, despite musicians' faster response times than non-musicians on both types of trials, they nevertheless took longer to switch between the two types of trials resulting in larger local switch costs.

Finally, a significant interaction was demonstrated between switch status and response compatibility, $F(1, 146) = 4.63$, $p = .033$, $\eta_p^2 = .031$. Follow-up paired samples *t*-tests revealed faster performance on non-switch versus switch trials for both compatible, $t(149) = -4.05$, $p < .001$, [$M_{\text{switch}} = 870$, $SD = 202$ vs. $M_{\text{n-switch}} = 823$, $SD = 226$], and incompatible trials, $t(149) = -6.68$, $p < .001$, [$M_{\text{switch}} = 971$, $SD = 228$ vs. $M_{\text{n-switch}} = 893$, $SD = 234$]. Moreover, participants displayed faster performance for compatible versus incompatible trials for both switch, $t(149) = -9.38$, $p < .001$, [$M_{\text{comp}} = 870$, $SD = 202$ vs. $M_{\text{incomp}} = 971$, $SD = 228$], and non-switch trials, $t(149) = -6.62$, $p < .001$, [$M_{\text{comp}} = 823$, $SD = 226$ vs. $M_{\text{incomp}} = 893$, $SD = 234$]. Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = .0125$).

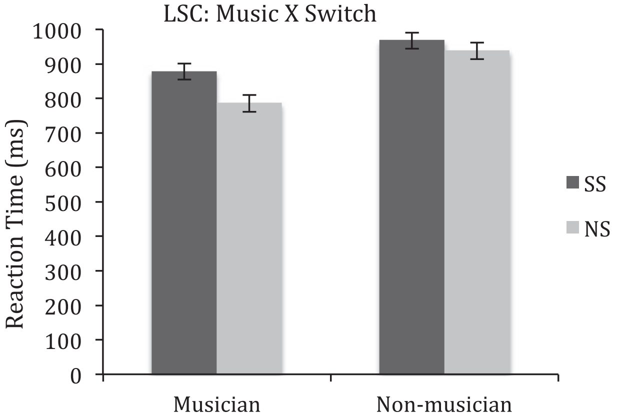

Fig. 2. Music by switch interaction in local switch cost. *Note.* SS = switch trial in switch (mixed-task) block; NS = non-switch trial in switch (mixed-task) block.

In terms of bilingualism, the results did not reveal any significant interactions between language status and other variables such as switch, compatibility, or musician status (*p*s > .26), and no main effects of language status were demonstrated ($p > .47$).

Percent error rates were calculated for global and local switch cost. A 2 × 2 × 2 × 2 (switch status [switch trials in switch blocks, non-switch trials in switch blocks] × response compatibility [compatible, incompatible] × musician status [musician, non-musician] × language status [bilingual, monolingual] repeated-measures ANOVA was run. Results showed a main effect of compatibility on percent error rates for global switch cost, $F(1, 146) = 148.0$, $p < .001$, $\eta_p^2 = .503$, with higher percent error on incompatible ($M = 5.84$, $SE = 0.42$) versus compatible ($M = 1.16$, $SE = 0.17$) trials. Next, percent accuracy results for local switch cost demonstrated a main effect of switch, $F(1, 146) = 49.44$, $p < .001$, $\eta_p^2 = .253$, with higher percent error on switch ($M = 6.42$, $SE = 0.42$) versus non-switch ($M = 3.56$, $SE = 0.32$) trials. In addition, a main effect of compatibility, $F(1, 146) = 177.85$, $p < .001$, $\eta_p^2 = .549$, was demonstrated for local switch cost, where percent error was higher on incompatible ($M = 8.65$, $SE = 0.56$) versus compatible ($M = 1.33$, $SE = 0.17$) trials. Finally, a switch by compatibility interaction was demonstrated for local switch cost, $F(1, 146) = 44.66$, $p < .001$, $\eta_p^2 = .234$. Follow-up paired samples *t*-tests revealed a significant difference in percent error between switch ($M = 11.30$, $SD = 9.31$) and non-switch ($M = 5.93$, $SD = 6.61$) trials but only for incompatible trials, $t(149) = 7.55$, $p < .001$. This difference in accuracy did not occur for compatible trials ($p > .27$). Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = .0125$). Results did not reveal any main effects or interactions for musician or language status for global (*p*s > .20) or local switch cost (*p*s > .19).

3.2. Dual-task performance

The Krantz paradigm involves measuring accuracy on two tasks that are presented simultaneously: (1) following a moving dot on a computer screen with a mouse, and (2) responding to the letter X (which flashes intermittently with other letters) with a mouse click. To obtain a single accuracy measure for dual-task performance that incorporated participants' performance on both tasks, an average dual-task score was computed. First, d-prime was computed for responses to letter X, from hits (identifying letter X when X appears) minus false alarms (identifying letter X when another letter appears). Second, the average distance between the moving dot and the tracking box location was computed. Then, to obtain an average dual-task score, the mean of the normalized scores for these measures was obtained. Since z-scores, which have a mean of zero, are the result of subtracting a data point from the population mean and then dividing this value by the population standard deviation, this formula will by necessity produce both positive and negative values. Given that the average dual-task score is composed of normalized z-scores for both d-prime and average tracking error, this dual-task score also contains both positive and negative values. For both tasks and modalities, d-prime for auditory and tracking for visual, raw scores were positive, on average, for each group.

A 2 × 2 (musician status [musician, non-musician] × language status [bilingual, monolingual]) between-subjects ANOVA showed a main effect of musician status, $F(3, 147) = 8.60$, $p = .004$, $\eta_p^2 = .055$, with musicians ($M_{\text{mus}} = 0.174$) outperforming non-musicians ($M_{\text{n-mus}} = -0.156$) on the average dual-task score (Fig. 3). There was neither a main effect of language status nor an interaction between musician and language status ($ps > .36$).

The dual n-back is another paradigm that measures dual-task performance. Accuracy data (Table 3) were provided for four conditions, including 1-back, 2-back, dual 1-back, and dual 2-back. Performance on the 1-back (the average of 1-back position and audio) was compared to the 2-back (the average of 2-back position and audio; and the dual 1-back was compared to the dual 2-back. First, a 2 × 2 × 2 (musician status [musician, non-musician] × language status [bilingual, monolingual] × difficulty level [1-back, 2-back]) repeated-measures ANOVA was run, which demonstrated a main effect of difficulty level, $F(3, 44) = 71.22$, $p < .001$, $\eta_p^2 = .62$, where participants had higher percent accuracy on 1-back ($M = 93$, $SE = 1.3$) compared to 2-back ($M = 68$, $SE = 3.1$). No interactions between difficulty level and musician or language status were demonstrated ($ps > .12$). Tests of between-subjects effects demonstrated a marginal interaction between musician and language status, $F(3, 44) = 3.34$, $p < .07$, $\eta_p^2 = .07$. However, follow-up *t*-tests comparing 1- and 2-back performance did not demonstrate significant differences between musicians and non-musicians, nor between bilinguals and monolinguals ($ps > .14$). Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = .025$).

A separate analysis was conducted to account for possible differences in 1- and 2-back performance based on modality (i.e., visual or position vs. auditory). A 2 × 2 × 2 × 2 (musician status [musician, non-musician] × language status [bilingual, monolingual] × difficulty level [1-back, 2-back] × modality [position, auditory]) repeated-measures ANOVA was run, which demonstrated a significant main effect of modality, $F(3, 44) = 11.44$, $p = .002$, $\eta_p^2 = .21$, where participants, in general, had higher percent accuracy on the auditory ($M = 83$, $SE = 2.1$) compared to position or visual ($M = 77$, $SE = 2.0$) modality. Results also demonstrated a main effect of difficulty level, which

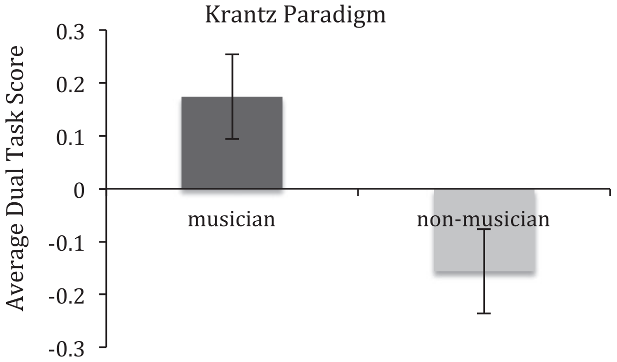

Fig. 3. Main effect of musician status in the Krantz paradigm.

Table 3
Mean percent accuracy (*SD*) on the dual n-back task by participant group

	Difficulty Level			
Group	1-Back	2-Back	Dual 1-Back	Dual 2-Back
Monolingual musician (*n* = 19)	97 (5)	76 (21)	94 (5)	56 (22)
Monolingual non-musician (*n* = 9)	88 (10)	62 (24)	81 (17)	38 (15)
Bilingual musician (*n* = 10)	92 (11)	65 (18)	85 (11)	38 (15)
Bilingual non-musician (*n* = 10)	94 (8)	67 (19)	85 (12)	45 (16)

was identical to that noted above. Finally, an interaction was demonstrated between modality and difficulty level, $F(3, 44) = 5.45$, $p = .024$, $\eta_p^2 = .11$. Follow-up paired samples *t*-tests demonstrated significantly higher accuracy on 1-back ($M = 93$, $SD = 11$) versus 2-back position ($M = 64$, $SD = 23$), $t(47) = 8.20$, $p < .001$, and higher accuracy on 1-back ($M = 94$, $SD = 10$) versus 2-back auditory ($M = 75$, $SD = 23$), $t(47) = 6.71$, $p < .001$. Finally, accuracy was significantly higher on 2-back auditory ($M = 75$, $SD = 23$) versus 2-back position ($M = 64$, $SD = 23$), $t(47) = -4.05$, $p < .001$. However, accuracy was not higher on 1-back auditory compared to 1-back position ($p > .43$). Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = .0125$). There were no interactions demonstrated between modality and musician or language status, or between difficulty level and musician or language status.

A similar analysis was used to explore participants' performance on the dual n-back conditions. A 2 × 2 × 2 (musician status [musician, non-musician] × language status [bilingual, monolingual] × difficulty level [dual 1-back, dual 2-back]) repeated-measures ANOVA was run. Results showed a significant main effect of difficulty level, $F(3, 44) = 221.84$, $p < .001$, $\eta_p^2 = .83$, where participants performed better on dual 1-back ($M = 86$, $SE = 1.6$) versus dual 2-back ($M = 44$, $SE = 2.8$). No interactions between difficulty level and musician or language status were demonstrated (*p*s > .35). Tests of between-subjects effects demonstrated a significant interaction between musician and language status, $F(3, 44) = 7.25$, $p = .010$, $\eta_p^2 = .14$ (Fig. 4). However, a follow-up *t*-test using an adjusted Bonferroni alpha level ($p = .025$) did not demonstrate significantly higher accuracy in musicians ($M = 70$, $SD = 12$) compared to non-musicians ($M = 62$, $SD = 14$), $t(46) = -2.01$, $p = .05$, based on this more stringent alpha level. Similarly, a follow-up *t*-test for language status using Bonferroni correction did not demonstrate significantly higher accuracy on this task in monolinguals ($M = 70$, $SD = 14$) relative to bilinguals ($M = 63$, $SD = 11$), $t(46) = 1.78$, $p = .08$.

Similar to the 1- and 2-back tasks, a separate analysis was conducted to account for possible differences in dual 1- and dual 2-back performance based on modality (i.e., visual vs. auditory). A 2 × 2 × 2 × 2 (musician status [musician, non-musician] × language status [bilingual, monolingual] × difficulty level [dual 1-back, dual 2-back] × modality [position, auditory]) repeated-measures ANOVA was run, which demonstrated a significant main effect of modality, $F(3, 44) = 5.35$, $p = .025$, $\eta_p^2 = .11$, where participants, in general, had higher percent accuracy on the auditory ($M = 67$, $SE = 1.9$) compared to visual ($M = 63$, $SE = 2.0$) modality. Results also demonstrated a main effect

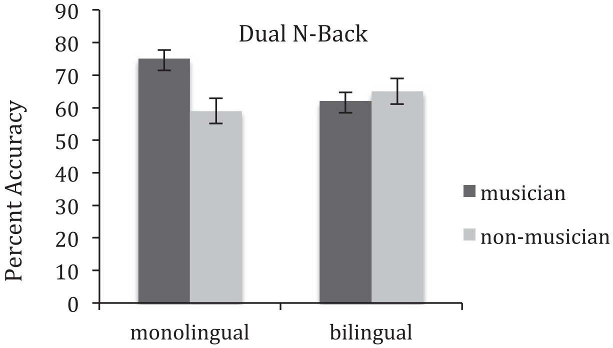

Fig. 4. Language by music interaction in dual n-back.

of difficulty level, which were identical to those noted above. Finally, results demonstrated an interaction between modality, language, and music, $F(3, 44) = 4.51$, $p = .039$, $\eta_p^2 = .09$. Follow-up independent samples *t*-tests demonstrate significantly higher accuracy among monolingual musicians ($M = 76$, $SD = 12$) than monolingual non-musicians ($M = 61$, $SD = 13$) on the collapsed dual 1- and 2-back auditory modality, $t(26) = -3.21$, $p = .003$, but the difference between monolingual musicians ($M = 72$, $SD = 12$) and monolingual non-musicians ($M = 58$, $SD = 18$) was not significantly different for the position modality, $t(26) = -2.42$, $p = .023$. Moreover, significant differences in accuracy between bilingual musicians and bilingual non-musicians were not demonstrated on the collapsed dual 1- and 2-back auditory ($p = .08$) or position modality ($p = .68$). Next, there were no differences detected between monolingual and bilingual non-musicians on both types of modality (*p*s > .15). However, accuracy was found to be significantly higher among monolingual ($M = 76$, $SD = 12$) than bilingual musicians ($M = 60$, $SD = 12$), $t(28) = 2.18$, $p = .001$, for the auditory modality, whereas this was not the case for the position modality ($p = .04$). Post-hoc analyses were based on an adjusted Bonferroni alpha level ($p = .0125$).[1]

3.3. Controlling for hours of weekly music practice

Given that a significant difference was found between monolingual and bilingual musicians on current weekly hours of music practice, it was important to account for this variable in the analysis. Consequently, participants were split into three groups, consisting of non-musicians, low-practicing musicians, and high-practicing musicians, and to classify musicians as high or low practicing, the median number of hours of weekly music practice was used to split the musician sample into two equal sized groups.

The results of the task-switching analysis demonstrated that despite differences in hours of weekly music practice, there continued to be significant musician benefits on global switch cost compared to non-musicians. The findings showed a music by switch interaction, $F(1, 146) = 4.88$, $p = .009$, $\eta_p^2 = .063$, indicating that both high ($p = .001$) and low ($p = .001$) practicing musicians performed significantly better than non-musicians on both switch, $F(2, 147) = 9.98$, $p < .001$, and non-switch, $F(2, 147) = 3.36$, $p < .03$, blocks. Post-hoc comparisons using the Tukey's HSD test indicated that the mean score for global switch cost in high practicing musicians was not significantly different from that of low practicing musicians ($p = .825$), but there was a significant difference between high practicing musicians ($p = .003$) and non-musicians, and low practicing musicians and non-musicians ($p < .001$).

Results for local switch cost were also consistent with initial findings. A music by switch interaction was maintained, $F(1, 146) = 5.53$, $p = .005$, $\eta_p^2 = .071$, indicating that both high and low practicing musicians performed significantly better than non-musicians on non-switch trials, $F(2, 147) = 9.98$, $p < .001$. However, only low practicing musicians outperformed non-musicians on switch trials, $F(2, 147) = 4.05$, $p < .02$. Post-hoc comparisons using the Tukey's HSD test indicated that performance of high practicing musicians was not significantly different from that of low practicing musicians ($p = .984$) on non-switch trials, but there was a significant difference between both high practicing musicians and non-musicians ($p = .001$), as well as low practicing musicians and non-musicians ($p = .001$) on non-switch trials. On switch trials, however, only a significant difference between low practicing musicians and non-musicians was demonstrated ($p < .021$). Moreover, a larger local switch cost was still present in both high and low practicing musicians compared to non-musicians.

The impact of hours of weekly music practice on dual-task performance was assessed using the same technique demonstrated earlier. Results of this analysis maintained a main effect of musician status in that musicians outperformed non-musicians on dual-task performance. However, a closer look at the groups using the Tukey's HSD multiple comparison test indicated that it was the difference between high practicing musicians and non-musicians ($p = .005$) on dual-task performance that was significant, and not between low practicing musicians and non-musicians ($p = .162$) or between high and low practicing musicians ($p = .448$). Significant differences were found in accuracy between high practicing musicians and non-musicians, but not between low practicing musicians and non-musicians. This finding indicates the significance of the degree or intensity of music practice in influencing cognitive functioning. As some studies suggest, intensity of musical practice may even be associated with structural brain differences among high practicing, low practicing, and non-musicians (Gaser & Schlaug, 2003). Due to insufficient sample size, this analysis was not performed on n-back data.

4. Discussion

This study investigated the association between musical training, bilingualism, and two aspects of executive function, namely, task switching and dual-task performance. Our results demonstrated that long-term musical training was associated with benefits in task switching and dual-task performance, while bilingualism was not related to such benefits. Moreover, there were no additive effects of musical training and bilingualism in these cognitive domains.

4.1. Task switching

Our findings were in line with the prediction that musicians would show advantages on global switch cost compared with non-musicians. Results showed an interaction between musician and switch status, indicating that musicians produced significantly smaller global switch cost than non-musicians. Specifically, musicians were more efficient than non-musicians in processing non-switch trials in mixed-task blocks (~150 ms faster), demonstrating musicians' superior ability to maintain and manipulate competing information in memory, allowing for efficient global processing. Musicians' extensive training requires maintenance and manipulation of complex stimuli in memory, such as notes, melody, pitch, rhythm, dynamics, and the emotional tone of a musical piece, which may help them to develop superior control to respond efficiently to stimuli in an environment where both switching and non-switching components exist. This trend is consistent with studies demonstrating superior working memory in musicians relative to non-musicians (Lee et al., 2007).

Results also demonstrated significant main effects for switch and compatibility, and a significant interaction between switch and compatibility. This result is common in task-switching studies, as individuals typically perform better on non-switch trials as compared with switch trials (Meiran, 2010), and better on compatible versus incompatible trials (Rogers & Monsell, 1995). Similarly, individuals performed better on non-switch, compatible trials compared to ones that involved switching or incompatible stimuli.

Results demonstrated a significant interaction between musician and switch status, indicating that musicians were more efficient than non-musicians on switch and non-switch trials within a mixed-task block. However, where switching was required between switch and non-switch trials, musicians demonstrated faster RTs that also resulted in larger local switch costs, a finding that was inconsistent with our predictions. Previous research has alluded to the connection between global switch cost and working memory (i.e., the maintenance and manipulation of task goals), as well as between local switch cost and inhibitory control. One possible explanation for the above trend may be that musicians' training may, to a greater extent, target and improve their working memory ability rather than inhibitory control, thereby resulting in lower global, but not local switch costs.

Our findings demonstrate that musical training is related to improvements in task-switching performance, specifically global switch costs. A few studies have indirectly assessed task-switching ability between musicians and non-musicians using paradigms such as the Trail Making Test (Bugos et al., 2007; Hanna-Pladdy & MacKay, 2011), which do not permit measurement of both global and local switch costs. Our study is unique in that it directly examined the association between musical training and task-switching ability using a valid and theoretically driven paradigm. Moreover, the findings for a music advantage in task switching are maintained even after controlling for variables such as hours of weekly music practice.

Our investigation of the relationship between bilingualism and task switching predicted bilingual benefits on global and/or local switch costs compared to monolinguals. Previous literature in this area has shown mixed results, with some studies supporting a global switch cost advantage and others supporting local switch cost advantages. However, most of these studies failed to control for SES or used tasks that were too easy for participants. This study addressed some of these limitations by controlling for SES and utilizing a paradigm with appropriate task difficulty. Despite these improvements, the results did not support benefits of bilingualism in either global or local switch cost. This finding was unusual given that previous literature with theoretically strong tasks has shown benefits of task switching in bilinguals compared with monolinguals (Bialystok & Martin, 2004; Prior & MacWhinney, 2010). The absence of a bilingual advantage in task switching in this study may be due to the type of paradigm used. In the current task switch paradigm, participants were provided written cues on each trial telling them to indicate "what number?" or "how many?" on the screen. Given that these cues were verbal as opposed to non-verbal, it is possible that they were more difficult for bilinguals to process. In fact, some research suggests that bilinguals have poorer lexical retrieval or access to vocabulary compared with monolinguals (Bialystok, 2009; Gollan, Montoya, Fennema-Notestine, & Morris, 2005). Therefore, it is possible that when bilinguals are exposed to tasks with verbal stimuli, the verbal components from one language might interfere with accessing vocabulary in another language, thereby causing delays in processing.

Alternatively, it is possible that bilingualism may not confer cognitive advantages under certain conditions. For example, Morton and Harper (2007) argue that a potential confound in bilingualism research is SES, and that controlling for differences on this variable (as well as ethnicity) can attenuate the bilingual advantage. However, studies that have controlled for SES using child (Barac & Bialystok, 2012) and adult (Emmorey, Luk, Pyers, & Bialystok, 2008) populations continue to show a bilingual advantage.

Another possible explanation may be that bilingualism does not confer far transfer effects in cognition (Hilchey & Klein, 2011). For example, recent work by Paap and Greenberg (2013) suggests the importance of convergent validity between tasks measuring similar constructs. That is, if bilingual benefits are found on some cognitive tasks but not on others measuring similar constructs, this absence of convergent validity does not provide compelling evidence for domain-general benefits of executive processing in bilinguals.

Additive benefits of musical training and bilingualism on global and local switch costs were predicted in this study. However, our data neither support nor refute this hypothesis. Given that we did not find a bilingual advantage, the absence of a combined effect may have been influenced by a lack of a bilingual effect in the first place. That is, it is possible that an additive effect may exist, but in this investigation there was not a bilingual effect to "add" to the music effect. It is possible that the tasks used in this study were not sensitive to differences between bilinguals and monolinguals, and thus, the potential combined effect of bilingualism and musician status could not be adequately examined. These results suggest that the combined effect of musical and language experience may be more complex than expected. This point is highlighted in a study by Cooper and Wang (2012), in which they compared the effects of linguistic and musical experience on Cantonese word learning. The findings demonstrated that native (Thai) tone language listeners who were musically trained did not perform better on (Cantonese) tone word learning relative to non-native (English) tone language listeners with or without musical experience, or native tone language listeners without musical training. Rather, English tone language listeners who were musically trained and Thai tone language listeners who were not musically trained performed better than Thai tone language listeners who were musically trained, as well as English tone language listeners without musical training. Given that having either musical experience or tone language background was shown to lead to performance benefits in this study, it was surprising that individuals with both musical and tone language experience performed worse than those with either of these skills. To explain this trend, the authors proposed that lower than expected performance among Thai listeners who were musically trained may reflect a conflict between the type of strategies they employ based on their musical and linguistic experience and the type of information that is presented to them. Although the results failed to support a combined effect of musical and linguistic experience on word learning, they suggest that contextual factors may play an important role in studies where additive effects of music and language are examined.

4.2. Dual-task performance

Musical training involves simultaneous processing of multiple musical elements such as notes, melody, rhythm, and pitch. Given that musically trained individuals have become experts in carrying out these mental processes as a result of years of practice and training, musicians were predicted to perform better on tasks of dual-task performance, which tap these abilities, compared to individuals with no musical training. The Krantz paradigm, a novel measure used to assess accuracy on two simultaneous tasks, was employed as a measure of dual-task performance. As predicted, results demonstrated that musicians performed significantly better on the dual-task paradigm compared to non-musicians.

Based on prior work demonstrating dual-task performance benefits in bilinguals (Bialystok et al., 2006), the bilingual group was predicted to outperform the monolingual group on dual-task performance. However, the predictions were not supported; no bilingual benefits were found on the Krantz paradigm. A potential explanation for why no significant differences were found between bilinguals and monolinguals on the Krantz paradigm may have been due to the nature of the task, that is, the paradigm may not be sensitive enough to detect differences between bilingual and monolingual groups. Moreover, the two task components in the current dual-task paradigm (i.e., tracking a moving dot and responding to the letter X) both involved visual stimuli and were similar in terms of task difficulty. This is in contrast to tasks used in other studies measuring dual-task performance where the dual-task paradigm used consists of a mixture of visual and auditory stimuli and where one task is typically more difficult than a second task (Bialystok et al., 2006; Jaeggi et al., 2003). For example, in Bialystok et al., bilinguals were more efficient than monolinguals in classifying visual but not auditory stimuli, and this level of efficiency was evident only on the easier of two tasks.

Another explanation for why differences were found between musician and non-musician groups, and not between bilingual and monolingual groups, on the Krantz paradigm may be that there are components of this task that tap into differential skills between the two groups. For example, musical training involves systematic learning of hand and eye movements and their coordination. Although some hand–eye coordination or movement is also involved in language learning, this usually occurs in the form of reading and writing text but does not occur to the same extent as in musical training where individuals are required to move and coordinate their hands and fingers regularly and in a very precise manner. This paradigm involved two tasks that both required considerable hand–eye movements and coordination, such as tracking a moving dot on the screen with a mouse while simultaneously attending to flashing letters and having to click the mouse in response to letter X. These skills may be especially developed in musicians, and they may have helped musicians to excel on this particular dual-task paradigm. In contrast, bilingualism involves simultaneous activation and manipulation of language modules, which require little motor movement. Thus, the current dual-task paradigm may not have tapped this form of dual-task process.

A second measure, called the dual n-back task, was employed to assess dual-task performance in different modalities (i.e., auditory and visual). Participants demonstrated better performance on conditions with lower memory load (i.e., 1-back and dual 1-back) than those with higher memory load (i.e., 2-back and dual 2-back), a finding consistent with previous research (Jaeggi et al., 2003). Within-subjects analyses for the n-back and dual n-back did not show any interactions between difficulty level and musician or language status. In contrast, between-subjects analyses for the dual n-back demonstrated an interaction between musician and language status, where musicians outperformed non-musicians and monolinguals appeared to show an advantage over bilinguals, although the effect was marginal. However, follow-up analyses using Bonferroni correction demonstrated that the difference between musicians and non-musicians, as well as between monolinguals and bilinguals, was not significant. Moreover, bilingualism also did not contribute to benefits on the dual n-back task. However, note that because the dual n-back task did not include our entire original sample, we did not have a sufficiently large sample size to properly power this analysis, and the non-significant musician benefit could be due to type II error. The results of the dual n-back may have been inconsistent with findings from the Krantz paradigm because of a properly powered analysis for the Krantz task and an underpowered analysis for the dual n-back task.

Contrary to our predictions, the findings did not support a bilingual advantage in dual-task performance. It must be acknowledged that the literature investigating the relationship between bilingualism and dual-task performance is scarce. This lack of published literature may be due to a lack of significant findings resulting from underpowered studies, a lack of use of theoretically valid paradigms to test these concepts, or a lack of true connection between dual-task performance and bilingualism. What is clear is that further investigation is needed to make definite claims regarding the relationship between bilingualism and dual-task performance. Aside from the above justifications, the lack of findings found between these domains may also be due to methodological limitations of this study.

4.3. Limitations

A few limitations to this study should be considered. First, our study consisted of a cross-sectional design and was correlational in nature. As such, it is possible that the findings may be a result of other factors that were not controlled given this type of design, such as motivation or personality. For example, it has been suggested that improvements in cognitive abilities may be due to motivation or personality traits of individuals who pursue music rather than a result of musical training in itself (Corrigall, Schellenberg, & Misura, 2013). Second, we used samples of experienced adults. Despite our efforts to match demographic background and IQ, there may have been characteristics or attributes that were not equivalent across groups. Ideally, future studies examining the relationship between musical training, bilingualism, and cognition will utilize randomized controlled designs, where participants are randomly assigned to groups, and tested before and after training to ensure that any differences in performance can be attributed to the effects of training. Alternatively, investigators may want to examine musical training or bilingualism on a continuum, rather than as discrete variables. Taken together, the present investigation revealed an association between musical training and enhanced dual-task performance and global switch costs, with musicians outperforming non-musicians.

4.4. Overall summary

The current findings suggest that long-term musical training is associated with advantages in task-switching ability and dual-task performance. Contrary to expectations, bilingualism was not associated with benefits in task switching or dual-task performance relative to monolinguals, and being both a bilingual and a musician did not appear to offer added benefits in these cognitive domains. Future studies should devote attention to higher level cognitive benefits of musical training, including complex forms of executive function benefit.

Acknowledgments

This research was supported by grant 410-2010-2747 to MW from the Social Sciences and Humanities Research Council of Canada (SSHRC). We thank Janet Kim, Nora Kharouba, Vanessa Foot, Gaby Levkov, Justeena Zaki-Azat, and Lee Unger for data collection and analysis assistance. We thank Annalise D'Souza, Denise Paneduro, and Tina Weston for feedback on previous versions of this manuscript, and the Cognitive Flexibility Lab for input throughout all stages of this project.

Note

1. Data analyses for all tasks were performed using more stringent classification criteria for bilingualism and musician status (Appendix). The secondary analyses produced results consistent with those reported in the primary text.

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Appendix:

To establish that sample selection criteria for this study was valid and comparable to that of other studies in the field (Bidelman et al., 2013) without influencing the reliability of our results, we conducted further analyses using more stringent classification criteria for bilingualism and musician status. For example, bilinguals in the Bidelman et al. (2013) sample consisted of only fluent bilinguals (i.e., they were able to converse fluently, and they actively used two languages every day), and musicians consisted of instrumentalists who played regularly, had at least 10 years of training beginning at or before the age of 13, and had a least 5 years of formal lessons. A total of 57 subjects in our sample did not meet these criteria and were removed from the sample. With the exception of the dual n-back task, where there was insufficient sample size to conduct a follow-up analysis, all tasks produced results consistent with those reported in the main results section of the study.

Task switching

Global switch cost. A 2 × 2 × 2 × 2 (switch block type [non-switch trials in switch blocks, non-switch trials in non-switch blocks] × response compatibility [compatible, incompatible] × musician status [musician, non-musician] × language status [bilingual, monolingual]) repeated-measures ANOVA was run. Results showed a main effect of switch block type, $F(1, 96) = 443.37$, $p < .001$, $\eta_p^2 = .822$, with faster RTs (in milliseconds) on non-switch trials in single-task blocks versus non-switch trials in mixed-task blocks. A main effect of response compatibility, $F(1, 96) = 58.40$, $p < .001$, $\eta_p^2 = .378$, was also demonstrated, with faster RTs on compatible versus incompatible trials. Moreover, a significant interaction between musician status and switch block type was demonstrated, $F(1, 96) = 8.37$, $p = .005$, $\eta_p^2 = .080$. Follow-up tests revealed faster RTs for musicians versus non-musicians on non-switch trials in mixed-task blocks, $t(94) = -4.35$, $p < .001$, and marginally faster RTs for musicians versus non-musicians on non-switch trials in single-task blocks, $t(94) = -1.88$, $p = .063$.

There was a significant interaction between switch block type and response compatibility, $F(1, 96) = 19.57$, $p < .001$, $\eta_p^2 = .169$, with faster performance on non-switch versus switch blocks for both compatible, $t(99) = -19.47$, $p < .001$, and incompatible trials,

$t(99) = -21.07$, $p < .001$. Moreover, participants displayed faster performance for compatible versus incompatible trials for both switch, $t(99) = -6.06$, $p < .001$, and non-switch blocks, $t(99) = -6.58$, $p < .001$. The remaining interactions were all non-significant (ps > .08).

Local switch cost. A 2 × 2 × 2 × 2 (switch status [switch trials in switch blocks, non-switch trials in switch blocks] × response compatibility [compatible, incompatible] × musician status [musician, non-musician] × language status [bilingual, monolingual] repeated-measures ANOVA was run. Results showed a main effect of switch status, $F(1, 96) = 24.70$, $p < .001$, $\eta_p^2 = .205$, with faster RTs on non-switch versus switch trials, and a main effect of response compatibility, $F(1, 96) = 82.58$, $p < .001$, $\eta_p^2 = .462$, with faster RTs on compatible versus incompatible trials. Findings also demonstrated a significant interaction between musician status and switch status, $F(1, 96) = 6.11$, $p = .015$, $\eta_p^2 = .060$. Follow-up tests revealed faster RTs for musicians versus non-musicians on switch, $t(98) = -2.71$, $p = .008$, and non-switch trials, $t(94) = -4.35$, $p < .001$, in mixed-task blocks. However, the size of local switch cost (difference between switch and non-switch trials in mixed-task blocks) was larger for musicians than non-musicians. Thus, despite musicians' faster response times than non-musicians on both types of trials, they nevertheless took longer to switch between the two types of trials resulting in larger local switch cost. The remaining interactions were all non-significant (ps > .07).

Dual-task performance

Krantz paradigm. Consistent with our previous findings for this task, the results of a 2 × 2 (musician status [musician, non-musician] × language status [bilingual, monolingual]) between-subjects ANOVA showed a main effect of musician status, $F(3, 96) = 4.89$, $p = .029$, $\eta_p^2 = .048$, with musicians ($M_{\text{mus}} = 0.258$) outperforming non-musicians ($M_{\text{n-mus}} = -0.097$) on the average dual-task score. However, there was neither a main effect of language status, nor an interaction between musician and language status (ps > .32).

n-Back task. After removing subjects who did not meet the more stringent classification criteria for musician and language status, the sample size for this task was not large enough to run additional data analyses.