CHAPTER 26

MUSIC TRAINING AND COGNITIVE ABILITIES: ASSOCIATIONS, CAUSES, AND CONSEQUENCES

SWATHI SWAMINATHAN AND
E. GLENN SCHELLENBERG

INTRODUCTION

OVER the years, a large body of research has examined associations between music lessons and non-musical cognitive abilities, with the aim of determining whether music training improves cognition. Because most studies have correlational designs, conclusions of causation are precluded. Thus, it remains a matter of great debate *whether* and *under what conditions* music lessons improve non-musical abilities.

Musicians' brains are structurally and functionally different from those of non-musicians (for reviews see Gaser & Schlaug, 2003; Herholz & Zatorre, 2012). Except in rare instances (e.g., Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995), these differences do not inform the issue of causation. Individual differences in demographics, personality, cognitive ability, and so on, could be associated with brain development *and* with the likelihood of taking music lessons. In the present chapter, our focus is on associations between music training and behavior.

As one would expect, musically trained individuals tend to perform better than other individuals on tasks that require them to perceive and discriminate sequences of tones or beats (Bhatara, Yeung, & Nazzi, 2015; Law & Zentner, 2012; Slevc, Davey, Buschkuehl, & Jaeggi, 2016; Swaminathan & Schellenberg, 2017; Swaminathan, Schellenberg, & Khalil, 2017; Swaminathan, Schellenberg, & Venkatesan, 2018; Wallentin, Nielsen, Friis-Olivarius, Vuust, & Vuust, 2010). Music training is also associated with a wide range of *non-musical* abilities (for reviews see Schellenberg & Weiss, 2013; Swaminathan & Schellenberg, 2016). Moreover, a limited amount of experimental evidence suggests that music training causes improvements in non-musical abilities, at least in some circumstances (e.g., Jaschke, Honing, & Scherder, 2018; Kaviani, Mirbaha, Pournaseh, & Sagan, 2014; Portowitz, Lichtenstein, Egorova, & Brand, 2009; Schellenberg, 2004; Slater et al., 2015).

Based on findings of widespread correlations and a handful of encouraging experimental results, researchers have proposed that music training is the perfect model for investigating plasticity and transfer of learning (e.g., Herholz & Zatorre, 2012 Münte, Altenmüller, & Jäncke, 2002; Wan & Schlaug, 2010). Consequently, correlations between music training and non-musical abilities are considered to provide evidence of causal effects. This tendency is problematic for at least three reasons.

First of all, the link between music training and non-musical abilities is not clear-cut. For example, experiments sometimes fail to document improvements in cognitive abilities after taking music lessons (e.g., Butzlaff, 2000; Mehr, Schachner, Katz, & Spelke, 2013). Those that succeed often adopt non-standard pedagogies, such as training music-listening skills rather than teaching participants to sing or play an instrument (Degé & Schwarzer, 2011; Moreno, Bialystok, et al., 2011; for a review see Swaminathan & Schellenberg, 2016). When children are assigned to more standard conservatory-style lessons at no cost to their parents (Schellenberg, 2004; Slater et al., 2015), the learning process bears little resemblance to the real world, because parents do not insist that their children practice between lessons. Even in correlational studies, associations with music training are not always evident (e.g., Boebinger et al., 2015; Brandler & Rammsayer, 2003; Helmbold, Rammsayer, & Altenmüller, 2005; Ruggles, Freyman, & Oxenham, 2014; Schellenberg & Moreno, 2010; Swaminathan & Schellenberg, 2017).

The second problem is more theoretical, concerning the relation between correlation and causation. As every student in an introductory psychology course learns, correlation does not imply causation. Nevertheless, this is not a reciprocal relation, and causation definitely implies correlation. In other words, if music training causes improvements in cognitive abilities, one should rightly expect this effect to be evident in everyday life, such that individuals who take years of music lessons exhibit the documented positive effects. In short, when a correlational study is well designed and adequately powered, a null result provides direct negative evidence against the hypothesized effect, whereas a positive effect is simply consistent with a putative causal association.

A third major issue involves *far transfer*, when training in a domain such as music leads to better performance or faster learning in a different (i.e., non-musical) domain. Although near transfer—to a highly similar task—is common, it is still unclear whether far-transfer effects are even possible, despite more than a century of research, (e.g., Brody, 1992; Jensen, 1969, 1998; Thorndike & Woodworth, 1901a, 1901b). For example, interventions designed specifically to improve general cognitive abilities, such as working memory, fluid intelligence, or academic performance, report weak or variable results (Guo, Ohsawa, Suzuki, & Sekiyama, 2018; Love, Chazan-Cohen, Raikes, & Brooks-Gunn, 2013; Melby-Lervåg & Hulme, 2013; Melby-Lervåg, Reddick, & Hulme, 2016; Rapport, Orban, Kofler, & Friedman, 2013; Shipstead, Redick, & Engle, 2012; Weicker, Villringer, & Thöne-Otto, 2016). In fact, recent meta-analyses find weak to no evidence that (1) chess instruction leads to better cognitive skills (Sala & Gobet, 2016), (2) working-memory training enhances cognitive ability or academic achievement (Sala & Gobet, 2017b; Soveri, Antfolk, Karlsson, Salo, & Laine, 2017), or (3) video-game playing improves cognition (Sala, Tatlidil, & Gobet, 2018). With this larger context in mind, the putative cognitive-training effects of music lessons should be considered with caution. In fact, a meta-analysis that examined directly whether music training has far-transfer effects on non-musical cognitive abilities reported similarly skeptical results (Sala & Gobet, 2017a).

In the remainder of this chapter, we first review the correlational and experimental evidence for music-training effects. Subsequently, we propose an analytic strategy as a possible way forward.

A Review of Existing Evidence

Researchers have examined whether music training is associated with general cognitive abilities, visuospatial skills, and language skills. Associations have also been studied in applied contexts, such as educational settings and interventions designed to promote healthy aging. In this section, we review these findings, paying close attention to inconsistencies in the literature.

Music Training and General Cognitive Abilities

Musically trained children and adults typically have higher IQ scores than their untrained counterparts (Gibson, Folley, & Park, 2009; Gruhn, Galley, & Kluth, 2003; Ho, Cheung, & Chan, 2003; Schellenberg, 2011a, 2011b; Schellenberg & Mankarious, 2012; Trimmer & Cuddy, 2008). In some instances, duration of training is associated positively with IQ or other measures of general cognitive ability (Corrigall, Schellenberg, & Misura, 2013; Degé, Wehrum, Stark, & Schwarzer, 2014; Schellenberg, 2006; Swaminathan et al., 2017, 2018; Swaminathan & Schellenberg, 2018). In other words, as music training tends to increase, so does IQ. Because intelligence-test scores predict educational and career outcomes, as well as health and longevity (e.g., Deary, Strand, Smith, & Fernandes, 2007; Judge, Higgins, Thoresen, & Barrick, 1999; Spinath, Spinath, Harlaar, & Plomin, 2006), correlations are often interpreted optimistically, as evidence that music training promotes wide-ranging cognitive benefits that have implications for an individual's success in life. An alternative view of these correlational findings, however, is that enrolling in music lessons, particularly for extended durations of time, is the *consequence* of better intellectual functioning.

Nevertheless, there is some experimental evidence indicating that music lessons *cause* small improvements in IQ scores, which we will now summarize and evaluate. In one study, 144 6-year-olds were assigned randomly to one year of keyboard or vocal music lessons or to control conditions (drama lessons or no lessons at all; Schellenberg, 2004). Before the intervention period began, the groups did not differ in their scores on the Wechsler Intelligence Scale for Children—III (WISC-III). After the intervention, all groups showed improvements on the WISC-III. These across-the-board improvements likely resulted from attending school or a retesting effect. A more provocative result revealed that children who received music lessons (keyboard or voice) showed larger improvements than their counterparts in the control groups. The effect was evident only when the two music groups were contrasted directly with the two control groups, however, and it was small (< 3 points), less than the average intra-individual difference between two administrations of the same test. Moreover, at post-test when parents were questioned about their child's practice habits, it became clear that children in the music groups practiced minimally (10–15 min per week). In any event, the observed effect could have stemmed from the school-like structure of the music lessons, which differed from the play-like structure of the drama lessons, and led to better test-taking skills. Alternatively, the effect may have been a Type I error. As a side note, an interesting non-musical result was that the children in the drama group had the largest improvements in social behavior.

In a more recent study of preschoolers in Tehran, children assigned to three months of weekly music lessons made statistically significant post-test gains on a standardized Farsi version of the Stanford-Binet IQ test (Kaviani et al., 2014). There was no evidence of improvement in the control group. The control group in the Iranian study was a passive control group (i.e., no lessons at all), however, which makes it impossible to attribute the positive findings of the musically trained group to the actual music training, rather than to other aspects of the intervention (e.g., contact with an adult instructor).

Another recent longitudinal study was conducted in the Netherlands (Jaschke et al., 2018). Randomization to different conditions involved entire schools rather than individual children (as in Portowitz et al., 2009). Two schools were assigned randomly to a music-training intervention, and two to a visual-arts program. The remaining two groups received the standard Dutch curriculum. A fourth group comprised children who were taking music lessons outside of school *and* assigned to the music intervention. The authors reported that the visual-arts group showed more improvement than the other groups in visuospatial ability, whereas the two music groups showed larger improvements in verbal IQ and executive functions (planning and inhibition). In short, children from different schools had different rates of improvement. It is impossible, however, to attribute the response patterns to the different interventions. Other differences between schools, such as teaching quality, may have played a major role, and no conclusions can be made about any analysis that included the fourth group because of self-selection.

Relatively weak positive results such as these are further belied by a fair dose of mixed or null findings. One issue is that enhancements are more likely on some IQ tests than on others. For example, group differences are less likely to be evident when a test of fluid intelligence is used as the measure of general cognitive ability (Bialystok & DePape, 2009; Brandler & Rammsayer, 2003; Helmbold et al., 2005; Schellenberg & Moreno, 2010; Swaminathan & Schellenberg, 2017), rather than a test that includes measures of crystallized intelligence, such as vocabulary (Jaschke et al., 2018; Kaviani et al., 2014; Schellenberg, 2004). It is also clear that music training is associated with IQ in some groups but not in others. For example, university music majors, who have presumably invested a lot of time and effort in acquiring musical skills, do not necessarily show an IQ advantage compared to students at the same level majoring in other disciplines (Brandler & Rammsayer, 2003; Helmbold et al., 2005). In other words, the association between music training and cognitive ability is strongest when music training is an add-on activity rather than the participant's primary focus. Otherwise, one would expect professional musicians (e.g., Celine Dion, members of symphony orchestras) to be geniuses.

There are other reasons to be cautious about the putative causal effect of music training on intelligence. For one, correlations between music lessons and cognitive ability may be explained by personality factors, particularly the Openness-to-Experience trait (Corrigall et al., 2013; Corrigall & Schellenberg, 2015). In other words, musically trained individuals may perform well on intelligence tests, at least in part, because they tend to be curious and particularly interested in learning new things (including, but not limited to, music). Moreover, common genetic factors underlie intelligence and the propensity to practice music (Mosing, Madison, Pedersen, & Ullén, 2016).

Findings from studies that examined personality or genetics raise the possibility that the association between music training and general cognitive ability in correlational studies and quasi-experiments is largely a reflection of pre-existing differences. Moreover, despite some experimental evidence for modest IQ enhancements after music training (Jaschke et al., 2018; Kaviani et al., 2014; Portowitz et al., 2009; Schellenberg, 2004), other experiments and longitudinal studies failed to find general cognitive improvements. For example, one longitudinal study in Hong Kong found no evidence for an IQ enhancement after six months of training (Ho et al., 2003, study 2). When researchers in Massachusetts assigned preschool children randomly to either six weeks of group music lessons or no lessons at all, they found no advantage in cognitive abilities for the children who took music lessons (Mehr et al., 2013, experiment 2). Such inconsistent results suggest that music training may not always result in cognitive advantages, or that the effect is very small.

One possibility is that music lessons lead to intellectual advantages only if they train some intermediate capacity that mediates the association between music training and intelligence. For example, it has been suggested that executive functions such as attention, a capacity closely associated with general cognitive ability (Salthouse, 2005), can be trained (Rueda, Rothbart, McCandliss, Saccamanno, & Posner, 2005). Working memory is similarly thought to be trainable (Klingberg, 2010; cf. Melby-Lervåg & Hulme, 2013), and there is some evidence that working-memory training transfers to improvements in fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). This particular report of far transfer has been questioned, however, because of the study's methodological irregularities, and because there was no evidence that the effect was long-lasting (Conway, Getz, Macnamara, & Engel de Abreu, 2011; Mackintosh, 2011; Moody, 2009).

Nevertheless, it is still possible that music lessons train executive functions, including working memory, which in turn promote general cognitive enhancements (Degé, Kubicek,

& Schwarzer, 2011; Hannon & Trainor, 2007; Posner, Rothbart, Sheese, & Kieras, 2008; Schellenberg & Peretz, 2008). In fact, musically trained adults perform better than their untrained counterparts on auditory (Bialystok & DePape, 2009; Roden, Grube, Bongard, & Kreutz, 2014; Zuk, Benjamin, Kenyon, & Gaab, 2014) as well as non-auditory (Bialystok & DePape, 2009; Okada & Slevc, 2018; Zuk et al., 2014) tests of executive functions, as do musically trained children and teenagers (Degé et al., 2011; Herrero & Carriedo, 2018; Jaschke et al., 2018). In one study of 9- to 11-year-olds, however, music training was associated with IQ but not with executive functions other than auditory working memory (Schellenberg, 2011a). Virtually identical results were evident when 6- to 8-year-olds were randomly assigned to a six-week music-training intervention, with more improvement, relative to controls, on a test of working memory but not on other measures of executive functions (Guo et al., 2018). Thus, it remains unclear whether executive functions mediate the effect of music training on cognition.

A second possibility is that the type of music training plays a role (Swaminathan & Schellenberg, 2016). Private music lessons (where one teacher attends to one student or a very small group of students) emphasize individual accomplishment and skill mastery. Group-based lessons (e.g., training in a high-school band), on the other hand, are more likely to emphasize collective outcomes over individual ones. Private music training may be more effective than group-based lessons at improving scores on tests of cognitive ability, which by definition measure individual ability and accomplishment. Alternatively, individual differences in cognitive ability may influence who takes private lessons. Either way, the association could be limited to the developed world, where private lessons are common. In developing countries, and throughout history, music making is and has been typically a group activity, in which virtually everyone takes part.

Considered as a whole, although associations between music training and intelligence are evident in many circumstances, it is unclear whether music training *causes* improvements in cognitive ability. If music lessons do improve intelligence or general cognitive ability, the effect appears to be: (1) small, (2) evident only among some individuals, or (3) a likely consequence of taking lessons that emphasize individual achievement. More generally, we know that far-transfer effects are very rare, and that parsimony rules the day in the world of science. In short, a simpler explanation of the available data is that high-functioning individuals are more likely than other individuals to take music lessons.

Associations with Specific Cognitive Abilities

Despite evidence of associations between music training and domain-general abilities such as general intelligence or IQ, it has often been suggested that musical abilities are more strongly related to some non-musical, cognitive abilities than they are to others. For example, a case has been made for special overlaps between musical and visuospatial skills (Leng, Shaw, & Wright, 1990; Rauscher & Shaw, 1998). Others have argued for associations with language skills, specifically that musically trained individuals exhibit enhanced performance on lower-level tasks that involve speech perception (e.g., Kraus & Chandrasekaran, 2010; Patel, 2003, 2011; Skoe & Kraus, 2012). These theories imply that the benefits of music training are especially likely to transfer to skills that are trained more directly during music lessons, such as navigating a piano keyboard or reading musical notation (which transfers to visuospatial skills), or listening skills more generally (which extend to speech perception). In this subsection, we review evidence for training-related transfer to the visuospatial and language domains.

Associations with Visuospatial Skills

Music training is associated with visuospatial skills. In fact, advantages on visual and spatial-reasoning tasks are evident in studies of musically trained adults (Bidelman, Hutka, & Moreno, 2013; Brochard, Dufour, & Deprés, 2004; Faßhauer, Frese, & Evers, 2015; Jakobson, Lewycky, Kilgour, & Stoesz, 2008; Patston & Tippett, 2011; Sluming, Brooks, Howard, Downes, & Roberts, 2007; Stoesz, Jakobson, Kilgour, & Lewycky, 2007) and children (Bilhartz, Bruhn, & Olson, 2000; Costa-Giomi, 1999; Gromko & Poorman, 1998; Hassler, Birbaumer, & Feil, 1985; Rauscher & Hinton, 2011; Rauscher & Zupan, 2000). For example, musically trained adults outperform their untrained counterparts on tests of visuospatial short-term memory (i.e., Corsi blocks; Bidelman et al., 2013), on tasks that require them to recreate line drawings from short-term or long-term memory (Jakobson et al., 2008), and when they are asked to determine whether two three-dimensional shapes are the same but rotated in space (Sluming et al., 2007). Examples from children indicate that music training predicts better performance on a task that asks them to remember the order of different colored beads on a string (Bilhartz et al., 2000), and when they are required to arrange blocks to form the shape of a previously seen staircase (Rauscher & Zupan, 2000).

Results from experimental studies provide only weak indications that music training actually causes improvements in visuospatial skills. For example, one study assigned preschool children to six months of 10–15 min of weekly keyboard lessons and 30 min of daily voice lessons, voice lessons only, computer training, or no lessons (Rauscher et al., 1997). Only the children in the keyboard/singing group exhibited improvement on the Object Assembly subtest of the Wechsler Preschool and Primary Scale of Intelligence—Revised (WPPSI-R). An unequivocal interpretation of these findings depends on the internal validity of the design, however, and it is doubtful that the computer training (with commercially available educational software) was an appropriate and equally engaging control activity. Moreover, the singing-only group had less contact with an adult instructor compared to the keyboard/singing group. Finally, children were not assigned randomly to the four conditions. Although a review of other studies from the same laboratory provided converging results (Rauscher & Hinton, 2011), there were not enough methodological details provided in the review to be confident about the findings.

Nevertheless, one meta-analysis of experimental studies concluded that music training causes improvements in spatial skills, even though six of the fifteen studies included in the analysis were conducted by a single research group (i.e., Rauscher and colleagues; Hetland, 2000). More recent studies report mixed results. For example, Mehr et al. (2013)

conducted two experiments. In one, children were randomly assigned to either music or visual-arts lessons for six weeks. After the intervention, the music group outperformed the art group on a spatial-navigation task, while the art group outperformed the music group on a geometry-perception task. In a second experiment, no significant group differences were evident when a new group of preschool children was randomly assigned to either six weeks of music lessons or no lessons at all.

One might question whether the effect of music training on visuospatial skills is evident only after a longer duration of training (i.e., longer than six weeks). Although this is a reasonable proposal, when Costa-Giomi (1999) assigned 9-year-olds to three years of piano lessons or no lessons, the piano-trained children had better spatial abilities after one and two years of lessons, but not after three years. In short, although there is ample evidence that music training is associated positively with visuospatial abilities, evidence that music training causes the association is weak and inconsistent.

Associations with Language Abilities

Because both language and music are rule-bound means of auditory communication, associations between musical and linguistic processing have received much attention from scholars who conduct research in these domains. The available evidence documents that musically trained individuals are better than their untrained counterparts at detecting linguistic stress patterns (Kolinsky, Cuvelier, Goetry, Peretz, & Morais, 2009), and at perceiving pitch and intonation in speech (Besson, Schön, Moreno, Santos, & Magne, 2007; Dankovičová, House, Crooks, & Jones, 2007; Delogu, Lampis, & Belardinelli, 2010; Good et al., 2017; Magne, Schön, & Besson, 2006; Marques, Moreno, Castro, & Besson, 2007; Thompson, Schellenberg, & Husain, 2004; Wong, Skoe, Russo, Dees, & Kraus, 2007; Wu et al., 2015). In some instances, they also tend to be better at perceiving speech under challenging conditions, such as comprehending speech in noise (Parbery-Clark, Skoe, Lam, & Kraus, 2009; Strait & Kraus, 2011; Strait, Parbery-Clark, O'Connell, & Kraus, 2013; Tierney, Krizman, Skoe, Johnston, & Kraus, 2013; Swaminathan et al., 2015; but see Boebinger et al., 2015; Ruggles et al., 2014), or perceiving acoustically degraded vowel sounds (Bidelman & Krishnan, 2010). Musicians also show advantages in speech-segmentation skills (François, Chobert, Besson, & Schön, 2013) and phonological perception (Chobert, François, Velay, & Besson, 2014; Chobert, Marie, François, Schön, & Besson, 2011; Zuk et al., 2013), and their brainstems appear to make higher-fidelity representations of speech stimuli (e.g., Kraus et al., 2014; Parbery-Clark, Tierney, Strait, & Kraus, 2012; Strait, O'Connell, Parbery-Clark, & Kraus, 2014; Strait, Parbery-Clark, Hittner, & Kraus, 2012; Weiss & Bidelman, 2015).

In addition to speech-specific auditory advantages, musically trained individuals show advantages on higher-level cognitive tests of verbal ability including verbal short-term (Chan, Ho, & Cheung, 1998; Franklin et al., 2008; Hansen, Wallentin, & Vuust, 2013; Ho et al., 2003), working (Franklin et al., 2008), and long-term memory (Franklin et al., 2008). In short-term and long-term tests of verbal memory, participants are required to read and recall a list of unrelated words, either immediately (short-term memory) or after a delay (long-term memory). In tests of working memory, listeners are required to remember a list of letters or numbers, but between each presentation of a to-be-remembered item, a secondary task requires them to determine whether a sentence makes sense, or to solve an addition problem.

Music training also predicts enhanced performance on tests of vocabulary (Forgeard, Winner, Norton, & Schlaug, 2008; Piro & Oritz, 2009) and second-language ability (Petitto, 2008; Posedel, Emery, Souza, & Fountain, 2012; Swaminathan & Gopinath, 2013; Talamini, Grassi, Toffalini, Santoni, & Carretti, 2018). One of the most reliable findings is that music training is correlated positively with phonological awareness (a skill important to the development of reading), which refers to the ability to perceive and segment phonological elements of speech (Gromko, 2005; Overy, 2003; Wandell, Dougherty, Ben-Shachar, Deutsch, & Tsang, 2008). It is therefore not surprising that music training is also associated positively with reading ability (Butzlaff, 2000; Corrigall & Trainor, 2011; Moreno et al., 2009; Standley, 2008; Swaminathan et al., 2018).

Some experimental evidence supports the idea that music training can promote language abilities. For example, Degé and Schwarzer (2011) randomly assigned preschool children to daily training in music, phonological skills, or sports. After twenty weeks, the phonological awareness of children in the music group matched those of children in the program designed specifically to improve these skills. Both groups outperformed the sports group, which ruled out the role of normal maturation.

Similar findings have been found in children with atypical language development. For example, one study assigned children with dyslexia to six weeks of a rhythm intervention, a commercially available phoneme-discrimination intervention, or a passive control group (Thomson, Leong, & Goswami, 2013). The rhythm intervention involved copying and synchronizing to non-speech rhythms on a hand drum, speaking and clapping to words in rhythm, and playing computerized games intended to train basic auditory skills linked to rhythm perception. Relative to the control group, both the rhythm group and the phonological skills group improved on tests of phonological processing. Another experiment randomly assigned children with dyslexia to thirty weeks of either music lessons (focused primarily on rhythm) or painting lessons (Flaugnacco et al., 2015). Despite similar performance at pre-test, after the intervention, the music group made larger gains on phonological and reading skills compared to the painting group.

Moreno and colleagues (Moreno, Bialystok, et al., 2011) assigned preschool children to twenty days of computerized training in music or visual arts. The children were tested on the Block Design and Vocabulary subtests of the WPPSI-III before and after the intervention. The music group made significant post-test gains on the Vocabulary subtest but not the Block Design subtest. Importantly, the arts group did not make any gains, which indicates that vocabulary improvements were specific to music training. In another article from the same sample of children (Moreno, Friesen, & Bialystok, 2011), the researchers reported that the music group was better at learning to map arbitrary visual symbols to words, a skill that is likely to be important for the development of reading.

The successful music-lesson interventions in the experimental studies described above were relatively short-term, and focused on listening rather than learning to play an instrument. Thus, listening training that focuses on music, particularly rhythm and timing, may indeed help children perceive rapid temporal changes in speech, such as those that distinguish adjacent phonemes. When children are trained with more standard pedagogies, however, the results tend to be weaker.

For example, in a recent longitudinal study that examined group-based music lessons, differences compared to a control group emerged only after extended training (Slater et al., 2015). Specifically, children improved on a test that measured their ability to perceive speech in noise after two years of community-based music lessons, which were taught using an established and successful curriculum. Nevertheless, children who received only one year of the same lessons did not make any statistically significant gains. Moreover, other studies failed to find correlations between music training and language skills (Boebinger et al., 2015; Ruggles et al. 2014; Swaminathan & Schellenberg, 2017), which implies that typical music lessons may not always improve speech and language abilities, or that the effect is relatively weak.

In general, however, music lessons that emphasize listening skills and temporal (rhythm) perception appear to promote phonological awareness and speech perception, at least for some groups of individuals. These improvements can, in turn, facilitate learning to read.

Music Training and Cognitive Performance in Real-World Contexts

The studies described in previous sections raise the possibility that music training causes small improvements on standardized tests and laboratory-based measures of speech perception and other aspects of cognitive ability. If such effects exist, they would have little importance unless they extend to performance in real-world situations. We now turn to two such situations: academic achievement and healthy aging.

Music Training and Academic Achievement

Participation in school-based musical activities predicts academic performance in later years (Catterall, Chapleau, & Iwanaga, 1999; Gouzouasis, Guhn, & Kishor, 2007; Winner & Cooper, 2000). For example, a meta-analysis of ten years of data from the American College Board found that high-school students with training in the arts, including music, performed better than students without any arts training on the SAT (formerly the Scholastic Aptitude Test; Vaughn & Winner, 2000). (SAT scores are used as a basis for admission to undergraduate colleges. Thus, the SAT is administered routinely to high-school seniors.) Longer duration of musical participation is also known to be associated with better SAT scores (Vaughn & Winner, 2000), and with higher average grades in school (Catterall et al., 1999; Schellenberg, 2006; Wetter, Koerner, & Schwaninger, 2009). These associations tend to be broad and general, rather than restricted to one or two school subjects. For example, the mathematics and geometry scores of musically trained participants tend to be higher than their untrained counterparts (Catterall et al., 1999; Cheek & Smith, 1999; Gardiner, Fox, Knowles, & Jeffry, 1996; Gouzouasis et al., 2007; Graziano, Peterson, & Shaw, 1999; Spelke, 2008; Vaughn, 2000; Vaughn & Winner, 2000), as is the case with language-related academic outcomes (Vaughn & Winner, 2000). Nevertheless, some types of music lessons may be more strongly associated with academic outcomes than others. For example, Canadian adolescents with keyboard lessons show advantages on high-school English tests, but those with vocal music training do not (Gouzouasis et al., 2007).

Interestingly, students who enroll in music classes—even theory-based music history classes—appear to demonstrate academic advantages compared to students who report having no training in any form of fine arts (Vaughn & Winner, 2000). In other words, actual instrumental or vocal training may not be unique in its association with academic performance. Indeed, high-school students who participate in any type of arts activity show advantages on the SAT, with *drama* students showing the strongest advantages (Vaughn & Winner, 2000). Moreover, children participating in sports are just as likely as arts participants to win academic awards (Winner, Goldstein, & Vincent-Lancrin, 2012), and they perform no differently from musically trained children on tests of mathematical ability (Spelke, 2008). Thus, participation in any type of extracurricular activity, not just music, predicts academic performance.

It is also unclear whether participation in music (or other) activities *causes* academic advantages. It is equally likely, if not more likely, that pre-existing individual differences in academic ability determine musical participation. Indeed, grades in elementary school predict participation in middle-school (Kinney, 2008) and high-school (Frakes, 1985) music classes, a timeline that rules out a causal role for music training. Moreover, better academic performance predicts longer participation in subsequent musical activities (e.g., Kinney, 2010; Klinedinst, 1991).

The association between music training and academic performance could also be an artifact of a third variable. For example, socio-economic affluence is associated with better scholastic performance (Sirin, 2005), as well as with musical participation (Corenblum & Marshall, 1998; Kinney, 2010; Klinedinst, 1991). However, the correlation between training and scholastic achievement is evident across socio-economic status (SES) levels (Catterall et al., 1999; Fitzpatrick, 2006) and persists even after holding SES constant (Corrigall et al., 2013; Degé et al., 2014; Schellenberg, 2006, 2011a, 2011b; Schellenberg & Mankarious, 2012), which indicates that the association between music training and academic achievement is at least partly independent of SES.

Pre-existing personality differences also appear to play a role. For example, musically trained children tend to do even better in school than one would predict from their elevated IQ scores (Corrigall et al., 2013; Degé et al., 2014; Schellenberg, 2006). This "special" association between music training and school performance disappears when conscientiousness is controlled in addition to IQ (Corrigall et al., 2013). In other words, in addition to being smart, musically trained children tend to be particularly hard-working and diligent, which explains why they do particularly well in school.

Finally, the results of longitudinal and experimental studies provide little evidence of a causal role for music training on academic performance. For example, one longitudinal study found evidence for a scholastic advantage after two years of piano lessons but not after the third year (Costa-Giomi, 2004). Another one-year longitudinal study found no evidence of improved performance on a standardized test of academic achievement, although children with music training had larger improvements, in absolute terms, on each of five subtests (Schellenberg, 2004). The most compelling negative result comes from a government-funded project in the UK that was organized by the Educational Endowment Foundation and the National Centre for Social Research. Over 900 children in Year 2 (7-year-olds) from nineteen schools were randomly assigned to music training (strings or voice), or to a control group that had drama lessons (Haywood et al., 2015). All participants received weekly training for thirty-two weeks in groups of approximately ten children. Improvements in mathematical abilities and literacy skills were similar for the music and drama groups, and there was no difference between the two music groups.

Meta-analytic reviews that include findings from published and unpublished sources also report no evidence for a causal role of music training in scholastic achievement (Winner & Cooper, 2000; Winner et al., 2012). As noted earlier, the most recent meta-analysis (Sala & Gobet, 2017b) found a very small association between music training and academic achievement, but this effect was due to contributions from poorly designed studies. Specifically, such associations are more likely to be evident when (1) studies do not have random assignment, such that self-selection plays a role in choosing to take music lessons, and (2) the control group is passive (no activity) rather than active, such that non-musical aspects of the music training (e.g., structured learning environment, additional contact with an adult teacher) are implicated. In sum, there is little evidence to support the notion that music training causes improvements in scholastic performance, despite much evidence that music training is associated positively with academic achievement.

Music Training and Healthy Aging

Older adults often experience declines in cognitive abilities, such as deficits in executive functions and difficulties with hearing in noisy environments (for reviews see Alain, Zendel, Hutka, & Bidelman, 2014; Salthouse, 2004). Because music training may cause small improvements in these skills in normally maturing children, it is plausible that it could also slow the onset of aging-related declines. To date, only a handful of studies have examined this possibility.

The available evidence suggests that middle-aged and older adults who have practiced music throughout their lives tend to outperform age-matched non-musicians on auditory perception tests, such as speech perception in noise (Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011; Zendel & Alain, 2012), categorical perception of speech sounds (Bidelman & Alain, 2015), frequency discrimination (Grassi, Meneghetti, Toffalini, & Borella, 2017), and the detection of gaps and mistuned harmonics in tones (Grassi et al., 2017; Zendel & Alain, 2009, 2012, 2013). In fact, some evidence implies that older-adult musicians perform almost as well as young adults at detecting mistuned harmonics (Zendel & Alain, 2013). In one instance, even a small amount of music training in childhood was related to better temporal precision in speech-evoked neural responses later in life (White-Schwoch, Carr, Anderson, Strait, & Kraus, 2013).

Middle-aged and older adults with music training also tend to show advantages in executive-function tasks, including auditory attention and working memory, verbal immediate recall, and verbal fluency (Amer, Kalender, Hasher, Trehub, & Wong, 2013; Fauvel et al., 2014; Grassi et al., 2017; Hanna-Pladdy & Gajewski, 2012; Parbery-Clark et al., 2011). Advantages appear to be strongest for individuals who began music lessons earlier rather than later in life (Fauvel et al., 2014). In the visuospatial domain, however, the evidence is less clear. Whereas two studies found no evidence for visual working-memory advantages in older musicians (Hanna-Pladdy & Gajewski, 2012; Parbery-Clark et al., 2011), three others reported that musicians outperform non-musicians on a visuospatial span task, the Simon Task, or other tests of visuospatial ability (Amer et al., 2013; Grassi et al., 2017; Hanna-Pladdy & MacKay, 2011).

One recent study of adults over 64 years of age compared those who were *currently* singing or playing a musical instrument to other participants (Mansens, Deeg, & Comijs, 2017). The older participants who were making music, particularly those who were playing an instrument, had higher scores on tests of episodic memory, executive functions, and attention. It is unknown, however, whether these individuals also played music earlier in life. In any event, playing music later in life appears to be a marker of healthy aging.

At the very least, these studies suggest that those who are inclined to engage in musical activities early in life are also likely to show cognitive advantages later in life, as they do when they are younger. The findings do not inform the issue of rates of cognitive decline. Thus, whether music training can be used to preserve cognitive abilities or even slow down cognitive aging processes is still an open question.

Suggestive evidence, however, comes from one experimental study in which 60- to 85-year-olds were assigned randomly to six months of piano lessons or a no-lessons (passive) control condition (Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh, 2007). The music group improved on two of five tests of executive function, whereas the control group did not appear to make gains on any of the tests. It is not clear, however, whether improvements in the intervention group were due to music training per se. As noted, the effect could be due to non-musical aspects of the training, such as an additional opportunity to engage with someone (the instructor), or simply the knowledge among the piano-group participants that they were somehow "special" because they were receiving an intervention. Moreover, it is not clear whether such improvements were long-lasting.

In sum, although it is possible that (1) music training in childhood may buffer against cognitive declines that are evident later in life, and (2) musical engagement in late adulthood could preserve or even improve already declining abilities, not enough evidence is available at the present time to confirm or disprove these hypotheses.

One Way Forward: Measuring Music Aptitude and Music Training

As noted, most of the research on music lessons and non-musical cognitive abilities is correlational in design. Such designs preclude inferences of causality. Experimental studies with random assignment are better suited to studying causal direction but are relatively rare because they are expensive to carry out. Moreover, training received in the context of an experiment is, no doubt, quite different from the experience of music lessons in the real world. For example, attrition limits the length of training in experimental studies. In the one-year study by Schellenberg (2004) with 144 children at baseline, 12 students (1 in 12, or 8.3 percent) dropped out and were not available for post-test. In the two-year study by Jaschke et al. (2018), 30 of 176 children (17.0 percent) who were tested at baseline were not available at post-test. Moreover, random assignment in experiments excludes motivational factors that promote long-term musical participation in the real world. In other words, correlational studies can capture ecologically valid information that experiments cannot.

Is there a way to improve the interpretability of correlational findings? In recent research, we made one such attempt by measuring duration of music training, performance on music aptitude tests, and other possible confounding variables (e.g., SES; Swaminathan & Schellenberg, 2017, 2018; Swaminathan et al., 2017, 2018). Music aptitude is typically quantified using tests that measure listeners' ability to perceive, remember, and discriminate melodies and rhythms (Gordon, 1965; Seashore, Lewis, & Saetveit, 1960). On each trial, the listener decides whether two musical sequences are identical. On trials with non-identical sequences, one event (i.e., a tone or drumbeat) in the second sequence is altered in pitch or time. In pedagogical contexts, aptitude is a measure of musical proclivities that should lead to subsequent success in musical activities, including training. As one would expect, music training does indeed predict performance on aptitude tests (e.g., Law & Zentner, 2012; Wallentin et al., 2010), but the causal direction is unclear. Importantly, music aptitude is also associated with performance on tests of general cognitive abilities and language abilities (for review, see Schellenberg & Weiss, 2013).

In our statistical analyses, we examined individual differences in performance on a non-musical variable (e.g., a test of speech perception or intelligence) as a function of music aptitude, with music training held constant, and music training, with music aptitude held constant. Depending on the particular research question, we also held constant other measures with overlapping variance, such as socio-economic status or personality. These analyses of partial associations allowed for more nuanced investigation about the relative role of learning and the environment (e.g., music training) on the one hand, and natural abilities (e.g., music aptitude, intelligence) on the other hand. With training held constant, associations of non-musical skills with performance on a music-aptitude test indicate that the association between musical and non-musical skills is independent of training, and possibly precedes it. With aptitude held constant, associations of non-musical skills with training provide more convincing evidence for training effects.

Although partial correlations, like simple correlations, do *not* allow for inferences of causation, this method serves to contextualize the size and location of hypothesized training effects relative to pre-existing associations between musical and non-musical abilities. When we used this method with adult participants, music aptitude was associated with intelligence (Swaminathan et al., 2017) and speech perception skills (Swaminathan & Schellenberg, 2017) when training was held constant, but music training was not associated with either outcome when music aptitude was held constant. In the case of speech perception, there was not even a simple association between music training and performance on a test of the ability to discriminate speech sounds that are relevant (i.e., phonemic) in a foreign language (Zulu) but not in English. Our interpretation of these data was that pre-existing differences in music aptitude and cognitive ability predict music training. Although taking music lessons may go on to increase music aptitude and cognitive abilities further (Figure 1), such training effects are likely to play a relatively small role in the overall picture.

In other correlational research, we used a similar approach to examine the association between music training and music aptitude (Swaminathan & Schellenberg, 2018). The simple association between the two variables was significant, as in previous research, with music training accounting for 24.5 percent of the variance in music aptitude. When socio-economic status, openness to experience, short-term memory, and general cognitive ability were considered jointly with music training, the predictive power of the model increased to 36.7 percent. Music training continued to have the largest partial association, accounting independently for 6.2 percent of the variance in music aptitude. Note that the reduction in variance explained (from 24.5 percent to 6.2 percent) highlights the overlap between music training and non-musical variables, which are typically overlooked in this line of research. When the non-musical variables were considered jointly, they accounted uniquely for 12.2 percent of the variance in music aptitude (with music training held constant). In other words, music aptitude was predicted better by the non-musical variables than it was by music training alone. These findings highlight that music aptitude is more than the simple consequence of music

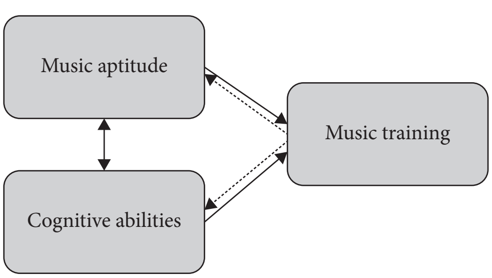

FIGURE 1. Individuals with high cognitive ability and music aptitude have an increased likelihood of taking music lessons, which could then go on to improve cognitive and musical abilities.

training. Although music training might be the best predictor variable, other, non-musical variables play an important role.

In a fourth study (Swaminathan et al., 2018), we used the same approach to examine the association between music training and reading ability among adults who were native or non-native speakers of English. As in previous research, reading ability was positively associated with duration of music training. We also found that reading ability improved in tandem with general cognitive ability, and it was better among native than non-native speakers of English. When these variables were considered jointly, general cognitive ability and native-language status had significant partial associations with reading ability, but music training did not. In other words, associations between music training and reading may be an artifact of other variables that are typically ignored in this line of research.

Conclusion

The evidence that music training causes improvements in non-musical domains is very weak, except for the effect of rhythm- and listening-based training, which appears to improve fine-grained listening skills in general, which can then enhance the ability to isolate and segment the sounds of speech. Because isolating speech sounds and matching them with letters or groups of letters is crucial for reading, rhythm- and listening-based training may go on to improve reading skills, particularly for those who have difficulty with reading (i.e., young children and children with dyslexia). These positive effects are evident primarily as a consequence of specially designed interventions that focus specifically on rhythm training and analytical listening. Typical conservatory-style training may not have the same effects, or much weaker effects.

Otherwise, although there is ample evidence that music lessons are predictive of benefits in general cognitive abilities, visuospatial abilities, or language abilities, the causal evidence is very weak. Large-sample, long-term studies with random assignment to music lessons are virtually impossible to conduct because of cost and attrition. Moreover, when such efforts are made, the results may fail to generalize broadly because it is difficult to know what one is studying when motivation, personality, music aptitude, demographics, and general cognitive ability are held constant. In the real world, these factors play a key role in determining who takes music lessons, particularly for long durations of time.

In short, evidence that traditional music pedagogies have non-musical cognitive benefits is lacking and unconvincing. Most of the available correlational evidence can be explained parsimoniously: high-functioning children are more likely than other children to take music lessons and to perform well on tests of many sorts. We therefore advocate a different approach—correlational designs that attempt to account for as many alternative explanations as possible. At the very least, this approach allows researchers to be sure that they are studying a real-world phenomenon, rather than an experimental or pedagogical artifact.

Future research on music and non-musical abilities is likely to find nuanced results if individual differences in music aptitude and other variables, such as SES, personality, and general cognitive ability (Corrigall & Schellenberg, 2015; Corrigall et al., 2013), are considered alongside music training. In other words, the causes of music training may be just as important as its consequences.

Acknowledgments

Supported by a grant from the Natural Sciences and Engineering Research Council of Canada awarded to EGS.

References

Alain, C., Zendel, B. R., Hutka, S., & Bidelman, G. M. (2014). Turning down the noise: The benefit of musical training on the aging auditory brain. *Hearing Research 308*, 162–173.

Amer, T., Kalender, B., Hasher, L., Trehub, S. E., & Wong, Y. (2013). Do older professional musicians have cognitive advantages? *PLoS ONE 8*(8), e71630.

Besson, M., Schön, D., Moreno, S., Santos, A., & Magne, C. (2007). Influence of musical expertise and musical training on pitch processing in music and language. *Restorative Neurology and Neuroscience 25*(3–4), 399–410.

Bhatara, A., Yeung, H. H., & Nazzi, T. (2015). Foreign language learning in French speakers is associated with rhythm perception, but not with melody perception. *Journal of Experimental Psychology: Human Perception and Performance 41*(2), 277–282.

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

Bidelman, G. M., & Alain, C. (2015). Musical training orchestrates coordinated neuroplasticity in auditory brainstem and cortex to counteract age-related declines in categorical vowel perception. *Journal of Neuroscience 35*(3), 1240–1249.

Bidelman, G. M., Hutka, S., & Moreno, S. (2013). Tone language speakers and musicians share enhanced perceptual and cognitive abilities for musical pitch: Evidence for bidirectionality between the domains of language and music. *PLoS ONE 8*(4): e60676.

Bidelman, G. M., & Krishnan, A. (2010). Effects of reverberation on brainstem representation of speech in musicians and nonmusicians. *Brain Research 1355*, 112–125.

Bilhartz, T. D., Bruhn, R. A., & Olson, J. E. (2000). The effect of early music training on child cognitive development. *Journal of Applied Developmental Psychology 20*(4), 615–636.

Boebinger, D., Evans, S., Rosen, S., Lima, C.F., Manly, T., & Scott, S. K. (2015). Musicians and non-musicians are equally adept at perceiving masked speech. *Journal of the Acoustical Society of America 137*(1), 378–387.

Brandler, S., & Rammsayer, T. H. (2003). Differences in mental abilities between musicians and non-musicians. *Psychology of Music 31*(2), 123–138.

Brochard, R., Dufour, A., & Deprés, O. (2004). Effect of musical expertise on visuospatial abilities: Evidence from reaction times and mental imagery. *Brain and Cognition 54*(2), 103–109.

Brody, N. (1992). *Intelligence* (2nd ed.). San Diego, CA: Academic Press.

Bugos, J. A., Perlstein, W. M., McCrae, C. S., Brophy, T. S., & Bedenbaugh, P. H. (2007). Individualized piano instruction enhances executive functioning and working memory in older adults. *Aging and Mental Health 11*(4), 464–471.

Butzlaff, R. (2000). Can music be used to teach reading? *Journal of Aesthetic Education 34*(3–4), 167–178.

Catterall, J., Chapleau, R., & Iwanaga, J. (1999). Involvement in the arts and human development: General involvement and intensive involvement in music and theatre arts. In E. Fiske (Ed.), *Champions of change: The impact of the arts on learning* (pp. 1–18). Washington, DC: The Arts Education Partnership and The President's Committee on the Arts and the Humanities.

Chan, A. S., Ho, Y. C., & Cheung, M. C. (1998). Music training improves verbal memory. *Nature 396*(6707), 128.

Cheek, J. M., & Smith, L. R. (1999). Music training and mathematics achievement. *Adolescence 34*(136), 759–761.

Chobert, J., François, C., Velay, J. L., & Besson, M. (2014). Twelve months of active musical training in 8- to 10-year-old children enhances the preattentive processing of syllabic duration and voice onset time. *Cerebral Cortex 24*(4), 956–967.

Chobert, J., Marie, C., François, C., Schön, D., & Besson, M. (2011). Enhanced passive and active processing of syllables in musician children. *Journal of Cognitive Neuroscience 23*(12), 3874–3887.

Conway, A. R. A., Getz, S. J., Macnamara, B., & Engel de Abreu, P. M. J. (2011). Working memory and fluid intelligence. In R. J. Sternberg & S. B. Kaufman (Eds.), *The Cambridge handbook of intelligence* (pp. 394–418). Cambridge: Cambridge University Press.

Corenblum, B., & Marshall, E. (1998). The band played on: Predicting students' intentions to continue studying music. *Journal of Research in Music Education 46*(1), 128–140.

Corrigall, K. A., & Schellenberg, E. G. (2015). Predicting who takes music lessons: Parent and child characteristics. *Frontiers in Psychology 6*, 282. doi: 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. doi: 10.3389/fpsyg.2013.00222

Corrigall, K. A., & Trainor, L. J. (2011). Associations between length of music training and reading skills in children. *Music Perception 29*(2), 147–155.

Costa-Giomi, E. (1999). The effects of three years of piano instruction on children's cognitive development. *Journal of Research in Music Education 47*(3), 198–212.

Costa-Giomi, E. (2004). Effects of three years of piano instruction on children's academic achievement, school performance and self-esteem. *Psychology of Music 32*(2), 139–152.

Dankovičová, J., House, J., Crooks, A., & Jones, K. (2007). The relationship between musical skills, music training, and intonation analysis skills. *Language and Speech 50*(2), 177–225.

Deary, I. J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence 35*(1), 13–21.

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

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Frontiers in Psychology 2*, 124. doi: 10.3389/fpsyg.2011.00124.

Degé, F., Wehrum, S., Stark, R., & Schwarzer, G. (2014). Music lessons and academic self-concept in 12- to 14-year-old children. *Musicae Scientiae 18*(2), 203–215.

Delogu, F., Lampis, G., & Belardinelli, M. O. (2010). From melody to lexical tone: Musical ability enhances specific aspects of foreign language perception. *European Journal of Cognitive Psychology 22*(1), 46–61.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science 270*(5234), 305–307.

Faßhauer, C., Frese, A., & Evers, S. (2015). Musical ability is associated with enhanced auditory and visual cognitive processing. *BMC Neuroscience 16*(1), 1. Retrieved from https://doi.org/10.1186/s12868-015-0200-4

Fauvel, B., Groussard, M., Mutlu, J., Arenaza-Urquijo, E. M., Eustache, F., Desgranges, B., & Platel, H. (2014). Musical practice and cognitive aging: Two cross-sectional studies point to phonemic fluency as a potential candidate for a use-dependent adaptation. *Frontiers in Aging Neuroscience 6*, 227. doi:10.3389/fnagi.2014.00227

Fitzpatrick, K. R. (2006). The effect of instrumental music participation and socioeconomic status on Ohio fourth-, sixth-, and ninth-grade proficiency test performance. *Journal of Research in Music Education 54*(1), 73–84.

Flaugnacco, E., Lopez, L., Terribili, C., Montico, M., Zoia, S., & Schön, D. (2015). Music training increases phonological awareness and reading skills in developmental dyslexia: A Randomized control trial. *PloS ONE 10*(9), e0138715.

Forgeard, M., Winner, E., Norton, A., & Schlaug, G. (2008). Practicing a musical instrument in childhood is associated with enhanced verbal ability and nonverbal reasoning. *PLoS ONE 3*(10), e3566.

Frakes, L. (1985). Differences in music achievement, academic achievement, and attitude among participants, dropouts, and nonparticipants in secondary school music. *Dissertation Abstracts International 46*, 370A. University Microfilms No. AAC8507938.

François, C., Chobert, J., Besson, M., & Schön, D. (2013). Music training for the development of speech segmentation. *Cerebral Cortex 23*(9), 2038–2043.

Franklin, M. S., Moore, K. S., Yip, C., Jonides, J., Rattray, K., & Moher, J. (2008). The effects of musical training on verbal memory. *Psychology of Music 36*(3), 353–365.

Gardiner, M., Fox, A., Knowles, F., & Jeffry, D. (1996). Learning improved by arts training. *Nature 381*(6580), 284.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *Journal of Neuroscience 23*(27), 9240–9245.

Gibson, C., Folley, B. S., & Park, S. (2009). Enhanced divergent thinking and creativity in musicians: A behavioral and near-infrared spectroscopy study. *Brain and Cognition 69*(1), 162–169.

Good, A., Gordon, K. A., Papsin, B. C., Nespoli, G., Hopyan, T., Peretz, I., & Russo, F. A. (2017). Benefits of music training for perception of emotional speech prosody in deaf children with cochlear implants. *Ear & Hearing 38*(4), 455–464.

Gordon, E. E. (1965). *Music aptitude profile*. Chicago: GIA.

Gouzouasis, P., Guhn, M., & Kishor, N. (2007). The predictive relationship between achievement and participation in music and achievement in core Grade 12 academic subjects. *Music Education Research 9*(1), 81–92.

Grassi, M., Meneghetti, C., Toffalini, E., & Borella, E. (2017). Auditory and cognitive performance in elderly musicians and nonmusicians. *PLoS ONE 12*(11), e0187881.

Graziano, A. B., Peterson, M., & Shaw, G. L. (1999). Enhanced learning of proportional math through music training and spatial-temporal training. *Neurological Research 21*(2), 139–152.

Gromko, J. E. (2005). The effect of music instruction on phonemic awareness in beginning readers. *Journal of Research in Music Education 53*(3), 199–209.

Gromko, J. E., & Poorman, A. S. (1998). Developmental trends and relationships in children's aural perception and symbol use. *Journal of Research in Music Education 46*(1), 16–23.

Gruhn, W., Galley, N., & Kluth, C. (2003). Do mental speed and musical abilities interact? *Annals of the New York Academy of Sciences 999*, 485–496.

Guo, X., Ohsawa, C., Suzuki, A., & Sekiyama, K. (2018). Improved digit span in children after a 6-week intervention of playing a musical instrument: An exploratory randomized controlled trial. *Frontiers in Psychology 8*, 2303. doi: 10.3389/fpsyg.2017.02303

Hanna-Pladdy, B., & Gajewski, B. (2012). Recent and past musical activity predicts cognitive aging variability: Direct comparison with general lifestyle activities. *Frontiers in Human Neuroscience 6*, 198. doi: 10.3389/fnhum.2012.00198

Hanna-Pladdy, B., & MacKay, A. (2011). The relation between instrumental musical activity and cognitive aging. *Neuropsychology 25*(3), 378–386.

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: Effects of enculturation and formal training on development. *Trends in Cognitive Sciences 11*(11), 466–472.

Hansen, M., Wallentin, M., & Vuust, P. (2013). Working memory and musical competence of musicians and non-musicians. *Psychology of Music 41*(6), 779–793.

Hassler, M., Birbaumer, N., & Feil, A. (1985). Musical talent and visuo-spatial abilities: A longitudinal study. *Psychology of Music 13*(2), 99–113.

Haywood, S., Griggs, J., Lloyd, C., Morris, S., Kiss, Z., & Skipp, A. (2015). *Creative futures: Act, sing, play. Evaluation report and executive summary*. London: Educational Endowment Foundation.

Helmbold, N., Rammsayer, T., & Altenmüller, E. (2005). Differences in primary mental abilities between musicians and nonmusicians. *Journal of Individual Differences 26*, 74–85.

Herholz, S. C., & Zatorre, R. J. (2012). Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron 76*(3), 486–502.

Herrero, L., & Carriedo, N. (2018). Differences in updating processes between musicians and non-musicians from late childhood to adolescence. *Learning and Individual Differences 61*, 188–195.

Hetland, L. (2000). Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education 34*(3–4), 179–238.

Ho, Y., Cheung, M., & Chan, A. S. (2003). Music training improves verbal but not visual memory: Cross-sectional and longitudinal explorations in children. *Neuropsychology 17*(3), 439–450.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences 105*, 6829–6833.

Jakobson, L. S., Lewycky, S. T., Kilgour, A. R., & Stoesz, B. M. (2008). Memory for verbal and visual material in highly trained musicians. *Music Perception 26*(1), 41–55.

Jaschke, A. C., Honing, H., & Scherder, E. J. A. (2018). Longitudinal analysis of music education on executive functions in primary school children. *Frontiers in Neuroscience 12*, 103. doi:10.3389/fnins.2018.00103

Jensen, A. R. (1969). How much can we boost IQ and scholastic achievement? *Harvard Educational Review 39*(1), 1–123.

Jensen, A. R. (1998). *The g factor: The science of mental ability*. Westport, CT: Praeger.

Judge, T. A., Higgins, C. A., Thoresen, C. J., & Barrick, M. R. (1999). The big five personality traits, general mental ability, and career success across the life span. *Personnel Psychology, 52*(3), 621–652.

Kaviani, H., Mirbaha, H., Pournaseh, M., & Sagan, O. (2014). Can music lessons increase the performance of preschool children in IQ tests? *Cognitive Processing 15*(1), 77–84.

Kinney, D. W. (2008). Selected demographic variables, school music participation and achievement test scores of urban middle school students. *Journal of Research in Music Education 56*(2), 145–161.

Kinney, D. W. (2010). Selected nonmusic predictors of urban students' decisions to enroll and persist in middle school band programs. *Journal of Research in Music Education 57*(4), 334–350.

Klinedinst, R. E. (1991). Predicting performance achievement and retention of fifth-grade instrumental students. *Journal of Research in Music Education 39*(3), 225–238.

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences 14*(7), 317–324.

Koelsch, S., Schröger, E., & Tervaniemi, M. (1999). Superior pre-attentive auditory processing in musicians. *Neuroreport 10*, 1309–1313.

Kolinsky, R., Cuvelier, H., Goetry, V., Peretz, I., & Morais, J. (2009). Music training facilitates lexical stress processing. *Music Perception 26*(3), 235–246.

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nature Reviews Neuroscience 11*, 599–605.

Kraus, N., Slater, J., Thompson, E. C., Hornickel, J., Strait, D. L., Nicol, T., & White-Schwoch, T. (2014). Music enrichment programs improve the neural encoding of speech in at-risk children. *Journal of Neuroscience 34*(36), 11913–11918.

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.

Leng, X., Shaw, G. L., & Wright, E. L. (1990). Coding of musical structure and the trion model of cortex. *Music Perception 8*(1), 49–62.

Love, J. M., Chazan-Cohen, R., Raikes, H., & Brooks-Gunn, J. (2013). What makes a difference: Early Head Start evaluation findings in a developmental context. *Monographs of the Society for Research in Child Development 78*(1), 1–173.

Mackintosh, N. J. (2011). *IQ and human intelligence* (2nd ed.). Oxford: Oxford University Press.

Magne, C., Schön, D., & Besson, M. (2006). Musician children detect pitch violations in both music and language better than nonmusician children: Behavioral and electrophysiological approaches. *Journal of Cognitive Neuroscience 18*(2), 199–211.

Mansens, D., Deeg, D. J. H., & Comijs, H. C. (2017). The association between singing and/or playing a musical instrument and cognitive functions in older adults. *Aging & Mental Health*. doi:10.1080/13607863.2017.1328481

Marques, C., Moreno, S., Castro, S. L., & Besson, M. (2007). Musicians detect pitch violation in a foreign language better than non-musicians: Behavioral and electrophysiological evidence. *Journal of Cognitive Neuroscience 19*(9), 1453–1463.

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.

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology 49*(2), 270–291.

Melby-Lervåg, M., Reddick, T. S., & Hulme, C. (2016). Working memory training does not improve performance on measures of intelligence or other measures of "far transfer." *Perspectives on Psychological Science 11*(4), 512–534.

Moody, D. E. (2009). Can intelligence be increased by training on a task of working memory? *Intelligence 37*, 327–328.

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.

Moreno, S., Friesen, D., & Bialystok, E. (2011). Effect of music training on promoting preliteracy skills: Preliminary causal evidence. *Music Perception 29*(2), 165–172.

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical training influences linguistic abilities in 8-year-old children: More evidence for brain plasticity. *Cerebral Cortex 19*(3), 712–723.

Mosing, M. A., Madison, G., Pedersen, N. L., & Ullén, F. (2016). Investigating cognitive transfer within the framework of music practice: Genetic pleiotropy rather than causality. *Developmental Science 19*(3), 504–512. A

Münte, T. F., Altenmüller, E., & Jäncke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience 3*(6), 473–478.

Okada, B. M., & Slevc, R. L. (2018). Individual differences in musical training and executive functions: A latent variable approach. *Memory & Cognition*. doi:10.3758/s13421-018-0822-8

Overy, K. (2003). Dyslexia and music. *Annals of the New York Academy of Sciences 999*, 497–505.

Parbery-Clark, A., Skoe, E., Lam, C., & Kraus, N. (2009). Musician enhancement for speech in noise. *Ear and Hearing 30*(6), 653–661.

Parbery-Clark, A., Strait, D. L., Anderson, S., Hittner, E., & Kraus, N. (2011). Musical experience and the aging auditory system: Implications for cognitive abilities and hearing speech in noise. *PLoS ONE 6*(5), e18082.

Parbery-Clark, A., Tierney, A., Strait, D. L., & Kraus, N. (2012). Musicians have fine-tuned neural distinction of speech syllables. *Neuroscience 219*, 111–119.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience 6*, 674–681.

Patel, A. D. (2011). Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. *Frontiers in Psychology 2*, 142. doi: 10.3389/fpsyg.2011.00142

Patston, L. L. M., & Tippett, L. J. (2011). The effect of background music on cognitive performance in musicians and nonmusicians. *Music Perception 29*(2), 173–183.

Petitto, L. (2008). Arts education, the brain, and language. In B. Rich & C. Asbury (Eds.), *Learning, arts, and the brain: The Dana Consortium report on arts and cognition* (pp. 93–104). New York/Washington, DC: The Dana Foundation.

Piro, J. M., & Oritz, C. (2009). The effect of piano lessons on the vocabulary and verbal sequencing skills of primary grade students. *Psychology of Music 37*(3), 325–347.

Portowitz, A., Lichtenstein, O., Egorova, L., & Brand, E. (2009). Underlying mechanisms linking music education and cognitive modifiability. *Research Studies in Music Education 31*(2), 107–128.

Posedel, J., Emery, L., Souza, B., & Fountain, C. (2012). Pitch perception, working memory, and second-language phonological production. *Psychology of Music 40*(4), 508–517.

Posner, M., Rothbart, M. K., Sheese, B. E., & Kieras, J. (2008). How arts training influences cognition. In B. Rich & C. Asbury (Eds.), *Learning, arts, and the brain: The Dana Consortium report on arts and cognition* (pp. 1–10). New York/Washington, DC: The Dana Foundation.

Rapport, M. D., Orban, S. A., Kofler, M. J., & Friedman, L. M. (2013). Do programs designed to train working memory, other executive functions, and attention benefit children with ADHD? A meta-analytic review of cognitive, academic, and behavioral outcomes. *Clinical Psychology Review 33*(8), 1237–1252.

Rauscher, F. H., & Hinton, S. C. (2011). Music instruction and its diverse extra-musical benefits. *Music Perception 29*(2), 215–226.

Rauscher, F. H., & Shaw, G. L. (1998). Key components of the Mozart effect. *Perceptual and Motor Skills 86*(3), 835–841.

Rauscher, F. H., Shaw, G. L., Levine, L. J., Wright, E. L., Dennis, W. R., & Newcomb, R. L. (1997). Music training causes long-term enhancement of preschool children's spatial-temporal reasoning. *Neurological Research 19*(1), 2–8.

Rauscher, F. H., & Zupan, M. A. (2000). Classroom keyboard instruction improves kindergarten children's spatial-temporal performance: A field experiment. *Early Childhood Research Quarterly 15*(2), 215–228.

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.

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccamanno, L., & Posner, M. I. (2005). Training, maturation and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences 102*, 14931–14936.

Ruggles, D. R., Freyman, R. L., & Oxenham, A. J. (2014). Influence of musical training on understanding voiced and whispered speech in noise. *PLoS ONE 9*(1), e86980.

Sala, G., & Gobet, F. (2016). Do the benefits of chess instruction transfer to academic and cognitive skills? A meta-analysis. *Educational Research Review 18*, 46–57.

Sala, G., & Gobet, F. (2017a). When the music's over: Does music skill transfer to children's and young adolescents' cognitive and academic skills? A meta-analysis. *Educational Research Review 20*, 55–67.

Sala, G., & Gobet, F. (2017b). Working memory training in typically developing children: A meta-analysis of the available evidence. *Developmental Psychology 53*, 671–685.

Sala, G., Tatlidil, K. S., & Gobet, F. (2018). Video game training does not enhance cognitive ability: A comprehensive meta-analytic investigation. *Psychological Bulletin 144*, 111–139.

Salthouse, T. A. (2004). What and when of cognitive aging. *Current Directions in Psychological Science 13*(4), 140–144.

Salthouse, T. A. (2005). Relations between cognitive abilities and measures of executive functioning. *Neuropsychology 19*(4), 532–545.

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychological Science 15*(8), 511–514.

Schellenberg, E. G. (2006). Long-term positive associations between music lessons and IQ. *Journal of Educational Psychology 98*(2), 457–468.

Schellenberg, E. G. (2011a). Examining the association between music lessons and intelligence. *British Journal of Psychology 102*(3), 283–302.

Schellenberg, E. G. (2011b). Music lessons, emotional intelligence, and IQ. *Music Perception 29*(2), 185–194.

Schellenberg, E. G., & Mankarious, M. (2012). Music training and emotion comprehension in childhood. *Emotion 12*(5), 887–891.

Schellenberg, E. G., & Moreno, S. (2010). Music lessons, pitch processing and g. *Psychology of Music 38*(2), 209–221.

Schellenberg, E. G., & Peretz, I. (2008). Music, language and cognition: Unresolved issues. *Trends in Cognitive Sciences 12*(2), 45–46.

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

Seashore, C. E., Lewis, D., & Saetveit, J. G. (1960). *The Seashore measures of musical talents*. New York: Psychological Corporation.

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin 138*, 628–654.

Sirin, S. R. (2005). Socioeconomic status and academic achievement: A meta-analytic review of research. *Review of Educational Research 75*(3), 417–453.

Skoe, E., & Kraus, N. (2012). Human subcortical auditory function provides a new conceptual framework for considering modularity. In P. Rebuschat, M. Rohrmeier, J. A. Hawkins, & I. Cross (Eds.), *Language and music as cognitive systems* (pp. 269–282). Oxford: Oxford University Press.

Slater, J., Skoe, E., Strait, D. L., O'Connell, S., Thompson, E., & Kraus, N. (2015). Music training improves speech-in-noise perception: Longitudinal evidence from a community-based music program. *Behavioural Brain Research 291*, 244–252.

Slevc, L. R., Davey, N. S., Buschkuehl, M., & Jaeggi, S. M. (2016). Tuning the mind: Exploring the connections between musical ability and executive functions. *Cognition 152*, 199–211.

Sluming, V., Brooks, J., Howard, M., Downes, J. J., & Roberts, N. (2007). Broca's area supports enhanced visuospatial cognition in orchestral musicians. *Journal of Neuroscience 27*(14), 3799–3806.

Soveri, A., Antfolk, J., Karlsson, L., Salo, B., & Laine, M. (2017). Working memory training revisited: A multi-level meta-analysis of n-back training studies. *Psychonomic Bulletin & Review 24*(4), 1077–1096.

Spelke, E. (2008). Effects of music instruction on developing cognitive systems at the foundation of mathematics and science. In B. Rich & C. Asbury (Eds.), *Learning, arts, and the brain: The Dana Consortium report on arts and cognition* (pp. 17–49). New York/Washington, DC: The Dana Foundation.

Spinath, B., Spinath, F. M., Harlaar, N., & Plomin, R. (2006). Predicting school achievement from general cognitive ability, self-perceived ability, and intrinsic value. *Intelligence 34*(4), 363–374.

Standley, J. M. (2008). Does music instruction help children learn to read? Evidence of a meta-analysis. *Update: Applications of Research in Music Education 27*(1), 17–32

Stoesz, B., Jakobson, L., Kilgour, A., & Lewycky, S. (2007). Local processing advantage in musicians: Evidence from disembedding and constructional tasks. *Music Perception 25*(2), 153–165.

Strait, D. L., & Kraus, N. (2011). Can you hear me now? Musical training shapes functional brain networks for selective auditory attention and hearing speech in noise. *Frontiers in Psychology 2*, 113. doi: 10.3389/fpsyg.2011.00113

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.

Strait, D. L., Parbery-Clark, A., Hittner, E., & Kraus, N. (2012). Musical training during early childhood enhances the neural encoding of speech in noise. *Brain and Language 123*(3), 191–201.

Strait, D. L., Parbery-Clark, A., O'Connell, S., & Kraus, N. (2013). Biological impact of preschool music classes on processing speech in noise. *Developmental Cognitive Neuroscience 6*, 51–60.

Swaminathan, J., Mason, C. R., Streeter, T. M., Best, V., Kidd Jr, G., & Patel, A. D. (2015). Musical training, individual differences and the cocktail party problem. *Scientific Reports 5*, 11628. doi:10.1038/srep11628

Swaminathan, S., & Gopinath, J. K. (2013). Music training and second-language English comprehension and vocabulary skills in Indian children. *Psychological Studies 58*(2), 164–170.

Swaminathan, S., & Schellenberg, E. G. (2016). Music training. In T. Strobach & J. Karbach (Eds.), *Cognitive training: An overview of features and applications* (pp. 137–144). New York: Springer.

Swaminathan, S., & Schellenberg, E. G. (2017). Musical competence and phonemic perception in a foreign language. *Psychonomic Bulletin and Review 24*(6), 1929–1934.

Swaminathan, S., & Schellenberg, E. G. (2018). Musical competence is predicted by music training, cognitive abilities, and personality. Manuscript submitted for publication.

Swaminathan, S., Schellenberg, E. G., & Khalil, S. (2017). Revisiting the association between music lessons and intelligence: Training effects or music aptitude? *Intelligence 62*, 119–124.

Swaminathan, S., Schellenberg, E. G., & Venkatesan, K. (2018). Explaining the association between music training and reading in adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. doi: 10.1037/xlm0000493

Talamini, F., Grassi, M., Toffalini, E., Santoni, R., & Carretti, B. (2018). Learning a second language: Can music aptitude or music training have a role? *Learning and Individual Differences 64*, 1–7.

Thompson, W. F., Schellenberg, E. G., & Husain, G. (2004). Decoding speech prosody: Do music lessons help? *Emotion 4*(1), 46–64.

Thomson, J. M., Leong, V., & Goswami, U. (2013). Auditory processing interventions and developmental dyslexia: A comparison of phonemic and rhythmic approaches. *Reading and Writing 26*(2), 139–161.

Thorndike, E. L., & Woodworth, R. S. (1901a). The influence of improvement in one mental function upon the efficiency of other functions (I). *Psychological Review 8*, 247–261.

Thorndike, E. L., & Woodworth, R. S. (1901b). The influence of improvement in one mental function upon the efficiency of other functions (II). The estimation of magnitudes. *Psychological Review 8*, 384–395.

Tierney, A., Krizman, J., Skoe, E., Johnston, K., & Kraus, N. (2013). High school music classes enhance the neural processing of speech. *Frontiers in Psychology 4*, 855. doi: 10.3389/fpsyg.2013.00855.

Trimmer, C. G., & Cuddy, L. L. (2008). Emotional intelligence, not music training, predicts recognition of emotional speech prosody. *Emotion 8*(6), 838–849.

Vaughn, K. (2000). Music and mathematics: Modest support for the oft-claimed relationship. *Journal of Aesthetic Education 34*(3–4), 149–166.

Vaughn, K., & Winner, E. (2000). SAT scores of students who study the arts: What we can and cannot conclude about the association. *Journal of Aesthetic Education 34*(3–4), 77–89.

Wallentin, M., Nielsen, A. H., Friis-Olivarius, M., Vuust, C., & Vuust, P. (2010). The Musical Ear Test: A new reliable rest for measuring musical competence. *Learning and Individual Differences 20*(3), 188–196.

Wan, C. Y., & Schlaug, G. (2010). Music making as a tool for promoting brain plasticity across the life span. *The Neuroscientist 16*(5), 566–577.

Wandell, B., Dougherty, R. F., Ben-Shachar, M., Deutsch, G. K., & Tsang, J. (2008). Training in the arts, reading, and brain imaging. In B. Rich & C. Asbury (Eds.), *Learning, arts, and the brain: The Dana Consortium report on arts and cognition* (pp. 51–59). New York/Washington, DC: The Dana Foundation.

Weicker, J., Villringer, A., & Thöne-Otto, A. (2016). Can impaired working memory functioning be improved by training? A meta-analysis with a special focus on brain injured patients. *Neuropsychology 30*(2), 190–212.

Weiss, M. W., & Bidelman, G. M. (2015). Listening to the brainstem: Musicianship enhances intelligibility of subcortical representations for speech. *Journal of Neuroscience 35*(4), 1687–1691.

Wetter, O. E., Koerner, F., & Schwaninger, A. (2009). Does musical training improve school performance? *Instructional Science 37*(4), 365–374.

White-Schwoch, T., Carr, K. W., Anderson, S., Strait, D. L., & Kraus, N. (2013). Older adults benefit from music training early in life: Biological evidence for long-term training-driven plasticity. *Journal of Neuroscience 33*(45), 17667–17674.

Winner, E., & Cooper, M. (2000). Mute those claims: No evidence (yet) for a causal link between arts study and academic achievement. *Journal of Aesthetic Education 34*(3–4), 11–75.

Winner, E., Goldstein, T. R., & Vincent-Lancrin, S. (2012). *The impact of arts education: What do we know?* Paris: Organisation for Economic Co-operation and Development.

Wong, P. C. M., Skoe, E., Russo, N. M., Dees, T., & Kraus, N. (2007). Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neuroscience 10*, 420–422.

Wu, H., Ma, X., Zhang, L., Liu, Y., Zhang, Y., & Shu, H. (2015). Musical experience modulates categorical perception of lexical tones in native Chinese speakers. *Frontiers in Psychology 6*, 436. doi:10.3389/fpsyg.2015.00436

Zendel, B. R., & Alain, C. (2009). Concurrent sound segregation is enhanced in musicians. *Journal of Cognitive Neuroscience 21*(8), 1488–1498.

Zendel, B. R., & Alain, C. (2012). Musicians experience less age-related decline in central auditory processing. *Psychology and Aging 27*(20), 410–417.

Zendel, B. R., & Alain, C. (2013). The influence of lifelong musicianship on neurophysiological measures of concurrent sound segregation. *Journal of Cognitive Neuroscience 25*(4), 503–516.

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.

Zuk, J., Ozernov-Palchik, O., Kim, H., Lakshminarayanan, K., Gabrieli, J. D., Tallal, P., & Gaab, N. (2013). Enhanced syllable discrimination thresholds in musicians. *PLoS ONE 8*(12), e80546.