Does Music Training Improve Inhibition Control in Children? A Systematic Review and Meta-Analysis

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Abstract

Inhibition control is an essential executive function and the cornerstone of important skills during children's development, like self-regulation and the development of social and language abilities. Better inhibition control is associated with higher academic achievement (e.g., reasoning skills, mathematics, and science). Music training requires inhibition control when learning new motor skills of an instrument, synchronized group training, monitoring performance, and auditory stream prioritization. This meta-analysis examined for the first time whether music-based training improves inhibition control in children. A rigorous search of the literature from 1980 to 2022 yielded 2182 records (N = 1528). Twenty studies had longitudinal designs, of which eight were randomized-clinical trials (RCTs) with an active control condition. Inhibition control measures included the flanker, go/no-go, and Stroop tests or similar preschool adaptations. A random-effects meta-analysis of these studies showed a moderate-to-large effect size for improvement in inhibition control after music training compared to control programs in the eight RCTs (*SMD* = 0.63, *CI* = 0.41 to 0.85, $p < .0001$). The full set of twenty longitudinal studies that included quasi-experimental designs and passive control groups showed a small-to-moderate effect size (*SMD* = 0.36, *CI* = 0.21 to 0.50, $p < .0001$). These findings highlight that music training, probably owing to its time-bound multisensory and multimodal demands fostering brain plasticity, plays a privileged role in improving executive functioning in children, especially inhibition control. We recommend further validation of music training to complement education and as a therapeutic tool for clinical populations with inhibition control difficulties (e.g., Autism, ADHD).

Public Significance Statement

This meta-analysis is the first to show that music training in children specifically improves inhibition control, a critical executive function for self-regulation. Children generally enjoy music training, a complex multimodal activity that engages cognitive and speech abilities. Our results demonstrate that music training is an effective approach for strengthening cognition and highlight its potential to complement the

rehabilitation of certain clinical disorders that involve inhibition control deficits. This review also identifies some limitations of current research and provides recommendations for future work.

Keywords: inhibition control, music training, child development, meta-analysis, skill transfer

Does Music Training Improve Inhibition Control in Children? A Systematic Review and Meta-Analysis

Music training is a rich and highly engaging experience for children and has the potential to strengthen cognitive skills that are essential for healthy child development. Merely listening to music in a brain imaging scanner elicits activation in the brain's reward circuits in both children (Fasano et al., 2022) and adults (Mas-Herrero et al., 2021; Vuust et al., 2022; Zatorre, 2015). Being internally motivated during learning experiences increases learning capacity and efficiency (Ryan & Deci, 2017), and this greater engagement is reflected in electrical brain activity following musical training (Kraus et al., 2014). The external setting in which learning occurs also plays an important role. Training music in a social environment increases positive feelings of bonding through shared emotions and group synchrony (Nummenmaa et al., 2021). In addition to being pleasurable and social, music training also engages an array of skills including executive functioning (Degé & Frischen, 2022; Rodriguez-Gomez & Talero-Gutiérrez C., 2022), language/communication (Gordon et al., 2015; Jäncke, 2012; Patel, 2008; Poeppel & Bergelson, 2008a), and socio-emotional functioning (Gaudette-Leblanc et al., 2021; Gerry et al., 2012). Music training is a valuable activity to study from the perspective of skill transfer effects. Some transfers are relatively close to the trained ability and considered near transfers, for example, between music training and sensorimotor integration. Conversely, some are considered more indirect or distantly related to the trained ability and are referred to as far transfers. Some examples of far transfer from music training include effects upon executive functioning, speech, and quality of life.

Music training and skill transfer

Researchers have studied far skill transfer over various domains (Thorndike & Woodworth, 1901). However, quantitative research on cognitive training often shows a small overall effect size in real-world/biopsychosocial outcomes (von Bastian et al., 2022) and in transfer to other laboratory-based tasks that use similar cognitive constructs (Edwards et al., 2018). Training of cognition through music has attracted considerable research attention over the last two decades and is currently part of an ongoing

debate (Sala & Gobet, 2020; see section "Current debate on far skill transfer"). Lack of clarity, and of consensus, on the question of far skill transfer from music stems in part from a predominance of cross-sectional studies, limited use of randomized control trials (RCTs), and methodological inconsistencies among existing meta-analyses (Bigand & Tillmann, 2021). The debate is still controversial — Sala and Gobet (2020); interpret their findings of null effect size as a sign that skill transfer from music to cognition is nonexistent. However, in that analysis, some studies' active control training conditions were considerably nearer (in transfer) to the cognitive outcome measure than was their music training condition. The meta-analytic dataset was re-analyzed to correct for this problem by Bigand & Tillmann, 2021, finding a small beneficial effect of music interventions. These results highlight the importance of considering equidistance of skill transfer in both the training of interest and the active control, and ultimately support the existence of transfer from musical training to cognitive skills.

A standard method to infer causality is the parallel-arm RCT design with an active control group (Chabé-Ferret, 2022; Kendall, 2003). Randomizing group assignment at the participant level mitigates selection biases that may artifactually influence empirical results. Additionally, the use of an active control group allows effects observed in the training group of interest to be interpreted with greater specificity. Participants from active control groups should experience a similar level of participation, reward, and type of activity as the treatment group. However, participants' experience in the control group should not involve the function targeted by the experimental training (e.g., music versus visual arts). Designing an appropriate active control group is paramount and, if poorly chosen, can equate to having a passive group. Active control groups offer more clarity in the interpretation of findings by controlling for placebo and expectancy effects (Boot et al., 2013; Foroughi et al., 2016) as well as non-specific changes that come with participating in an intervention, like learning to adhere to a regular training schedule (von Bastian & Oberauer, 2014). When examining skill transfer effects, it is also crucial for the trained skills in both groups to be equidistant to the outcome measure. For example, comparing

music training to poetry slam training on a speech measure outcome is unequal, because poetry slam training has more in common with speech than does music training. Poetry slam training consequently would have a higher likelihood of showing improvements in the speech outcome than music training. A recent article by Grau-Sánchez et al. (2022) provides general recommendations for choosing active control groups for music-based training.

The starting age for music training is an essential consideration to benefit from sensitive learning periods during brain development. Studying children during a specific time window for the development of their cognitive and musical abilities (4 to 7 years of age) may help increase the impact of shorter music training programs on brain plasticity (Bailey & Penhune, 2013; Best & Miller, 2010; Garon et al., 2008; Steele et al., 2013). A new series of short longitudinal experiments using active control groups and an RCT approach with targeted outcomes in 4 to 8-year-old children shows converging and promising evidence of far skill transfer effects (Frischen et al., 2019; Patscheke et al., 2019; Safay Honarvari & Moshkbid Haghighi, 2019; Williams & Berthelsen, 2019; 480 min-960 min training time over 12-16 weeks). These studies highlight a growing interest in theory-based and mechanism-driven RCTs with targeted outcomes and active controls in music training. Music training is a highly complex activity and studying it through the lens of specific mechanism-based transfer effects is pivotal for understanding and interpreting skill transfers involving music training from the bottom up.

Music training and inhibition control

Music training requires executive functioning for several attentional processes like inhibition control, cognitive flexibility, and working memory. During the early training phases, children learn to start and stop the appropriate motor actions on an instrument or to utilize each hand and foot independently (e.g., on piano, xylophone, organ, or drum). In addition, they monitor and control the correct perceptual and motor coordination in time with the music, all of which require inhibition control. Performing accurate movements and coordinating them in time is also paramount in expert

music performance (Loehr & Palmer, 2011; Palmer & Zamm, 2017). These abilities play a critical role when learning to play a musical instrument. Children likely also develop cognitive flexibility skills through set-shifting when taking turns to play different musical sections and switching between musical rules (tempos, time signatures, and musical scales). As children learn to read music scores and perform music simultaneously, working memory becomes a critical function to rely on (Bergman Nutley et al., 2014).

During this learning phase, the most critical executive function is inhibition control. This functionality is essential for paying attention to one's performance with fellow musicians, responding appropriately to musical cues, and starting/stopping/switching various rhythmic patterns within a music piece. The construct of inhibitory control consists of response inhibition - stopping a repeated response, and attentional inhibition - the suppression/filtering of goal-irrelevant stimuli (Tiego et al., 2018). It is the first and fastest executive function to develop during childhood starting as early as two years of age (Best & Miller, 2010; Senn et al., 2004; Wiebe et al., 2008). Inhibition control is a crucial factor in preschool, showing a quick improvement curve that becomes more gradual later in childhood (Best & Miller, 2010; Carlson, 2014; Nesbitt et al., 2015). Inhibition control is vital during child development for academic achievement (Allan et al., 2014; Liu et al., 2015; Wilkinson et al., 2020), goal-directed behavior (Allom et al., 2016), reducing compulsive behavior during childhood (Fogel et al., 2019) and for making healthy lifestyle choices later in life (Bowley et al., 2013).

Inhibition control also underlies executive functions like set-shifting and selective attention (Diamond, 2013; Tiego et al., 2018). Parts of music training that involve set-shifting and focusing attention, therefore, may train inhibition control indirectly as a form of near transfer. As a result, inhibition control may be the most reliable executive function to transfer from music training (Degé & Frischen, 2022; Rodriguez-Gomez & Talero-Gutiérrez C., 2022). Set shifting requires inhibition to stop following a set of rules and filter out irrelevant information for the new rules. Music training requires

inhibition control when: 1) self-monitoring (e.g., correcting intonation while singing a song or paying attention to potential errors) or when inhibiting behavior; 2) following global changes in musical structure (change of key, tempo, or rhythmic pattern), local music changes in structure to evoke emotions/energy (dynamics, micro-timing, polyrhythms, emotional expression) and when musicians play together and coordinate (Jentzsch et al., 2014; Okada & Slevc, 2019; Vuust et al., 2006, 2011; Zuk et al., 2014). There is empirical evidence supporting the critical role of inhibitory control in music training. Several RCT studies comparing musical training to an active control group have found improved cognitive skills in children for 1) inhibition control compared to visual arts training (Bowmer et al., 2018; Moreno et al., 2011), Lego training (Bugos & DeMarie, 2017), motor training (Bolduc et al., 2021), sports training (Frischen et al., 2019); 2) set shifting and short-term memory compared to an after-school homework program (Holochwost et al., 2017); 3) planning compared to visual arts (Jaschke et al., 2018); 4) working memory compared to free play (Guo et al., 2018).

Interestingly, in a study by Frischen et al., 2019), a rhythm-based music program showed improvements in inhibition control whereas a program focused on pitch-based components of music did not, which may be due to the cognitive demands required during motor synchronization to a beat. In a similar study, pitch-based music training showed greater effects on phonological awareness than rhythmic-based music training (Patscheke et al., 2019). The authors attribute this effect to a relationship between the elementary units of music (musical notes) and those of language (phonemes), in line with Patel's OPERA hypothesis (Patel, 2011). In a similar vein, there is evidence that the entrainment of a regular rhythm in a training protocol strengthens emotional regulation and cognitive flexibility in children via "neural entrainment" (Williams, 2018; Williams & Berthelsen, 2019). These findings highlight the effectiveness of targeting specific outcomes based on theory and mechanisms for studying skill transfers in music training.

Two key theoretical frameworks have helped elucidate the potential mechanisms behind skill transfer from music training. First, the OPERA hypothesis proposed by Patel (2011) places attention as a central process that is focused and improved through intense repeated practice, melodic, rhythmic, and language-related processes. One of the mechanisms by which music training transfers to verbal ability may be through the mediating effect of attentional regulation, a sub-function of inhibition control (Tiego et al., 2018). Second, the Dynamic Attending Theory explains that processing a temporally regular stimulus, like the underlying beat of the music, can be modeled by the "entrainment" of internal attentional oscillations (Jones, 1976; Large & Jones, 1999). More recently, Nozaradan (2014) provided the neurophysiological foundations of this theory using oscillatory neural dynamics. In this model, music with a regular beat provides a highly coherent structure making it possible to form predictions about upcoming events further in the future than everyday temporal processes like speech (Dalla Bella et al., 2013). Training rhythmic abilities through music may then optimize the "neural entrainment" of computations recruited by other music-related operations, like executive functioning or speech and socioemotional processing. These findings show that considering the roles of specific music components and the mechanisms by which they are processed in the brain can provide insight for understanding skill transfer effects from music training.

Music training and other skill transfers

During music training, children engage in and attend to speech, language and socio-emotional communication. As a result, the synchronous recruitment and overlap of these processes may lead to skill transfer in all of these functionalities. We will briefly discuss skill transfer between music training and speech, language, communication, and socio-emotional abilities.

Coordinating musical practice among musicians and synchronizing during a concert pose non-verbal communication demands, which likely share important underlying processes with speech and language abilities (Brandt et al., 2012; Jäncke, 2012; Milovanov & Tervaniemi, 2011; Patel, 2008;

Poeppel & Bergelson, 2008b). Phonological awareness, an essential ability for reading and writing, positively correlates with pitch perception skills in children (Loui et al., 2012). Music training programs have resulted in improvements in phonological awareness in children (Degé & Schwarzer, 2011) and preschoolers (Politimou et al., 2019). Studies of musical expertise show that professional musicians process phonetic information differently than non-musicians (Ott et al., 2011) and have advantages in accurately perceiving speech embedded in background noise on both a behavioral and neural level (Strait & Kraus, 2011). These are only a sample of the immense work that has been carried out to highlight the likely overlap of neural resources between learning music and language-related abilities.

The practice of coordinating with fellow musicians and sustaining joint action in time (Keller et al., 2014) helps children to develop social and emotional skills such as turn-taking, cooperation, sharing, and social responsibility (Buren et al., 2021; Kirschner Sebastian & Tomasello, 2010) as well as pro-social skills (Ilari et al., 2021). Inhibition control is a crucial skill for extracting social and emotional cues in real-time from purely musical cues during musical performance. Children use inhibition control to pick out these cues from non-relevant incoming information (attentional inhibition) in order to inform their own performance, such as when to slow down the music or play a phrase louder. Inhibition control is also required to stop a prepotent behavior (response inhibition) when switching to a new set of rules, such as transitioning from a fast forte section to a slow pianissimo. There is converging evidence supporting the critical role that music training plays in terms of social and emotional development. A recent meta-analysis by Gaudette-Leblanc et al. (2021) on longitudinal early childhood music programs (ages 0 - 6 years) and socio-emotional development reported a moderate positive effect size (d = 0.57) for ten programs using both observational (clinician assessment or researcher assessment) and reported measures (parent/teacher-reports). Music interventions are also promising tools to promote social and emotional skills in clinical populations with socio-emotional impairments, such as children on the autism

spectrum (for reviews, see: Dahary et al., 2022; Quintin, 2019). These encouraging results highlight that music is a complex activity with potential to strengthen socio-emotional development.

Social interactions are often integral to music training and contribute significantly to indirectly strengthening socio-emotional skills in children. To our knowledge, no study to date has controlled the social component of music training. Without dissociating the benefits of social interaction from those of music, it is difficult to conclude which aspect is responsible for improvement. Interestingly, social, and emotional skills can be trained through simulation/emulation using computerized music programs based on rhythm. We enjoy tapping our finger to a beat, and the mere tracking of a beat activates pleasurable responses in the brain, in addition to cognitive, language-related, and socio-emotional processing areas (Chen et al., 2008; Coull et al., 2011; Fujii & Wan, 2014; Grahn & Brett, 2007; Grahn & Rowe, 2009). Synchronization to a beat likely resonates with pleasurable feelings during social synchrony, connection, and joint action, thus engaging socioemotional processes (Trost et al., 2012; Yoo & Kim, 2018).

The emergence of enjoyable music training provided via mobile technologies has been successful in many ways for strengthening socio-cognitive development or as a complement to rehabilitation for clinical populations (for reviews, see Agres et al., 2021; Johnston et al., 2019). For example, externally cued rhythm training tablet applications have been used as a tool to help remediate some symptoms of Parkinson's disease - pain, fatigue, and falls remained stable during a 1-month program; fear of falling decreased, and quality of life improved (Cochen De Cock et al., 2021; Puyjarinet et al., 2022). A recent systematic review of 19 studies in young adults on the autism spectrum shows that computer-based cognitive training is as practical if not more effective than non-computerized training in improving executive functioning and social skills in people on the autism spectrum (Pasqualotto et al., 2021). A series of studies by Srinivasan et al. (2015, 2016) were successful in demonstrating the effectiveness of robotic rhythm-based interventions on spontaneous responses to social attention patterns in children on the autism spectrum.

In sum, music training carried out in a social context often overlaps with speech/language and poses demands on socio-emotional functioning. Inhibition control is required in many social situations and likely has an important role in social music training environments. In some instances, computerized music programs can emulate social demands and train social skills in neurotypical and socially impaired children on the autism spectrum. Music training is, therefore, an interesting activity capable of fostering socio-emotional development and has significant ramifications for child development (Planalp & Braungart-Rieker, 2015), academic achievement, and psychological well-being over time (Denham & Brown, 2010; Kamper-DeMarco et al., 2020). To understand the potential neural changes that underlie this skill development and transfer, we turn next to brain plasticity, the effects of which have been extensively studied in musicians.

Music training and brain plasticity

Plasticity is the capacity of the brain to undergo lasting changes that alter its functional and behavioral range (Kühn & Lindenberger, 2015; Lindenberger & Lövdén, 2019). Neural overlap in the mechanisms underlying music abilities and those supporting non-musical skills may increase the capacity and efficiency of non-musical skills through intense repeated music practice. Training programs aiming at cognitive transfer can generally induce transfer through two pathways (von Bastian & Oberauer, 2014): cognitive capacity (increasing availability of mental resources) or cognitive efficiency (increasing effectiveness of existing capacity by strategy usage and automization). To date, a wide range of brain imaging studies have examined the effect of music training on brain plasticity (see reviews by: Dalla Bella, 2015; Jäncke, 2009; Reybrouck et al., 2018; Rodrigues et al., 2010; Zatorre et al., 2007).

Evidence from cross-sectional studies shows musicians have distinct brain structural differences in auditory and motor regions as well as areas involved in multisensory integration (Bermudez et al., 2009; Bermudez & Zatorre, 2005; Gaser & Schlaug, 2003; Han et al., 2009; Sluming et al., 2002; Zatorre et al., 2007). Outside of the auditory cortex, structural differences in frontal and parietal regions

coincide with networks involved in more complex processing such as syntax, including musical syntax (Kunert et al., 2015), as well as a diversity of executive functions (Bettcher et al., 2016; Foster & Zatorre, 2010; Friedman & Robbins, 2022; Sluming et al., 2007). In sum, there is considerable evidence that music training may have specific, lasting effects on the brain that are linked with the progression of skills being trained (e.g., Foster & Zatorre, 2010). However, cross-sectional studies do not allow strong causal inferences about directionality.

Several longitudinal studies have measured the brain functional and structural changes imparted by musical training. Two years of music training in children results in increased white matter size and organization in the anterior part of the corpus callosum, an important pathway for interhemispheric communication (Habibi et al., 2018; Schlaug et al., 2009). An RCT of computerized music training in children showed correlated improvement in inhibition control scores and task-related brain activity after training compared to visual arts training (Moreno et al., 2011). An RCT study by Hyde et al. (2009) using MRI-based structural deformation analysis showed that 30 hours of private music training over 15 months led to brain anatomical changes in musically relevant auditory and motor areas that were correlated with individual differences in auditory and motor skill improvement. A subsequent larger-scale neuro-imaging study by Habibi et al. (2018) showed that approximately 500 hours of community-based music training induced structural brain plasticity in the corpus callosum and in auditory association cortex, an essential area for auditory feature extraction and processing complex sounds including music. A functional MRI analysis of this cohort by Sachs et al. (2017) showed that the group that received regular music training outside of school exhibited higher activation in regions of the cognitive control network during an inhibition task. Together, these promising brain imaging findings provide a foundation to contemplate the brain mechanisms/systems that could explain the effects of skill transfer from music training to extra-musical brain functions.

The current debate on far-skill transfer driven by musical training

Previous meta-analyses have examined music training on broader cognitive abilities, and methodological disagreements have fueled a debate over the extent of such transfer effects. Cooper (2020) reported a small overall effect size (g = 0.28) of music training on cognitive skills (verbal and non-verbal). That analysis included both active and non-active control groups, and a moderating effect of intervention setting was found. In the same year, Sala and Gobet (2020) undertook a multilevel meta-analysis examining music training and non-verbal ability, verbal ability, memory, and executive functioning speed, finding no effect of skill transfer (g = 0.06) for music training. In the context of the current debate around skill transfer, the study from Sala and Gobet (2020) was criticized for methodological issues including the selection of non-equidistant far skill transfer comparisons between groups and inclusion of studies that did not report pre-training scores (Bigand & Tillmann, 2021). In their paper, Bigand and Tillmann re-analyzed the meta-analysis of Sala and Gobet using the same dataset but adjusting the study and inclusion criteria to mitigate those identified issues. They found a small but reliable effect of music training (g = 0.23). A follow-up meta-analysis by Román-Caballero et al. (2022) also found that music training had a small positive effect on cognitive and academic skills (g = 0.28). In sum, there is evidence for a small effect size for far transfer from music training to a range of executive functions.

These results encourage future meta-analytic work on music training and far skill transfers to cognitive domains. Importantly, the commentary by Bigand & Tillmann (2021) highlights that meta-analyses are a work in progress and require care to avoid unintended biases in the selection of studies and conditions for analysis — especially in cognitive science where experimental methodologies may vary greatly across studies. Although several meta-analyses have been published examining far transfer from music training to various executive functions, no meta-analysis has narrowed the focus to a specific executive function. In 2022, two systematic reviews were carried out investigating the effects of music

training on a variety of executive functions and found that inhibition control was the most predominantly studied and showed the most reliable impact (Degé & Frischen, 2022; Rodriguez-Gomez & Talero-Gutiérrez C., 2022). Our meta-analysis builds on previous work by targeting a specific executive function, inhibition control, which may serve as a key driver of skill transfer from music training to executive functioning.

Rationale and Overall Goals of the study

This meta-analysis study sought to assess for the first time the effect of musical training in children on inhibition control. To this aim, we reviewed existing studies in children during a critical developmental age range for transfer effects from music training to inhibition control using a quantitative meta-analysis technique. To our knowledge, no meta-analysis on music training and inhibition control has been conducted for longitudinal research designs. Our meta-analysis is especially novel in calculating this effect size in RCT studies having active control groups. To assess the generalizability of these findings we also examine all existing parallel-arm longitudinal work, including quasi-experimental designs.

Study objectives and specific hypotheses

The main objective of our study is to assess the existing causal evidence that music training administered in children leads to skill transfer to a non-musical ability and, more specifically, to improve inhibition control. The secondary objective is to examine whether this causal evidence is generalizable across real-world training contexts. The third objective is to investigate if the expected skill transfer from music training to inhibition control depends on age, training intensity, training context, and randomization procedure.

Specific aims & hypotheses

Aim 1: To determine if music training increases inhibition control in children by assessing RCT designs with active control training conditions.

Aim 2: To determine if music training increases inhibition control in children in an ecologically valid sample of longitudinal music training programs, including quasi-experimental designs.

Based on the outcomes of systematic reviews on executive functions and music training (Degé & Frischen, 2022; Rodriguez-Gomez & Talero-Gutiérrez C., 2022), we expected to find an increase in inhibition control as a result of participating in a music training program for *Aim 1* and *Aim 2*.

Aim 3: To examine if training inhibition control through music training is dependent on the following moderating variables:

a. Age. Based on work by (Penhune, 2011) on critical learning periods, we expected that children in this meta-analysis would benefit equally from music training because the developmental window (4-8 years of age) is in the range of the critical brain plasticity window for music.
b. Training intensity. Based on the prediction that repeated music practice generates greater skill transfer (Patel, 2011), we expected the programs with the most prolonged training time to produce the greatest increases in inhibition control.
c. Training context. Since more formal and individualized training makes children more accountable for their progress, we expected programs with more individualized training components and specialized institutions to be more effective than school-based programs.
d. Randomization. We expected music training would exhibit greater effects in non-randomized studies due to pre-existing social cohesion of school classes.

Methods

Inclusion criteria

In this meta-analysis, we included studies that met the following criteria:

1. Music training was in the human neurotypical childhood and adolescent population.
2. The studies included an experimental group trained using music alone. Music was an activity that involved a production aspect using a musical instrument such as singing or drumming, or the music training required perceptual/motor skills related to music, such as in a computerized music training program.
3. The studies involved training music abilities.
4. The studies were longitudinal, with either an active or passive control group comparison.
6. The studies included a performance-based inhibition control measure as an outcome.
7. The studies were in peer-reviewed journals from January 1980 to October 2022.

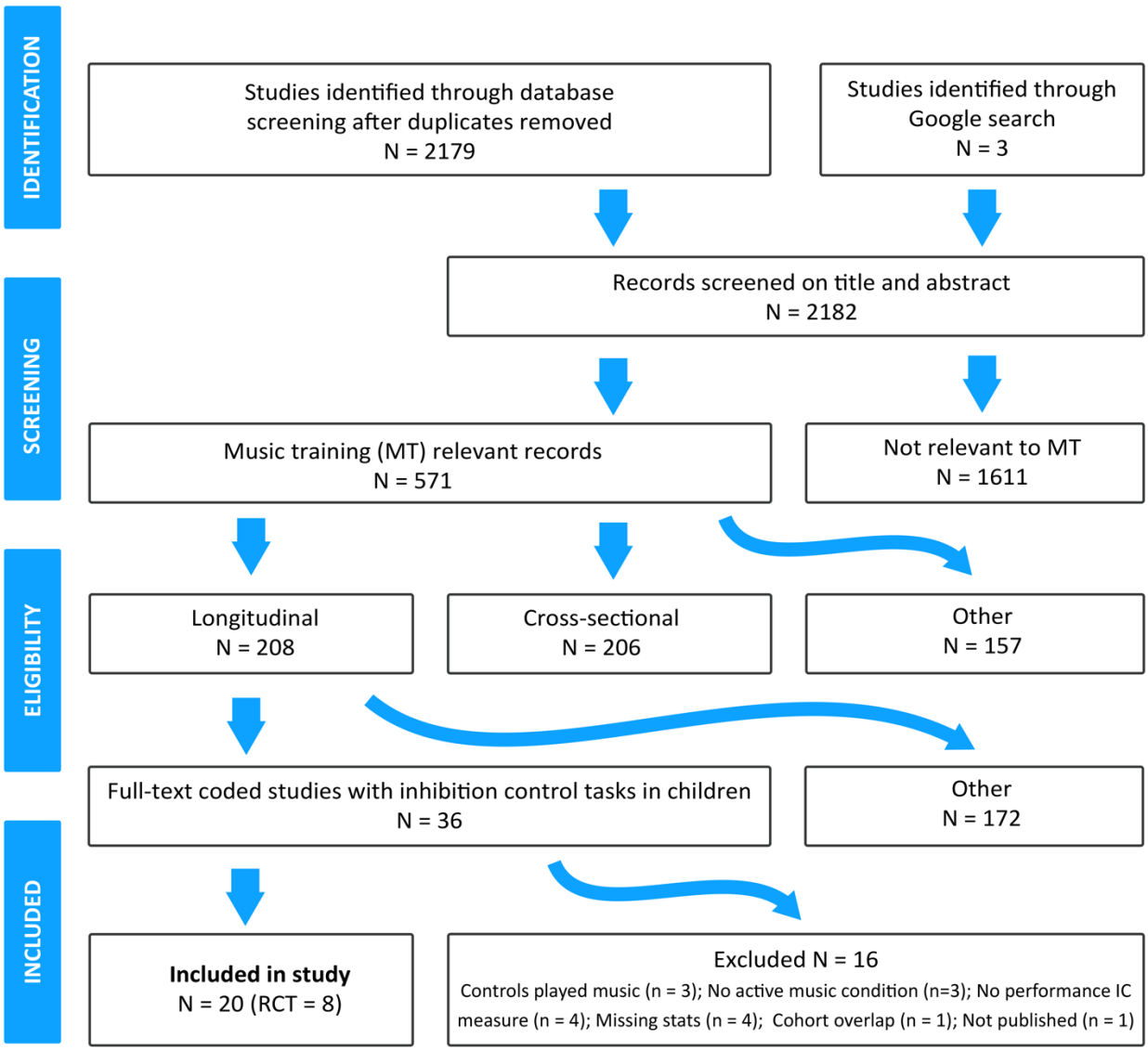
Searching procedure and collection process

We conducted an exhaustive literature search for music training and inhibition control studies in children and adolescents in various databases such as PubMed, PsychInfo, Web of Science, and Scopus. The following search keywords to cover music training were included: "music* training or music* learning or music* education or music* lessons or musician*"; and search keywords to cover inhibition control included: "executive* or executive function* or executive control or cognitive function* or cognitive control or inhibition"; and search keywords to cover development included: "development* or child or learning or cognitive development or childhood or children or adolescent*." The search results were exported into EndNote software (version X20; Clarivate Analytics, New York, USA). After duplicates were removed, 2179 studies remained. A search on Google identified three additional unpublished manuscripts making a total of 2182 screened records. A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Liberati et al., 2009) diagram summarizing the number of studies meeting the search criteria is shown in Figure 1. The first author XX, a doctoral candidate with a MSc, evaluated these studies based on title and abstract and found 571 studies relevant to music training. For this procedure, if the title and abstract did not provide sufficient information, XX decided based on the

full content of the publication. XX then screened all musically relevant studies based on title and abstract and determined that 208 studies had longitudinal designs, 206 had cross-sectional designs and 157 records did not fall in either category. After screening all the longitudinal studies based on the title and abstract, XX retained 36 studies that used inhibition control measures in children for full-text review. Following this, XX and the second author (YY), a research associate with a PhD, evaluated the full content of 36 studies, and 16 were excluded (see Supplemental Table A). Independent coding was carried out by XX and YY on the included 20 studies for quality assessment, and the resulting tables were compared and discussed to reach a consensus. Of the 20 included studies, 8 involved participant-level randomization with an active control group and were classified as RCTs.

Figure 1

PRISMA Chart Showing the Number of Studies Included in the Meta-Analysis



Tasks & Measures

The present work targeted studies with inhibition control measures involving prepotent response inhibition and resistance to distractor interference. We included the following inhibition control tasks: The Stop-Signal task, the Go-NoGo, the Eriksen Flanker, and the Stroop test. Similar adaptations of these tasks were included, for example in pre-schoolers (Bowmer et al., 2018; Brown et al., 2022; Kosokabe et al., 2021). Each of these tasks had different primary outcome variables for measuring inhibition. Some, like the Go-NoGo and the Stroop test, recorded accuracy scores and focused on the percentage of correct withheld responses. Paradigms like the Eriksen Flanker task

typically use correct response times as indicators of cognitive resource allocation. For example, trials with more incongruent information show slower response times than trials with congruent information. When the means of these two trial types are subtracted from each other, the remaining response time represents the added cognitive delay of resolving conflicting information. The smaller this value is, the greater the participant's inhibition control and resistance to distractor interference.

For this analysis, we calculated effect size estimates for accuracy and reaction times based on the most suitable measure for a meta-analysis. In the event of missing data, we contacted the corresponding authors of the respective studies three times. We subsequently omitted studies if authors did not respond, or if means and standard deviations were not reported or calculable. When studies only provided data visualizations of means and standard deviations, we manually extracted numerical data using WebPlotDigitalizer (http://automeris.io/WebPlotDigitizer), a tool designed to estimate values from graphical visualizations. In addition to collecting data on inhibition control measures, we coded the following information for each study:

a. Age
b. Music training intensity (number of sessions, session durations, total minutes of training)
c. Context of the training (school-based or a specialized music organization)
e. Participant-level randomization

Specific decisions about inhibition control measures for analysis are shown in Supplemental Table B.

Unpublished studies

There are arguments for and against including unpublished studies in meta-analytic methodology (Sterling et al., 1995). When sourcing studies only from peer-reviewed journals, a risk of publication bias increases in favor of studies with significant results, thus inflating the global effect size (Rosenthal & DiMatteo, 2001). In contrast, including studies that have not undergone a rigorous peer-reviewed process may decrease the overall quality of study designs and interpretability of the findings.

Given the 42-year scope of the current meta-analysis, obtaining a representative sample of unpublished works was not feasible due to technical limitations (i.e., contact information no longer valid, research institutes or laboratories closed). We carried out search queries for this meta-analysis on Scopus and ProQuest Dissertations and found one relevant study. We decided not to include unpublished studies in the present work.

Moderator variable coding

We coded and analyzed a range of potential moderators to assess if the variations in the effect of music training on inhibition control depended on these variables. The mean participant age in each study was estimated based on available information. Training intensity was estimated as the total number of minutes in the music intervention based on the information in the published material. When information about intervention duration was given in terms of school years, unless specified otherwise, we used 32 weeks per year to estimate the training intensity. Training environment was classified based on whether music training occurred at school, or in a context outside the school environment. Randomization was classified based on whether or not participants were individually randomized to a training group.

Quality Assessment

To assess the potential impact of bias in the reviewed studies, we conducted a rigorous quality assessment based on the CONSORT criteria (Moher et al., 2010). For detailed information on individual studies, see Supplemental Table C, Supplemental Table D, Supplemental Table E, and Supplemental Table F. Specific information in this assessment included sample sizes, adherence to randomization, reported participant information (age, sex, IQ, socio-economic makeup, ethnic background), group matching status, attrition during training, training description, control group information, training intensity, outcome measure type, quality of music instruction, and participants' prior music training. We assessed the quality of each study using the Cochrane Collaboration tool (Higgins et al., 2011). It is

difficult to blind participants from knowing if they are in a music intervention (Clark et al., 2012), and no study in this analysis reached the quality level of a double-blind placebo-controlled design. As a result, all studies were of “moderate” quality based on the Cochrane standards.

Attrition during training

Attrition was calculated separately by group in each study, based on the number of participants who started the training and who completed both the training and post-training measures. To assess potential attrition bias, differences in attrition between music and control groups in the full set of studies were evaluated using a mixed-effects model on these N values (i.e., interaction between timepoint and group).

Quantitative meta-analysis

Following meta-analytic guidelines (Lipsey et al., 2001), we synthesized and analyzed the set of longitudinal studies. This procedure involved the following steps: describing relevant characteristics of studies in a table, calculating standardized mean difference effect sizes (Hedges' g) for each comparison, determining overall effect size, and identifying potential moderator variables (Rosenthal, 1995; Rosenthal & DiMatteo, 2001). Hedges’ g effect sizes, reflecting the difference in pre-post performance change between groups in each study, were calculated using R version 4.2.0 software (R Core Team, 2022). In several studies, results were reported separately for participant age strata, or more than one performance measure was selected for inclusion in our meta-analysis. In these cases, we calculated individual effect sizes per age strata and/or measure, and then combined these to a single effect size for each study by running a supplemental fixed-effects meta-analysis using the "rma.mv "function and "FE" method of the "metafor" package 4.2.0 in R (Viechtbauer, 2010). The final meta-analyses of eight RCT studies and 20 longitudinal studies thus each contained one effect size per study. Effect sizes are described in the text as "small" (g ~ 0.2), "medium/moderate" (g ~ 0.5), or "large" (g ~ 0.8) based on

values suggested by Cohen (1988) and commonly used in studies of skill transfer effects in cognitive training (e.g., Bediou et al., 2018; Edwards et al., 2018; Sala et al., 2018).

Hedges' g effect sizes were calculated using equation 8 of Morris (2008), who refer to this effect size as d_{ppc2}. This calculation incorporates Bessel's correction as well as Hedges' correction for small sample bias.

$$d_{ppc2} = c_P \left[\frac{(M_{post,T} - M_{pre,T}) - (M_{post,C} - M_{pre,C})}{SD_{pre}} \right]$$

where

$$SD_{pre} = \sqrt{\frac{(n_T - 1)SD^2_{pre,T} + (n_C - 1)SD^2_{pre,C}}{n_T + n_C - 2}}$$

and

$$c_P = 1 - \frac{3}{4(n_T + n_C - 2) - 1}$$

The variance of effect sizes was calculated using equation 25 of Morris (2008), where delta indicates the effect size calculated above:

$$\sigma^2(d_{ppc2}) = 2(c_P^2)(1-\rho)\left(\frac{n_T + n_C}{n_T\, n_C}\right)\left(\frac{n_T + n_C - 2}{n_T + n_C - 4}\right)\left(1 + \frac{\Delta^2}{2(1-\rho)\left(\frac{n_T + n_C}{n_T\, n_C}\right)}\right) - \Delta^2.$$

The variance equation requires specifying a correlation value (rho) between the pre- and post-training values. As this value was not reported by the published studies, we imputed a value of rho = .5 when performing the meta-analyses. We additionally verified that the significance of the meta-analysis results did not change if a value of rho = .001 or .999 is used instead.

Each meta-analysis was calculated in R using the "rma.mv" function in "metafor" (Viechtbauer, 2010). The "rma.mv" function performs a random-effects multilevel analysis that accounts for variation across studies and is recommended when studies vary in their samples or methodology. Moreover, random effects provide greater control for sample size differences when estimating effect sizes. (Borenstein et al., 2009). We assessed between-study heterogeneity using the restricted maximum likelihood (REML) method, and confidence intervals of effect sizes were estimated using the Q-profile method, following the recommendations of (Veroniki et al., 2016).

Following analysis, we summarized heterogeneity across studies using the I^2 measure (Higgins & Green, 2008). This measure provides an estimate of the proportion of variation of effect sizes that arises from clinical and methodological heterogeneity rather than chance and is recommended by Cochrane Reviews (Higgins et al., 2019). We created forest plots to display all the effect estimates and confidence intervals for individual studies and the combined meta-analytic result (Lewis & Clarke, 2001). These plots also provide a visual indication of heterogeneity among studies (Phan et al., 2015). We reported confidence intervals at the 95% level, p values were considered significant at values < 0.05, and we noted non-significant trends at $p < 0.10$, considering the low power of generally small sample sizes in the reviewed studies.

Small study bias

Small study bias refers to the probability of small studies driving the overall effect size of the meta-analysis, thus impacting the validity of the findings. We used two techniques to determine the presence of a small study bias. First, as a visual diagnostic, funnel plots were generated to present the effect size of individual studies against the standard error associated with each study. Asymmetry around the triangular funnel provides an indication of potential publication bias (Rothstein et al., 2006). Second, we used Egger’s regression test (Egger et al., 1997) as a statistical evaluation of asymmetry, as

implemented in the "regtest" function of the "metafor" package using a weighted regression model with a multiplicative dispersion term.

Transparency and Openness

We adhered to the MARS guidelines for meta-analytic reporting (Appelbaum et al., 2018). The present work abides by the Transparency and Openness Promotion (TOP) at level 2 (Nosek et al., 2015):

1. Citation: Level 2, All data, program code, and other methods developed by others are appropriately cited in the text and listed in the references section.
2. Data Transparency: Level 2, processed data on which study conclusions are based are available and accessible on the anonymized OSF link: https://osf.io/d36gk/?view_only=8f57b9eef4fe42089f0a59ac1e03c26e
3. Analytic Methods (Code) Transparency: Level 2, computer code to reproduce analyses in an article is available on the anonymized OSF link: https://osf.io/d36gk/?view_only=8f57b9eef4fe42089f0a59ac1e03c26e
4. Research Materials Transparency: Level 2, Requirement—Materials described in the method section are available on the anonymized OSF link: https://osf.io/d36gk/?view_only=8f57b9eef4fe42089f0a59ac1e03c26e
5. Design and Analysis Transparency (Reporting Standards): Level 2, Authors complied with APA Style Journal Article Reporting Standards (JARS and MARS)
6. Citation: Level 2, All data, program code, and other methods developed by others are appropriately cited in the text and listed in the references section
7. Study Preregistration: Level 2, The study design and hypotheses for the present work were not preregistered. However, the study design and hypotheses, including half the study sample, were presented at the 16th Annual NeuroMusic Conference, 2020 and are publicly accessible at: [LINK DISCLOSES IDENTITY OF AUTHORS BUT IS ON TITLE PAGE]

8. Analysis Plan Preregistration: Level 2, The study analysis plan for the present work was not preregistered. However, the analysis plan, including half the study sample, was presented at the 16th Annual NeuroMusic Conference, 2020 and are publicly accessible at: [LINK DISCLOSES IDENTITY OF AUTHORS BUT IS ON TITLE PAGE]

Results

Qualitative review

Sample and demographics

A total of 20 studies (1528 participants across studies) were included in this review and meta-analysis. Sample sizes were calculated based on the data analyzed during pre- and post-training testing sessions. These samples sizes were equal at the pre-training and post-training time points for all studies. The mean age across studies included in the meta-analysis was five years and nine months, ranging between three and eleven years. All studies included boys and girls, with a reported average of 54.8% girls, ranging between 40.9% to 71.8% across all studies.

Randomization

A total of eight studies used randomized group assignment at the participant level and had active control training conditions (Bolduc et al., 2021; Bowmer et al., 2018; Bugos & DeMarie, 2017; Degé et al., 2020; Frischen et al., 2019, 2021; Moreno et al., 2011). Some studies were conducted in a school context with existing classroom groups, which did not permit participant-level randomization. See Supplemental Table F for study-level detail about randomization procedures.

Control groups

Overall, seven out of twenty studies did not have an active control group condition (Brown et al., 2022; Fasano et al., 2019; Guo et al., 2018; Hallberg et al., 2017; Shen et al., 2019; Suppalarkbunlue et al., 2022; Williams & Berthelsen, 2019). Of the thirteen studies with active control conditions, eleven had non-musical control conditions such as sports, visual arts, or Lego activities. Two studies (D'Souza &

Wiseheart, 2018; Linnavalli et al., 2018) had dance lessons as an active control condition, which potentially bears more similarity with music training than other active control group conditions, for example in terms of auditory-motor synchronization demands. Comparing dance and music lessons may underestimate the effect size of the music training program on inhibition control. For the complete list of control group conditions, see Supplemental Table C. A total of 8 studies were considered randomized control trial designs, representing 40% of the studies in this meta-analysis.

Group matching and demographics

All studies reported group matching on age, and 80% reported being matched on sex. 60% of studies reported group matching on socio-economic status and IQ. Of the RCTs, matching information was not reported in Bowmer et al. (2018). One study reported marginal group matching for sex with a p-value of 0.07 between groups (Fasano et al., 2019). In (Hennessy et al., 2019), group matching was challenging to assess because it was a multi-year study and the participant data available for inhibition control analysis was a subset of the baseline sample. For a study-level report on these parameters, consult Supplemental Table D. In total, 90% of studies included information describing the socio-economic makeup of their sample and 40% about the ethnic background of participants. For details of each study, see Supplemental Table E. Studies in this meta-analysis came from 11 countries in North America, Europe, Oceania, and Asia.

Blinding

In 55% of studies, personnel who performed coding and analysis of data were blind to group assignment. One study reported being unable to blind the research team but noted that the eight weeks between time point 1 and time point 2 likely limited the extent of bias. Eight studies did not report information about their blinding procedure (Brown et al., 2022; Bugos & DeMarie, 2017; Fasano et al., 2019; Hallberg et al., 2017; Hennessy et al., 2019; Shen et al., 2019; Suppalarkbunlue et al., 2022; Vazou et al., 2020).

Music training programs

Overall, 40% of the studies were conducted in a school environment, and the rest were in music training facilities outside of school. The instruments used to produce music were varied (singing, harmonica keyboard, percussion, xylophones) as well as the musical components that were prioritized (pitch versus rhythm). For further details about music training approaches, see Supplemental Table C. These studies represent a wide range of music training possibilities and support the generalizability and ecological validity of our findings.

Attrition

Calculation of per-group attrition between commencement of training and completion of post-training measures was possible for 90% of the studies. A mixed-effects analysis of these attrition values did not find any difference in attrition between the music training and control groups across studies ($p = 0.93$).

Quantitative meta-analysis

As detailed above, 20 studies met the criteria for quantitative analyses. Individual effect sizes and variances were calculated for each study's most suitable inhibition control measure and are shown in the forest plot of Figure 1.

The effect of randomized control trials (active control) of music training on inhibition control

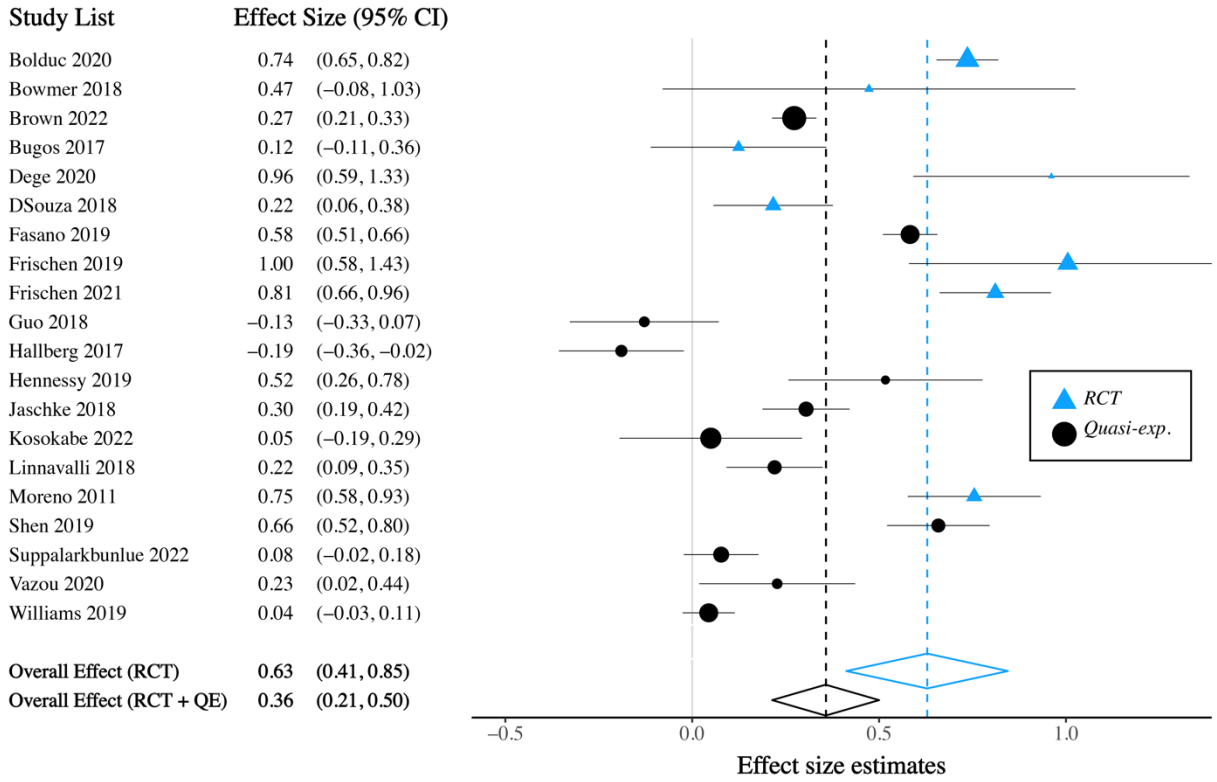
A random effects meta-analysis of 8 RCT studies indicated a significant overall effect size of $g = 0.63$ ($SE = 0.11$; $CI = 0.41\text{-}0.85$; $p < 0.0001$). This moderate-to-large effect indicates that inhibition control improves in children who participated in RCTs of music training compared to non-musical active control training. Individual effect sizes for studies in this analysis are shown in Figure 2. Results were robust when the value of rho = .001, where $g = 0.64$ ($SE = 0.15$; $CI = 0.34\text{-}0.94$; $p < 0.0001$) or rho = .999, where $g = 0.59$ ($SE = 0.12$; $CI = 0.36\text{-}0.82$; $p < 0.0001$).

The effect of longitudinal music training on inhibition control (active and passive control)

A random effects meta-analysis of all 20 longitudinal studies indicated a significant overall effect size of g = 0.36 (SE = 0.07; CI = 0.21-0.50; p < 0.0001). This small-to-moderate effect indicates that inhibition control improves in children who participated in music training programs compared to non-musical conditions (active and passive combined). Individual effect sizes for studies in this analysis are shown in Figure 2. All studies except Guo et al. (2018) and Hallberg et al. (2017) had a positive effect size. Results were robust when the value of rho = .001, where g = 0.36 (SE = 0.08; CI = 0.20-0.52; p < 0.0001) or rho = .999, where g = 0.36 (SE = 0.08; CI = 0.21-0.50; p < 0.0001).

Figure 2

Forest Plot of Effect Sizes (Hedges' g) Showing That Music Training Improves Inhibition Control



Note: Positive values to the right of the dotted line at 0 on the X-axis indicate better inhibition control after training in the music group

Results of moderators of interest

Individual random effects meta-analyses were conducted in the set of 8 RCTs and the 20 longitudinal studies for age, training intensity (total minutes), intervention setting (in school environment or not), and randomization (participant level or not). All analyses showed non-significant effects for these moderators of interest ($p \geq 0.10$; see Table 1 for analysis statistics).

Table 1

Results of Moderators of Interest

Moderator	RCTs				RCTs and Quasi-Experimental			
	g	SE	CI	p-value	g	SE	CI	p-value
Age	-0.06	0.13	-0.32 – 0.20	0.65	0.06	0.07	-0.08 – 0.19	0.44
Training Intensity	0.05	0.13	-0.21 – 0.30	0.72	0.05	0.09	-0.13 – 0.23	0.58
Intervention Setting	-0.11	0.11	-0.12 – 0.32	0.33	-0.12	0.07	-0.27 – 0.02	0.10
Randomization Procedure					0.08	0.08	-0.07 – 0.23	0.27

Measuring between-study heterogeneity

Heterogeneity between studies was anticipated in this analysis due to variation in inhibition control measures available in each study, the characteristics of musical training and control groups, and differences in sample demographics such as age. The I^2 estimate of inter-study heterogeneity was 0.0% for the analysis of RCT studies and 29.95% for the analysis of all longitudinal studies. These values

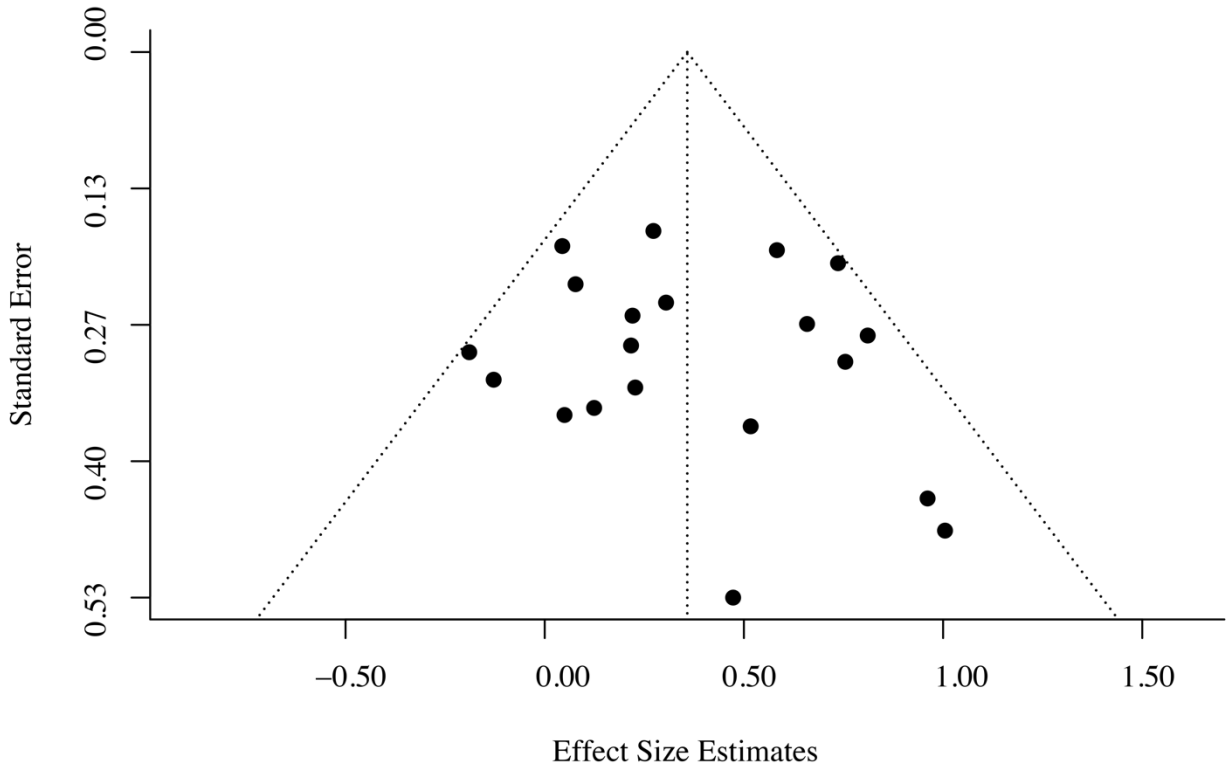
indicate a medium to low degree of variability between the studies (Higgins et al., 2019). Lower variability for RCTs is expected, given that they have more homogeneous methodologies.

Small study bias

The potential for a small study bias was assessed first by visual inspection of the symmetry of a funnel plot of the superset of longitudinal parallel-arm studies (Figure 3). No asymmetry in the funnel plot is observed, consistent with absence of small study bias. Subsequently, Egger's regression test was performed and confirmed a lack of asymmetry for both the RCTs analysis and the superset of longitudinal parallel-arm studies ($p > 0.57$).

Figure 3

Funnel Plot Showing No Small Study Bias When Comparing Effect Sizes with Standard Errors for the Superset of Longitudinal Parallel-Arm Studies



Note: The dotted line represents a 95% CI

Discussion

A significant finding emerging from our meta-analysis is that the effect size estimates are greater than earlier meta-analyses on music training and skill transfer to executive functioning (Bigand & Tillmann, 2021; Román-Caballero et al., 2022; Sala & Gobet, 2020). We show converging evidence that music training improves inhibition control with a moderate-to-large effect size estimate across 8 RCTs (g = 0.63), and a small-to-moderate effect size estimate in a superset of 20 longitudinal studies (g = 0.36). These results confirm skill transfer from music training to inhibition control, an effect hinted at by previous systematic reviews (Degé & Frischen, 2022; Rodriguez-Gomez & Talero-Gutiérrez C., 2022). Compared to the majority of intervention effect sizes in education, the RCT effect size estimate of this meta-analytic work is of particular interest, according to Hattie (2008)'s barometer of influence. After analyzing over 800 meta-analyses, Hattie (2008) reported that the median value of intervention effect sizes in education is 0.40. The author considers any effect size above that threshold to have a practical educational use. These findings also indicate that music training is more impactful in improving inhibition control than other types of activity aiming to generate skill transfer to inhibition control, such as video games. Effect size estimates for video games range between g = 0.27 (Sala et al., 2018) and g = 0.31 (Bediou et al., 2018). To our knowledge, music training presents a unique advantage in training inhibition control compared to any other training program.

The goal of this meta-analysis was to assess for the first time the effect of music training in children on inhibition control, an essential executive function for child development (Allan et al., 2014; Liu et al., 2015; Wilkinson et al., 2020). Music training requires inhibition control when learning an instrument for coordinating sensorimotor actions in time with music and playing with fellow musicians (Jentzsch et al., 2014; Okada & Slevc, 2019; Vuust et al., 2006, 2011; Zuk et al., 2014). This meta-analysis

included studies between January 1980 and October 2022 in 4 to 11-year-old children. Our findings highlight that larger effect sizes can be identified when the analytic criteria focus on a specific theory-driven research question. We further discuss the beneficial effects of music training on inhibition control in the current debate about far skill transfer in music-based training. Strengthening inhibition control in children has critical implications for education, language/speech/communication, socio-emotional processing, and music-based interventions for pediatric clinical populations. Innovative approaches for training inhibition control via music-based technologies and accessible adaptive training programs for typically developing children and children with neurodevelopmental disorders will be presented at the end, paving the way for future research.

Effects of music training on skill transfer effects

Music training involves several mechanisms underpinning the perception of the core elements of musical structure (pitch, rhythm, timbre), production (motor control and coordination), auditory-motor integration, reward, and social interaction. Music training can be studied holistically or by focusing on independent driving mechanisms (Frischen et al., 2019; Patscheke et al., 2019). The holistic approach examines all components of music during training and seeks to generalize skills from music training to several extra-musical skills at once. Holistic training promotes rich implicit interconnections between music components and processes involved during the learning experience. Another way of studying the effects of music training is by targeting a specific musical element or mechanism. This approach singles out one or a few musical components in a dedicated training, such as a rhythm-based or pitch-based program and aims to target generalization from that music training to a specific near or distant skill like inhibition control or phonological awareness. This approach is theory-driven and allows the testing of causal hypotheses linking underlying cognitive and brain mechanisms. This original meta-analysis's scope differs from previous meta-analyses on music training because it focused on a single targeted executive function, inhibition control. The narrower scope likely contributed to the sensitivity

to resolve a strong transfer effect, and also provides a clearer path to consider the implications and potential mechanisms of transfer.

Our findings contribute to a more extensive ongoing debate about far skill transfer effects in the context of music training and report a higher effect size estimate than any other meta-analyses involving music training and executive functioning (Bigand & Tillmann, 2021; Román-Caballero et al., 2022; Sala & Gobet, 2020). The present effect size estimates for both RCTs and mixed active/passive-control longitudinal designs are significant and robust across potential confounding factors of age, training intensity, intervention setting, and the presence or absence of participant-level randomization ($p \geq 0.10$). The lack of an age effect may be due to the age range being relatively narrow within each study (2-3 years) and the mean age of 5 years and 9 months falling within the expected sensitive period window for music training and child development (Penhune, 2011). Contrary to expectations, the training intensity of the music programs did not moderate skill transfer effects from music training to inhibition control in children. The lack of a moderating effect of training intensity may be due to the focused approach of the training and a sufficiency of the lower range of the training time to generate skill transfer. We found no moderating effects of the intervention environment for music training on inhibition control in children. These findings suggest that music training at school is as impactful on inhibition control outcomes as in a music facility. Overall, these findings suggest that improvements in inhibition control after music training are achievable in varying training intensities above 300 minutes and different training environments.

The present meta-analysis sought to draw out specific and equidistant far-transfer comparisons between experimental and control groups. We included two studies comparing music to dance training, for which near-transfer confounds were plausible and explicitly discussed. In this case, the directionality of the bias makes our effect size, in fact, a more conservative estimate than if it included far-transfer comparisons only. Dance training has similar auditory-motor synchronization demands as music training.

For instance, dancing often involves the independent coordination of limbs, head, and hips to the beat, which may pose similar inhibition control motor demands as the early phases of music training. In Linnavalli et al. (2018), music and dance lessons had individual and group lessons. In the D'Souza and Wiseheart (2018) study, both music and dance programs were in a group context. We favored an active control comparing near transfer over a passive control group because it helps the interpretation of our findings, even though this comparison likely underplays the effect of music training. As a result, studies with dance control conditions showed smaller effect sizes than those with active non-dance training control conditions.

This meta-analytic work only included studies that reported baseline and post-training scores, and effect sizes were calculated based on group differences in the magnitude of change from baseline to post-training. Only one study by (Fasano et al., 2019) reported unmatched baseline scores for inhibition control. Mixing community-based, quasi-experimental, and RCT designs adds ecological validity to our results and helps assess the generalizability of our conclusions (Habibi et al., 2022). The analysis of 8 studies using RCT designs in this meta-analysis yielded a greater effect size estimate than the analysis of all longitudinal studies. The latter analysis included studies having passive control groups that could, in principle, overestimate the effect of music training. The fact that the RCT studies, which compared music training with an active control condition and randomly assigned participants to their training group, found the greatest improvement in inhibition control outcome for music training emphasizes the importance of strong experimental design and supports future focus on RCT designs for studying music training.

Practical applications of the findings

Our findings have practical implications for various domains: education, auditory perception, language/communication, social functioning, emotion/reward, and clinical populations.

Education

Inhibition control is essential in child development for self-regulation, reasoning, goal-directed behavior, maintaining focus during school, and reducing compulsive behavior during childhood and later in life (Allom et al., 2016; Bowley et al., 2013; Fogel et al., 2019; Liu et al., 2015; Palermo & Bartoli, 2019; Wilkinson et al., 2020). Music training may benefit the critical skills necessary for succeeding during children's education. Music is generally a rewarding and motivating activity for children (Koops & Kuebel, 2018), and greater motivation is associated with enhanced learning (di Domenico & Ryan, 2017) and dopaminergic goal-directed action planning (Bogacz, 2020). By promoting greater motivation and engagement, music training may offer a cost-effective complement to general education programs.

Inhibition control deficits are present in clinical disorders, including the characteristic attention impairments of attention-deficit / hyperactivity disorder (ADHD) and repetitive and maladaptive behaviors on the autism spectrum. Explicit cognitive training on inhibition control tasks shows mixed results in neurodevelopmental populations (de Vries et al., 2021; Robinson et al., 2014). Training inhibition control indirectly through music may be more efficient because music training provides an enjoyable, meaningful learning context for children (Takacs & Kassai, 2019). When geographically relevant, music training at schools is also an opportunity for children with clinical diagnoses to mix at school with children from mainstream schools and share new experiences that foster greater acceptance and openness.

Auditory perception, speech, language, and communication

Music training shares neural and functional overlap with auditory, speech, and language skills. There is evidence that training inhibition directly facilitates switching languages in bilinguals (Wu et al., 2021). Training inhibition control in that study was associated with functional activation changes in a brain area associated with both domain-general inhibitory control and language control in particular. Training rhythm through music results in benefits to language skills, including rhyming abilities (Gordon

et al., 2015) and lyrical recall (Gordon et al., 2011). Rhythm-based training also extends to clinical settings and improves phonological awareness and reading skills in dyslexia (Flaugnacco et al., 2015). These findings support models of neural phase entrainment (Large & Jones, 1999; Nozaradan, 2014) to predict upcoming words based on certain regularities in language. Rhythmic structure in language units may thus make learning language, speech, and vocabulary more efficient.

Attentional inhibition demands posed on pitch-related information may help optimize speech-related information efficiency. Pitch perception skills have been shown to be positively associated with children's phonological awareness (Loui et al., 2012). This link can be targeted by training, as demonstrated in improved phonological awareness following a program of pitch-based music training (Patscheke et al., 2019). The OPERA hypothesis Patel (2011) helps explain the link between pitch training and phonological awareness, because of their overlapping requirement for precise pitch encoding combined with the use of emotion, repetition and attentional demands in the course of music training. These phonological abilities are essential foundations for reading and writing; therefore, advantages carried over from musical practice in the speech domain may benefit in the context of education and reading/learning disorders.

Social functioning, emotion, and reward

Coordinating with other musicians requires a significant amount of inhibition control. Maintaining the steady synchronized joint action of a musical rhythm may help hone social skills, including turn-taking, cooperation, sharing, social responsibility, and self-regulation (Buren et al., 2021; Keller et al., 2014). Recent work by Gaudette-Leblanc et al. (2021) provides empirical evidence that music training in children aged 0 to 6 years moderately improves socio-emotional development in both reported and observational measures (d = 0.57). Music programs provide opportunities to strengthen social and emotional skills during the early phases of child development in families, childcare, and preschool settings.

Inhibition control plays a crucial role in social and emotional functioning. Monitoring the flow of one's own emotions and identifying appropriate feelings to guide one's thoughts and actions require inhibition control skills. Essential abilities for children to cultivate at the emotional level include self-awareness in identifying emotions, social awareness for perspective-taking, caring for others, and self-regulation in managing emotions, cognition, and behavior (Rose-Krasnor & Denham, 2009). Synchronizing to a beat mentally or physically is a pleasurable activity reflecting a connection with the reward system and positive emotion. The combination of positive affective experiences and internal mechanisms involved in predictive timing may help explain why rhythm-based activities have a beneficial effect on language, as mentioned earlier, and social abilities (Brodal et al., 2017; Nummenmaa et al., 2021; Reybrouck et al., 2018; van Noorden et al., 2017; Vuust et al., 2011). The development of these social and emotional abilities has important implications for child development and growth (Planalp & Braungart-Rieker, 2015), academic achievement, and psychological well-being over time (Denham & Brown, 2010; Kamper-DeMarco et al., 2020).

Clinical applications

These findings have practical implications for neurodevelopmental disorders like children on the autism spectrum and with ADHD (Zhang et al., 2017). Deficits in speech, social skills and emotional processing characterize children on the autism spectrum, however some music abilities seem preserved (Jamey et al., 2019). A neuroimaging RCT study by Sharda et al. (2018) showed that a music intervention with children on the autism spectrum improved parent-reported communication abilities compared to an active arts and crafts intervention. Increased auditory-motor/frontotemporal resting-state functional connectivity after training in the music therapy group was correlated with the increased communication scores. A video-coding analysis of behavior during these interventions showed that the children on the autism spectrum who participated in the music intervention had greater improvement in joint attention and movement than those who participated in the active control intervention (Latif et al., 2021).

Interestingly, in autism, musical interventions without a social component like computerized training also show benefits, including spontaneous responses to social attention patterns in children (Srinivasan et al., 2015, 2016) and a range of socio-cognitive skills in young adults (for a review (Diamond, 2013; Pasqualotto et al., 2021). These effects suggest that training internal brain mechanisms related to music may be sufficient to generate skill transfer from music to inhibition control. Additionally, computerized training programs may be particularly relevant for children on the autism spectrum because a lack of interest in social bonding characterizes the disorder, and in-person group-based music interventions may be overwhelming for some children on the autism spectrum. These findings support future tools that could complement remediation of clinical populations from a distance.

In sum, inhibition control may be a key mediating factor in skill transfer from music training to extra-musical activities due to a hierarchy in the development of executive functioning (Diamond, 2013) and the importance of inhibition control for appropriate communication, impulse control, and socio-emotional skills. Music training can help supplement education by strengthening children's education and can help to complement the rehabilitation and telerehabilitation of specific clinical populations.

Limitations

This meta-analysis shows a robust overall effect among longitudinal designs and is sufficiently powered to assert the ecological validity of our results. RCTs comprised 40% of the included studies and had a greater overall effect size than the full set of longitudinal studies. Nonetheless, the set of studies is relatively small, and future RCTs will benefit the field and establish the causality of music training interventions upon executive function outcomes with further certainty. Even though studies included in this meta-analysis controlled for baseline measures and generally matched their groups on relevant demographic variables, some studies were not randomized at the participant level. Another limitation is that only single blinding was possible, given the nature of the comparison between musical and non-musical interventions. Future studies should also conduct follow-up testing to assess the temporal

stability of inhibition control improvements after music training. Many studies did not report an intelligence quotient (IQ) measure at baseline, which is an important variable for group matching. Most studies in this meta-analysis set research objectives without incorporating a hierarchical approach to the development of executive functioning in children. For instance, cognitive flexibility requires inhibition control but is a higher-order executive function because it also involves set-shifting. The benefit of this approach is that it considers interdependencies between executive functions (Diamond, 2013; Tiego et al., 2018). Future work would benefit from integrating these theoretical and practical recommendations. For general recommendations on developing RTC music intervention research, refer to the recent consensus publication by (Grau-Sánchez et al., 2022).

Future Directions

Studying near and far transfer effects

Our findings contribute to the ongoing conversation on skill transfers generated by music-based training programs. Drawing a precise line between near and far skill transfer can be daunting (Barnett & Ceci, 2002). In the case of music training, some researchers frame improvements in non-musical executive functioning skills as a far transfer (D'Souza & Wiseheart, 2018; Miendlarzewska & Trost, 2013), while others argue that it involves a transfer of skills across similar domains (Diamond & Lee, 2011; Frischen et al., 2021). For instance, playing music involves the continuous use of several executive functions (Jäncke, 2009; Okada & Slevc, 2019). This dispute may seem particularly tangible when studying music training under a holistic lens. Considered as a whole, both musical and non-musical functions are often inherent in music training, and this may confound the demarcation of near vs. far skill transfers. Part of this ambiguity thus arises from how music training is implemented in research. When training focuses on particular components of music (e.g., pitch or rhythm), it is easier to hypothesize a mechanism and to define a boundary between near and far transfers. Studying music at the level of its components offers more clarity and causal directionality for understanding skill transfer.

Conversely, studying music as an integrated multi-component activity does not carry these advantages, but offers greater ecological validity and is closer to how people usually enjoy learning music. Research to date has predominantly favored integrated music training, and there are consequently many open questions about the mechanisms and necessary conditions for transfer effects attributed to music. Future research should seek to fill in these gaps. In studying both integrated and component-based musical training programs, we can gain a better and more reliable overall understanding of skill transfer effects stemming from music training. This knowledge can be used in practical applications for educational and health-related domains and developing new technologies.

Building mechanism-based models around specific components of music training could help optimize music intervention programs. For instance, if rhythmic elements of music training drive transfer effects to inhibition control, this can guide the implementation of large-scale community-based music interventions, such as El-Sistema. Similarly, music interventions targeting improvements in vocabulary and phonological awareness may target pitch-based musical skills when designing the music intervention, as shown by (Patscheke et al., 2019). The findings of the present meta-analysis inform us about a specific executive function, inhibition control, which is trained indirectly through music. Future research can provide a more complete understanding of this transfer effect by examining the contribution of rhythmic-based music training compared to pitch-based training or training that combines pitch and rhythm demands.

Using technological approaches

Music training effects on cognition are understood to benefit from a combination of cognitive demands in a social setting and pleasure drawn from joint action and synchronized music performance (Keller et al., 2014; Nummenmaa et al., 2021; Wheatley et al., 2012). Recent studies have demonstrated that tapping a finger to the beat of the music, and even the mere mental tracking of the beat are enough to activate the brain's reward network as well as sensorimotor, cognitive, verbal, social, and

emotional processing (Chen et al., 2008; Coull et al., 2011; Fujii & Wan, 2014; Grahn & Brett, 2007; Grahn & Rowe, 2009). These findings suggest that the benefits of music training/interventions may be accessible without direct social interaction, and this in turn prompts research to explore possibilities for computerized music training/intervention.

Present-day technology allows us to devise exciting music-based interventions using mobile devices and sensor connections (Agres et al., 2021). Games with an intent beyond entertainment, or "serious" games, provide a unique opportunity to generate an abundance of multisensory experiences suitable for cognitive improvement and rehabilitation. They offer the flexibility of specifically targeting musical components such as pitch production or beat-synchronization to adapt to the needs and profiles of various populations (children, older adults, and people with cognitive or physical impairments). This flexibility also provides a particular methodological opportunity to design music interventions with a greater degree of double blinding. Until now, music interventions have been limited to single blind designs because it is challenging to hide expected music intervention improvements from participants (Clark et al., 2012). However, when targeting a more specific component of music such as beat-synchronization, the active control game can use a similar interface and amount of motor movement as well as the same music as the main training, but without the synchronization demands, making the research objective of the study much less evident to participants. In this way, a randomized, double blind parallel-arm design with active control is feasible, mitigating sources of performance bias (Higgins et al., 2019) and providing impactful conclusions for health and educational policy.

In the evolving hybrid remote/in-person world, the mobile aspect of these games renders them particularly suitable for regular, accessible, at-home, in-between-school/therapy training. Although many commercial games already exist to train music, such as "Yousician" and "VoxTrain," (Dalla Bella, 2022) argues that they have not been shown to be suitable for rehabilitation. These games were designed for general use and were not tested in evidence-based studies for clinical use or validated for

cognitive strengthening. "Serious" games use evidence-based testing to isolate the mechanisms responsible for rehabilitation or cognitive strengthening. Only a few "serious" games have been tested so far with a clinical goal, showing effectiveness in Parkinson's, dementia, ADHD, dyslexia, autism, and stuttering (see Bégel et al., 2018; Dalla Bella, 2022; Johnston et al., 2019; Pasqualotto et al., 2021; Srinivasan et al., 2015, 2016).

Compared to standard therapy, computerized training allows extensive opportunities to monitor and control training online and offline by recording quantitative data during the training (e.g., time of play, progression in the game levels, reaction times). Access to this type of data helps clinicians evaluate the individual trajectories of patients, verify patient compliance outside of therapy, and adapt the treatment strategy when required. Validating music intervention using mobile technologies additionally addresses societal and health questions regarding social inequality by reducing geographical and economic constraints on therapeutic availability and remains accessible even in global health crises such as pandemics.

Testing individual differences

Music training/interventions may impact individuals in different ways. An essential part of studying the impact of a training/intervention is to understand if additional factors (for example, age, baseline performance, clinical severity) influence individual training outcomes. Studies that plan their designs to understand the impact of individual differences on the training outcome can then offer more specific recommendations to tailor the training/intervention based on certain critical personal characteristics. For example, scaling the level of difficulty of the training to individual ability helps optimize the motivation to learn and sustain a state of flow during the training (Ryan & Deci, 2017), as an interplay between brain reward systems, prediction errors, action planning, and goal-directed behavior optimizes the cognitive efficiency of learning (Bogacz, 2020) and attentional control (di Domenico & Ryan, 2017). Additionally, for computerized training there is considerable flexibility to

accommodate individual differences, such as providing a simplified interface for less technologically savvy people, e.g., preschoolers and people with cognitive impairments. Combining an individual differences approach with new technologies offers a powerful opportunity to capitalize on the full potential of adaptive training and overcome obvious roadblocks to the training for specific individuals (Karbach et al., 2017; Katz et al., 2016). Recent findings from our laboratory highlight the importance of taking individual differences into account in a musical therapeutic context in Parkinson's disease (Bella et al., 2017; Dalla Bella et al., 2018; Puyjarinet et al., 2022). In sum, a movement toward studying individual differences and tailored/adaptive training can create powerful and accessible music training programs in the future.

Conclusion

This meta-analytic work is the first to examine skill transfer from music training to inhibition control. Our findings show that inhibition control improves after music training with a moderate-to-large effect size in RCT studies, and a small-to-moderate effect size in a superset of longitudinal studies that included quasi-experimental designs and passive control groups. Both effect size estimates are greater than those found in previous meta-analyses on music training and skill transfer to broader sets of executive functions (Bigand & Tillmann, 2021; Román-Caballero et al., 2022; Sala & Gobet, 2020). Here, a narrower focus on a single executive function, inhibition control, likely contributed to the sensitivity to resolve a transfer effect, and also provides a clearer path to consider the implications and potential mechanisms of transfer. We note that the effect size of skill transfer is also higher than found in other training programs, such as video games, that aim to improve cognitive skills through skill transfer effects. In this meta-analysis, we always selected the more conservative option when making methodological choices that could bias our findings. As a result, the actual effect size of music training on inhibition control may be higher than calculated in the present work. The overall effect size we

estimated meets the threshold for practical use in education policy and exceeds that of most meta-analyses of educational interventions (Hattie, 2008).

For music training transfer to inhibition control, there remain relatively few studies that use single or double blind parallel-arm randomized control trials with active equidistant control groups. Further research incorporating these important design criteria will help to clarify the mechanisms and necessary conditions of this transfer effect. Additionally, a specific focus on the contribution of the core elements of music, such as pitch, rhythm, and non-social music training, will help determine what components of music training most drive this effect. Because inhibition control is a developmentally fundamental executive function and is important for language/communication abilities and socio-emotional skills, studying inhibition as a potential mediating factor for improving outcomes in education and clinical populations with socio-communicative deficits is a promising avenue of research. Using theory-based and mechanism-driven predictions for specific targeted outcomes will help develop the potential of music training to strengthen children's cognitive abilities and complement remediation as well as teleremediation in clinical populations.

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Computer Code

Runnable computer code can be found at the following URL: https://osf.io/d36gk/?view_only=8f57b9eef4fe42089f0a59ac1e03c26e