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# Does music training provide non-musical benefits? Evidence from auditory, linguistic, and socio-emotional processing.

Leonor Neves

Ph.D. in Psychology

Supervisors:
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ISCTE – Instituto Universitário de Lisboa

M.D. Bogdan Draganski, Associate Professor,
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CIÊNCIAS SOCIAIS
E HUMANAS

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*To my aunt, whose guiding light continues to inspire me, and with heartfelt dedication to my beloved niece Beatriz, a symbol of hope and limitless possibilities. This Ph.D. thesis is a tribute to the pursuit of knowledge across generations.*

# Acknowledgments

*"Man is a social animal."* At some point this was the opening sentence of my master thesis. A few years later, it was the opening sentence of the acknowledgments of my brother's PhD thesis. Today, I revisit this opening statement and devote my acknowledgements to my family, friends and colleagues that made this thesis possible.

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My family, friends and colleagues are the proof that man is indeed a social animal.

Leonor Neves,
Porto, 27th May 2023

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# Resumo

Existem cada vez mais estudos focados nos efeitos de transferência do treino musical. Enquanto possíveis efeitos em domínios próximos da música são frequentemente negligenciados, a possibilidade de transferência para domínios substancialmente diferentes da música é controversa. Considerando a estreita associação entre música, processamento cognitivo, e processamento sócio-emocional, a presente tese foca-se em três tópicos: (1) uma revisão sistemática e meta-análise de estudos longitudinais que examinam efeitos de transferência no processamento auditivo e linguístico, ao nível cerebral e comportamental. Os resultados apontam para um efeito positivo em ambos os domínios. Contudo, o tamanho do efeito é pequeno, existe elevada heterogeneidade, e evidência sugestiva de viés de publicação; (2) um estudo transversal que analisa associações entre o reconhecimento emocional em crianças e o seu ajustamento sócio-emocional. Um melhor reconhecimento emocional em prosódia está positivamente associado ao ajustamento sócio-emocional, independentemente de fatores cognitivos e sócio-demográficos; e (3) um estudo longitudinal com crianças que examina efeitos do treino musical em domínios próximos da música (competências auditivas e motoras), assim como uma ampla variedade de competências sócio-emocionais. O treino musical melhorou significativamente as competências motoras. Contudo, os efeitos nas competências auditivas são inconclusivos e não houve efeitos significativos no processamento sócio-emocional. Estes resultados sugerem que o treino musical pode ter efeitos em domínios próximos da música, mas a evidência para efeitos em domínios substancialmente diferentes da música é escassa. Globalmente, estes resultados permitem avançar novos conhecimentos quanto aos efeitos de transferência do treino musical, particularmente considerando as competências sócio-emocionais de crianças, um tópico pouco explorado.

*Palavras-chave*: Neurociência cognitiva, treino musical, efeitos de transferência, processamento auditivo, processamento linguístico, processamento sócio-emocional

PsycINFO Classification Categories and Codes:
**2300 Human Experimental Psychology**
2340 Cognitive Processes

# Abstract

There is a growing body of research on the potential non-musical effects of music training. While transfer to domains tightly related to music (near transfer) are often taken for granted, the possibility of far transfer (to domains substantially different from music) remains controversial. Given the close associations between music, cognitive and socio-emotional processing, we focus on three topics: (1) a systematic review and meta-analysis of longitudinal studies on neural and behavioral effects of music training on auditory and linguistic processing. We report a positive neurobehavioral enhancement of music training on both domains with a small effect size, high levels of heterogeneity and suggestive evidence of publication bias; (2) a cross-sectional study analyzing associations between children's emotion recognition skills and socio-emotional adjustment. Higher emotion recognition in prosody is associated with better socio-emotional adjustment, even after accounting for cognitive and socio-demographic factors; and (3) a longitudinal study with children investigating music training effects on near transfer domains (auditory and motor skills), and on a wide range of socio-emotional abilities (far transfer). Music training significantly improved motor skills. Effects on auditory skills were inconclusive, however, and we found no effects of music training on socio-emotional processing. These results are suggestive of near transfer from music training, but not of far transfer. Altogether, these findings advance new knowledge on the extent of music training transfer effects, particularly considering children´s socio-emotional abilities, a topic poorly explored.

*Keywords*: Cognitive neuroscience, music training, transfer effects, auditory processing, linguistic processing, socio-emotional processing

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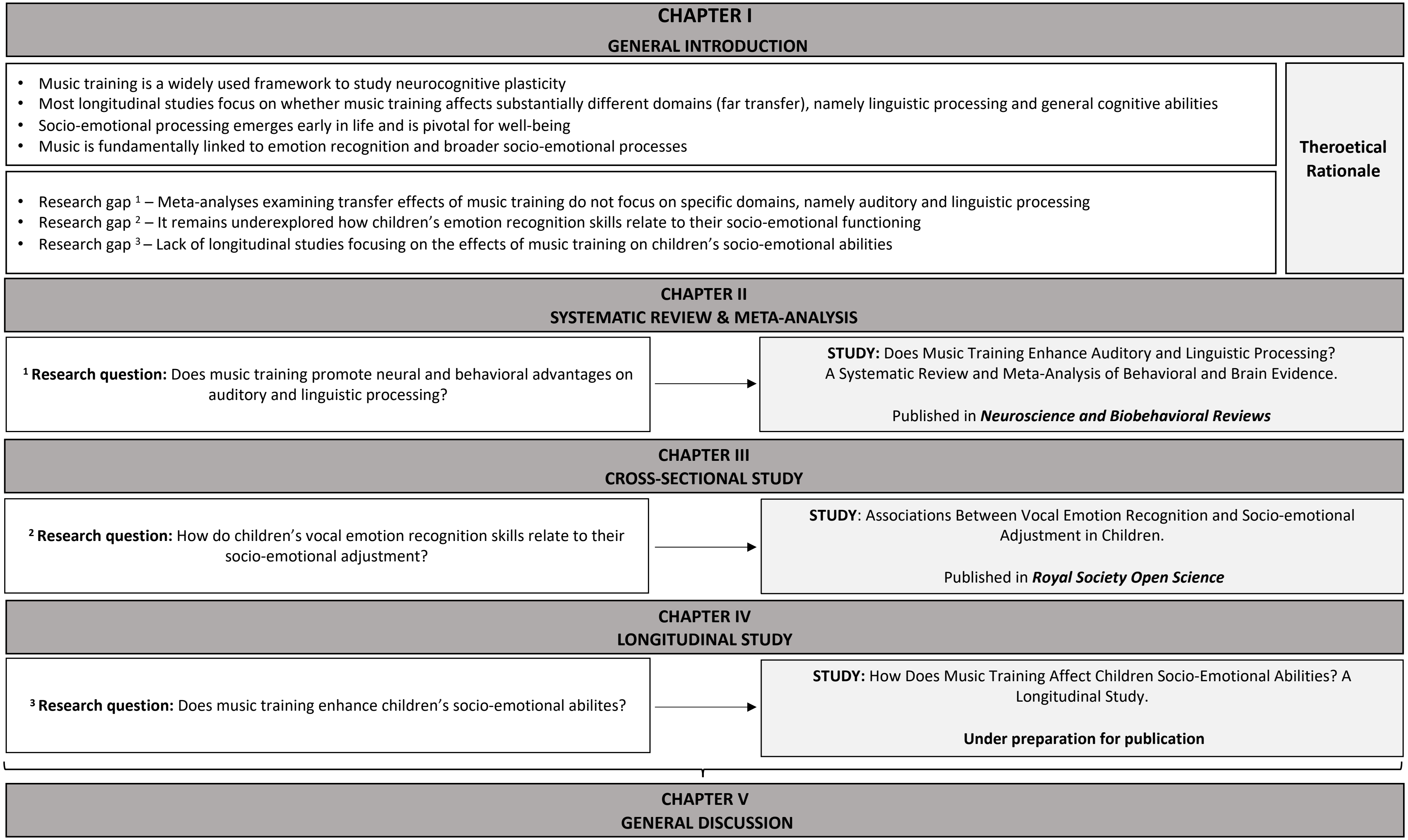
# CHAPTER I | GENERAL INTRODUCTION

# Overview

Music training is a widely used framework to study plasticity (Herholz & Zatorre, 2012). In cognitive neuroscience, plasticity refers to changes in the structure and function of the brain that can affect behavior and that are related to experience or training (Kolb, 2018). Research on the effects of music training has flourished over the past decades, with a growing number of longitudinal studies implementing music training programs, especially in childhood (Ilari, 2020). The possibility of transfer of learning from music training to other domains has received considerable attention (Bigand & Tillman, 2022). Transfer refers to the use of previously acquired knowledge and skills in new learning situations (Haskell, 2000). While transfer to domains tightly related to music is frequently overlooked (e.g., auditory processing - near transfer), most longitudinal studies focus on whether music training has benefits on substantially different domains (e.g., linguistic processing - far transfer). Language is one of the most extensively examined far transfer domains, due to its shared cognitive mechanisms with music and auditory processing (Patel, 2017). Despite many studies stating that music training has far transfer effects, the evidence is mixed (Sala & Gobet, 2020), and there is an ongoing debate about the existence of transfer through music training (Bigand & Tillman, 2022; Degé, 2021). A few meta-analyses have been conducted to inform this debate, but these mostly focus on general cognitive abilities and the findings are heterogeneous (e.g., Cooper, 2020; Román-Caballero et al., 2022). Comprehensive reviews that focus on specific domains, namely on auditory and linguistic processing, are scant. Furthermore, potential transfer to socio-emotional processing remains underinvestigated (Martins et al., 2021). Socio-emotional processing includes a wide range of abilities, from emotion recognition to broader aspects such as self-regulation (Edwards & Denham, 2018). These processes start to develop early in infancy, and emotion recognition is presumed to play an important role in socio-emotional adjustment (Besel & Yullie, 2010). However, little is known about the relationship between emotion recognition and broader aspects of socio-emotional processing. Moreover, most research on emotion recognition is focused on the visual domain, while the human voice is a major source of emotional information (Grandjean, 2021). Furthermore, voice and music are tightly related and constitute important mechanisms for socio-emotional processing (Lima & Castro, 2011). Therefore, understanding if music training benefits children's socio-emotional processing should be a central topic in the literature.

*This thesis examines whether music training improves auditory, linguistic, and socio-emotional processing.*

The work presented in this thesis is organized into five chapters, which are depicted in Figure 1. **Chapter I** provides a general introduction in which the theoretical rationale underlying the developed work is detailed. The following three chapters correspond to three studies that aim to address the identified research gaps. Specifically, **Chapter II** presents a systematic review and meta-analysis summarizing the findings of longitudinal studies assessing the neural and behavioral effects of music training on auditory and linguistic processing. **Chapter III** presents a cross-sectional study analyzing associations between children’s vocal emotion recognition and socio-emotional adjustment. **Chapter IV** describes a longitudinal study with children, inspecting the effects of music training on near transfer (auditory and motor skills) and far transfer domains, particularly socio-emotional abilities. The first two studies are published in international peer-reviewed journals, and the third is under preparation for publication. Finally, **Chapter V** provides a general discussion of the obtained findings.



**CHAPTER I**
**GENERAL INTRODUCTION**

- Music training is a widely used framework to study neurocognitive plasticity
- Most longitudinal studies focus on whether music training affects substantially different domains (far transfer), namely linguistic processing and general cognitive abilities
- Socio-emotional processing emerges early in life and is pivotal for well-being
- Music is fundamentally linked to emotion recognition and broader socio-emotional processes

- Research gap ¹ – Meta-analyses examining transfer effects of music training do not focus on specific domains, namely auditory and linguistic processing
- Research gap ² – It remains underexplored how children's emotion recognition skills relate to their socio-emotional functioning
- Research gap ³ – Lack of longitudinal studies focusing on the effects of music training on children's socio-emotional abilities

**Theroetical Rationale**

**CHAPTER II**
**SYSTEMATIC REVIEW & META-ANALYSIS**

¹ **Research question:** Does music training promote neural and behavioral advantages on auditory and linguistic processing?

**STUDY:** Does Music Training Enhance Auditory and Linguistic Processing? A Systematic Review and Meta-Analysis of Behavioral and Brain Evidence.

Published in ***Neuroscience and Biobehavioral Reviews***

**CHAPTER III**
**CROSS-SECTIONAL STUDY**

² **Research question:** How do children's vocal emotion recognition skills relate to their socio-emotional adjustment?

**STUDY**: Associations Between Vocal Emotion Recognition and Socio-emotional Adjustment in Children.

Published in ***Royal Society Open Science***

**CHAPTER IV**
**LONGITUDINAL STUDY**

³ **Research question:** Does music training enhance children's socio-emotional abilites?

**STUDY:** How Does Music Training Affect Children Socio-Emotional Abilities? A Longitudinal Study.

**Under preparation for publication**

**CHAPTER V**
**GENERAL DISCUSSION**

***Figure 1***. Roadmap of the present thesis.

## Plasticity through the lens of cognitive neuroscience

All living organisms change over time. Throughout our existence, we face many challenges that require behavioral adaptation. These adaptations allow us to thrive and promote the survival of our species (Darwin, 1859). A key aspect that underlies change and behavioral adaptation is plasticity. The psychologist William James first defined plasticity as the possession of a structure weak enough to yield to an influence but strong enough not to yield all at once (James et al., 1890). The nervous system is a great example of a structure that is prone to plasticity.

One of the most intriguing questions in psychology and neuroscience concerns how neuronal networks and behavior are changed by experience (e.g., Berlucchi & Buchtel, 2009; Bryck & Fisher, 2012). Brain plasticity reflects an interplay between experience, brain, and behavior: experience modifies brain structure and function, and behavioral changes reflect modifications in the brain. Behavior itself can also change brain activity (Kolb, 2009). In other words, if neuronal networks are changed by experience, then there should be some corresponding change in the behavior. Conversely, if behavior changes, then there should be some change in the neuronal circuitry that produced that behavior (Kolb, 2018).

Research on plasticity has been progressing rapidly over the last few decades, along with the development of cognitive neuroscience. Cognitive neuroscience is a branch of both psychology and neuroscience, thus merging these scientific fields (Bennett, 2008). The focus of cognitive neuroscience is on the neural underpinnings of changes in cognition and psychological functioning (Albright et al., 2000). Three types of plasticity coexist: experience-independent, experience-expectant, and experience-dependent (Kolb, 2018). Experience-independent plasticity is ubiquitous, unfolds over time, and does not rely on external sensory information (e.g., fetal brain development). Experience-expectant plasticity occurs during specific periods of development and relies on expected and widely available sensorial information, such as language (e.g., a child does not learn a language until hearing speech). Childhood is a stage marked by a rapid and intensive brain development, which generates windows of heightened plasticity (Fandakova & Hartley, 2020). These windows are defined as critical/sensitive periods. A critical period is the time when environmental input is required for the proper development of a specific brain circuit (i.e., experience-expectant plasticity), and a sensitive period is the time when experiences have the greatest impact on the brain (Hensch & Bilimoria, 2012). For instance, it is easier to learn a second language as a toddler than as an adult (e.g., DeKeyser, 2000; Kuhl, 2010). Finally, experience-dependent plasticity changes are unique to each person, reflecting individual experiences. It is a process of changing preexisting neuronal networks and/or giving rise to new ones, and it may occur at any stage of the life span (Kolb, 2018). The way the brain is shaped by these unique experiences is a topic of great interest in cognitive neuroscience (e.g., Mateos-Aparicio et al., 2019; Willis & Schaie, 2009).

Plasticity can be inferred from data collected at several levels of analysis, ranging from changes in single cells to behavioral expression. At the brain level, plasticity has been examined through different noninvasive imaging techniques (Carter & Shieh, 2015). For instance, structural brain imaging techniques, such as structural magnetic resonance imaging (sMRI) and diffusion-weighted MRI (DWI), produce data inferring on macro- and microstructural properties of the brain. These techniques allow us to inspect brain morphometry changes (Mills & Tamnes, 2014). At the behavioral level, plasticity is examined through performance on tasks that tackle different domains, such as language (e.g., reading), auditory processing (e.g., melody discrimination), and general cognitive abilities (e.g., reasoning; Solso et al., 2005). For instance, the Wechsler intelligence scales are commonly used tests to measure intelligence in adults, children, and preschoolers (Hebben & Milberg, 2009). In cognitive neuroscience, brain and behavioral measures are often combined (e.g., Correia et al., 2019; Hillman et al., 2008; Lima et al., 2021).

Plasticity has been investigated in a wide range of experimental paradigms and individuals (Bryck & Fisher, 2012). An exciting and growing avenue of plasticity research focuses on individuals with training on specific domains (Karbach & Schubert, 2013; Söderqvist et al., 2012). A pioneer study found that individuals who engaged in juggling training showed significant brain changes as compared with a control group, namely a transient increase in grey matter in regions associated with motion processing, which was linked to juggling performance (Draganski et al., 2004). Beyond the adult population, research on training-induced plasticity is being most often conducted with children (Tymofiyeva & Gaschler, 2021). Over the past two decades, there has been a widespread interest in the idea that music training is a useful framework for studying plasticity (e.g., Herholz & Zatorre, 2012; Moreno & Bidelman, 2014; Wan & Schlaug, 2010). Why should music interest cognitive neuroscience as a relevant object of study?

## Music and plasticity

Music has been present as long as mankind exists (Mehr et al., 2019). It is one of the most universal ways of expression, and the first evidence of known instruments built extends back at least 35,000 years ago (flutes made of vulture bones; Koelsch, 2011). The question of what are the origins of music emerges often, being a matter of debate (Wallin et al., 2001). Music has often been assumed to be a result of evolutionary processes, for instance, for reproductive benefits (adaptative theories - Cross, 2003; Darwin, 1871). By contrast, other theories describe music as a mere cultural artifact (non-adaptative theories - Marcus, 2012; Patel, 2010). More recently, human musicality has been characterized as an interplay of cultural invention and biological evolution (Patel, 2021). That is, the concept of gene-culture coevolution posits that music may have started as a cultural invention that served adaptative purposes, such as promoting social bonds. The proliferation of musical behaviors, such as coordinated group rhythmic vocalizations, might have led to the appearance of a new music-related genetic trait (Podlipniak, 2017). In fact, different musical aspects develop without explicit training and are culturally widespread, suggesting that musical behaviors are guided by predispositions (Bigand & Poulin-Charronnat, 2006; Peretz, 2002). For example, newborn infants show beat perception skills (Winkler et al., 2009), and the ability to carry a tune is widespread (with just a few exceptions, such as tone-deaf individuals; Dalla Bella et al., 2007). There has been an exponential increase in studies of music processing and cognition (e.g., Chorna et al., 2019; Levitin & Tirovolas, 2009; Peretz & Zatorre, 2005). These studies tackle aspects ranging from music listening (e.g., Schäfer et al., 2013), learning (e.g., Hille & Schupp, 2015), to performance (e.g., Mornel & Wulf, 2019). The increased use of neuroimaging methods to inform theories about the brain basis for musical behaviors was an important paradigm shift (Peretz & Zatorre, 2003), as it allowed remarkable advances in terms of the neurocognitive (e.g., Wilson et al., 2009), and the genetic bases of music cognition (e.g., Tan et al., 2014), as well as the development of music abilities (e.g., Peretz, 2002). There are several ongoing discussions around the latter (e.g., Kragness et al., 2021; Swaminathan & Schellenberg, 2021).

## Nature versus nurture

The extent to which musical abilities are determined by preexisting differences (nature) or by music practice (nurture) has been intensely debated. On the one hand, proponents of the nature perspective argue that music abilities are mostly influenced by genetics. In this vein, several studies show that music skills are highly genetic, such as auditory-discrimination skills (Ullén et al., 2014), and studies with monozygotic twins have found that associations between music practice and music abilities were predominantly genetic (e.g., Mosing et al., 2014). On the other hand, advocates of the nurture perspective argue that music abilities are developed through training, regardless of the genetic background (e.g., Ericsson, 2014). This idea is corroborated by several studies showing that long-term deliberate music practice is accompanied by the acquisition of new, domain-specific skills (Platz et al., 2014). More recent research has shown that musical abilities are diverse and influenced by an interplay between genetic predisposition and formal music instruction, as well as other factors such as socio-economic status, personality, and informal listening experiences (e.g., Correia et al., 2022; Hambrick et al., 2015; Ullén et al., 2016). For example, musical abilities were found to be positively associated with multiple factors beyond formal instruction, such as cognitive ability and personality traits, namely openness-to-experience (Swaminathan & Schellenberg, 2018).

In cognitive neuroscience, there are typically two different design types to examine the effects of music training: cross-sectional and longitudinal designs. Both have been used to inform the nature versus nurture debate (Olszewska et al., 2021). In cross-sectional designs, studies usually inspect brain and behavioral differences between musicians and non-musicians (e.g., Bianchi et al., 2017; Gaser & Schlaug, 2003). The underlying rationale is that extensive music practice is related to plasticity, as it is accompanied by the acquisition of domain-specific cognitive and sensorimotor skills (Herholz & Zatorre, 2012; Patel, 2021). In the cross-sectional literature, a variety of music expertise criteria is used to distinguish between musicians and non-musicians. Nonetheless, there is a consensus in this literature that a musician has at least six years of instrumental training (Zhang et al., 2020). These cross-sectional studies provide important insights into music cognition but often presume that the differences found are caused by musical experience. However, it is doubtful to assume that music training is the causal agent (Schellenberg, 2020). Put differently, it is uncertain whether the differences stem from the musicians´ deliberate practice over the years (i.e., experience-dependent plasticity), or if innate predispositions play a role. For example, individual differences in musical abilities may determine who enrolls in music lessons (Swaminathan & Schellenberg, 2018). Studies employing longitudinal designs with random assignment of participants can provide a more direct examination of the contributions of nature and nurture, because they account for preexisting differences (Ilari, 2020; Schellenberg, 2020).

One of the pioneering studies gave rise to the so-called Mozart effect (Rauscher et al., 1993). This study aimed to test the hypothesis that music listening and spatial task performance are causally related. A group of subjects listened to 10 minutes of a Mozart's sonata (experimental group), another group listened to relaxation instructions (active control), and a third one was in silence (passive control). For all participants, spatial reasoning skills were assessed previously and after the respective listening session (or silence). The authors concluded that the mean spatial IQ scores were significantly higher after listening to Mozart, as compared to the other two groups (Rauscher et al., 1993). In the following years, many studies failed to reproduce this effect, however, concluding that there is no significant evidence supporting the claim that passive exposure to Mozart´s music can enhance spatial IQ (e.g., McKelvie & Low, 2002; Newman et al., 1995). Beyond passive listening paradigms, in the following years, several studies have been implementing music training programs (e.g., Hennessy et al., 2021; Martins et al., 2018; Moreno et al., 2015). These studies assess participants before and after a music training program and compare them to a control group that does nothing (passive control), and/or to an active control group that takes part in a different form of training (e.g., sports). The inclusion of active control groups has been increasing in the literature, since it minimizes the possibility that music-related benefits stem from non-musical aspects of the training, such as the time spent in a structured learning environment. Most of these studies are with children, as music lessons typically start early in life, within educational contexts and community settings (Habibi et al., 2022; Ilari, 2020). Longitudinal studies can provide invaluable insights into the effects of music training and training-induced plasticity, but implementing them can be difficult, as they require a significant number of resources and constraints over a relatively long period of time (VanderWeele et al., 2020). For instance, longitudinal studies typically require substantial financial resources to cover aspects like the implementation of the training programs, and retaining participants over a long period of time can be a major challenge (e.g., participants may relocate or lose interest). Therefore, it is common to find suboptimal designs. For example, short training periods and lack of random assignment of participants to the experimental groups (Schellenberg, 2020). Random assignment is an important methodological feature that reduces the possibility of self-selection effects (e.g., motivational differences), as it randomly allocates participants to the respective experimental groups before training. Therefore, while randomized controlled studies are the gold standard of scientific inquiry, these studies are difficult to conduct, especially within educational contexts (Ilari, 2020). Along with the fact that design features vary across these studies, one longstanding open question is whether and how music training transfers to other cognitive domains.

## Transfer of learning

Transfer of learning refers to how previously acquired knowledge and skills affects new learning situations (Haskell, 2000). There are multiple ways to characterize transfer of learning. A primary distinction is between negative and positive transfer: negative transfer occurs when learning in one context negatively influences performance in another. For instance, switching from driving a manual transmission vehicle to an automatic one may hinder the task. On the other hand, positive transfer occurs when learning in one context improves performance in another context. For instance, a person who is driving a scooter for the first time may find this experience like the experience of driving a motorbike (Willis & Schaie, 2009). Furthermore, transfer to domains that are highly similar to the original learning experience is called near transfer, while transfer to domains that differ significantly from the situation of the original learning is called far transfer (Barnett & Ceci, 2002).

There has been a widespread interest in studying transfer of learning induced by specific training programs (e.g., nonverbal reasoning - Bergman et al., 2011; working memory – Loosli et al., 2011). The greatest effects of training are observed on tasks that most closely mirror the trained task (near transfer). For example, positive effects of working memory training on performance in working memory tasks (Minear et al., 2016). On the other hand, there is controversy about the existence of far transfer (Degé, 2021; Sala & Gobet, 2017). Indeed, far transfer is difficult to induce and has been raised the possibility that it only occurs through demanding multi-skills training (Miendlarzewska & Trost, 2014). For instance, training in action video games requires a wide range of skills simultaneously, such as visuo-spatial perception and attentional control (Green & Bavelier, 2012).

Music training is an excellent framework to investigate the existence of transfer of learning, in line with the idea of its potential to induce plasticity (Degé, 2021; Mosing et al., 2016), and allied to the fact that it is a demanding, yet joyful activity (Bigand & Tillmann, 2022). Thus, a large body of research has been focusing on this topic (e.g., Schellenberg, 2004; Moreno et al., 2011). Some skills are recognized as near transfer domains of music training, such as the processing of fine-grained acoustic features, and fine motor skills (Kraus & Chandrasekaran, 2010; Miendlarzewska & Trost, 2014). Accordingly, some studies have found positive effects of music training on these domains (e.g., Hyde et al., 2009; Martins et al., 2018), as well as evidence of cortical and subcortical plasticity related to these domains (e.g., Herholz & Zatorre, 2012; Hyde et al., 2009; Pantev & Herholz, 2011). For example, Hyde et al. (2009) found that music training increased cortical volume in the right primary auditory region in children, and this increase was associated to behavioral performance in a melody/rhythm discrimination task. However, other studies have found null near transfer effects of music training, such as considering changes in volume and cortical thickness of auditory cortices in children (Habibi et al., 2018), and considering behavioral performance in a rhythm perception task (Ilari et al., 2016).

The possibility of far transfer effects of music training has received much more interest, as compared to near transfer. This excitement comes from the potential associated theoretical and practical implications: understanding far transfer sheds light on the generalizability and mechanisms of learning (Willis & Schaie, 2009), which can help to enhance the effectiveness of clinical and educational practices, such as teaching methods to optimize learning, and the development of rehabilitation programs to improve functional abilities (e.g., Hajian, 2019; Nejati, 2020). Therefore, most studies that examine the effects of music training focus on far transfer to a wide variety of domain-general abilities, such as intelligence (e.g., Schellenberg, 2004) and executive functions (e.g., Rodriguez-Gomez & Talero-Gutiérrez, 2022). While some studies have found positive effects of music training on these domain-general abilities (e.g., Schellenberg, 2004), others have found null results (e.g., Mehr et al., 2013). A few reviews examining the effects of music training on children's domain-general abilities have been conducted with the purpose of clarifying these disparate findings (e.g., Cooper, 2020; Román-Caballero et al., 2022). However, the findings are heterogeneous (Bigand & Tillmann, 2022; Sala & Gobet, 2020). For example, a meta-analysis found significant music training effects, but only for studies with passive control groups, as opposed to those with active control groups (Sala & Gobet, 2017). On the other hand, a subsequent meta-analysis also found significant music training effects, but not a significant influence of the type of control group (Román-Caballero et al., 2022). Beyond general cognition, some longitudinal studies focus on specific domains, such as language abilities (e.g., Moreno et al., 2011; Vidal et al., 2020). In fact, language is one of the far transfer domains most extensively examined in the music training literature. These effects are examined in a wide range of linguistic domains, such as reading (e.g., Carioti et al., 2019), speech-in-noise perception (e.g., Hennessy et al., 2021), and prosody perception (e.g., Moreno et al., 2009). Why are researchers interested in the effects of music training on language?

## Auditory and linguistic processing

Music and language share profound similarities (McMullen & Saffran, 2004). The similarities range from their origins to acoustics, structure, and even their use in social situations (Oesch, 2019). For example, many authors argue for a common evolutionary genesis for both language and music (Masataka, 2009; Molino, 2000). In terms of their structure, both are rule-governed and rely on a hierarchical organization of elements (e.g., from sounds/phonemes to melodies/sentences), and in terms of their acoustics, pitch carries the melody in music, and it also underlies prosody in speech (Tervaniemi et al., 2022). Importantly, music and language overlap in the recruitment of the auditory pathways (Zatorre et al., 2002). When a sound reaches the eardrum, it sets into motion a complex cascade of mechanical, chemical, and neural events, beginning in the cochlea and being progressively transformed in the auditory brainstem. This cascade of events rapidly results in a percept (Koelsch, 2011). Auditory processing sets the stage for complex human behaviors, such as understanding language and playing a musical instrument (Kraus & Banai, 2007). Moreover, the auditory system is malleable to experience, namely to music and language (Kraus et al., 2009). For example, we are born with the ability to discriminate all possible speech sounds, but throughout development this ability is progressively reconfigured to discriminate sounds from our native language, reducing our sensitivity to the sounds of other languages (Kuhl, 2004; Kraus & Banai, 2007). In the same vein, musicians exhibit enhanced auditory cortical representations for musical timbres of the instrument they play, as compared to timbres from other instruments that they have not been trained (Kraus & Banai, 2007; Pantev et al., 2001; Peretz & Zatorre, 2005). Accordingly, several longitudinal studies have found training-related plasticity in auditory processing following both language (e.g., Song et al., 2012; Tervaniemi et al., 2022) and music training (e.g., Hennessy et al., 2021; Schneider et al., 2022). On the other hand, musicians' auditory brainstem responses to linguistic pitch were stronger, as compared to non-musicians (Kraus & Chandrasekaran, 2010), and inherent auditory skills related to music abilities are associated with enhanced encoding of speech (Mankel & Bidelman, 2018). Notwithstanding, findings from individual studies vary. That is, some studies found advantages of musicians in speech perception (e.g., Mankel & Bidelman, 2018; Parbery-Clark et al., 2009), but other studies found that speech perception skills are similar for musicians and non-musicians (e.g., Boebinger et al., 2015; Madsen et al., 2019). Systematic reviews and meta-analyses focused on auditory and linguistic processing would be important to clarify whether music training transfers to these domains. However, such reviews are scant.

The shared mechanisms between music and language have been extensively discussed (e.g., Kraus & Slater, 2015; Patel, 2003; Patel, 2017). The OPERA hypothesis is a well-known conceptual framework on this matter of shared mechanisms between music and language (Patel, 2011; Patel, 2012; Patel, 2014). This theory proposes that music training enhances speech and language processing because it places higher demands on shared neuronal networks, requires repetition and attention, and elicits emotional rewards. That is, there are five conditions necessary for music training to induce plasticity in linguistic networks: (1) music engages sensory and cognitive networks that overlap with those engaged by speech (e.g., auditory working memory); (2) music requires more processing precision because it places higher demands on these networks than speech; music activities occur in a context that involves (3) extensive repetition, (4) focused attention, and (5) positive emotion.

## Socio-emotional processing

Socio-emotional processing is a multidimensional concept that includes the ability to recognize emotions, regulate our own behavior, and establish relationships, among other processes (Edwards & Denham, 2018; Denham et al., 2015). Emotion recognition refers to the ability to encode and interpret the wide range of emotional signals that coexist during social interactions, such as facial, body, and vocal cues (Ferretti & Papaleo, 2019; Lavan & Lima, 2014). Thus, emotion recognition plays a crucial role in our interactions (Chronaki et al., 2015). For instance, identifying that someone's tone of voice is sad might indicate that the person needs help, or identifying a fearful facial expression might alert to a potential danger. On the other hand, abnormalities in emotion recognition are distinctive features in several disorders linked to social interaction deficits, such as autism spectrum disorder and schizophrenia (Ferretti & Papaleo, 2019). Most research on emotion recognition focusses on facial expressions (e.g., Lawrence et al., 2015; Leppänen & Nelson, 2006). Nonetheless, most of the time we are producing, listening to, and interpreting voices. Therefore, the human voice is a major source of emotional information (Ghazanfar & Rendall, 2008; Latinus & Belin, 2011). In addition to linguistic information, voices convey varied nonverbal emotional cues, which cannot be easily ignored, even when they are not task-relevant (Liu et al., 2012). Nonverbal vocal cues can be divided into two domains: inflections in speech (i.e., emotional prosody), and purely nonverbal vocalizations, such as laughter and crying (e.g., Grandjean, 2021). Nonverbal vocalizations are an auditory equivalent of facial expressions (Belin et al., 2004). Emotional prosody refers to suprasegmental and segmental modifications in spoken language during emotional episodes. Prosodic cues include pitch, loudness, *tempo*, rhythm, and timbre, as embedded in linguistic content (Grandjean et al., 2006; Schirmer & Kotz, 2006).

The development of emotion recognition has been proposed to reflect experience-expectant plasticity, as emotion-processing brain circuits mature at developmental stages and are experience-driven (Leppänen & Nelson, 2009). For instance, several studies have shown that infants develop a perceptual narrowing, becoming more specialized in processing emotional information that is most relevant and frequent in their environment. Specifically, human infants that were exposed to non-native facial expressions showed a facilitated discrimination of monkey faces at 9 months of age, a time when the ability to discriminate facial expressions from other species is lost, due to the infant´s face representation system becoming increasingly restricted to faces with which infants are most familiar (Pascalis et al., 2005). Emotion recognition abilities start to develop early in infancy, gradually improving over childhood and declining with aging (Ruffman et al., 2023; Sauter et al., 2013). For example, newborns can discriminate between happy and sad facial expressions (e.g., Farroni et al., 2007; Field et al., 1982). Moreover, infants can discriminate emotional expressions in prosodic cues (Flom & Bahrick, 2007), as well as in purely nonverbal vocalizations (Soderstrom et al., 2017). By the age of 5 years, children are proficient at identifying several emotions, such as anger, sadness, fear, disgust, and happiness, in facial expressions (Ruffman et al., 2023; Russel & Widen, 2002), nonverbal vocalizations, and emotional prosody (Sauter et al., 2013). Although it is not well established when emotion recognition skills peak, several studies show that older adults are less accurate than younger adults in emotion recognition, both in facial and vocal cues (Isaacowitz et al., 2007; Mill et al., 2009).

Emotion recognition sets the stage for a range of other crucial and broader socio-emotional processes, such as self-regulation, empathy, and emotion comprehension (Ferretti & Papaleo, 2019; Frith & Frith, 2007). For example, when someone can identify their own emotions, engaging in effective self-regulation strategies could be more likely, such as seeking support (Grewal et al., 2006). Moreover, being able to recognize others' emotions may increase the likelihood of responding with empathy and support (Besel & Yullie, 2010). On the other hand, being able to respond with empathy and support may also offer opportunities for interactions and for developing emotion recognition skills (Besel, 2006). However, research on associations between emotion recognition and broader socio-emotional functioning is scarce and mostly focuses on the visual domain (i.e., facial expressions; Russel & Widen, 2002), or more basic acoustic, perceptual, and neurocognitive aspects of vocal emotions (e.g., Grandjean, 2021; Schirmer & Kotz, 2006). Nonetheless, understanding how vocal emotion recognition skills relates to other socio-emotional processes is of great interest. For example, childhood is a pivotal period for socio-emotional development, and understanding whether vocal emotion recognition plays a role on everyday social interactions might inform interventions aimed at fostering socio-emotional skills in childhood (Edwards & Denham, 2018; Denham et al., 2015).

## Music and socio-emotional processing

Several theories posit that music evolved to serve socio-emotional purposes, such as group cohesion (e.g., Oesch, 2019), soothing infants (e.g., Mehr & Krasnow, 2017), and social bonding, which encompasses a wide range of phenomena like prosociality and synchronization (Savage et al., 2021; Tarr et al., 2014). Associations between music and emotion is becoming increasingly popular as a research topic (Eerola & Vuoskoski, 2013; Juslin & Zentner, 2002). Most research on this matter focuses on music-evoked emotions, namely on how these are expressed and perceived in music (Swaminathan & Schellenberg, 2015), as well as the underlying neuronal mechanisms (Koelsch, 2020).

Music represents powerful means of emotional expressiveness (Pankseep, 2009). For example, caregivers constantly use musical cues to communicate emotions (Trehub, 2003), and play songs to engage and soothe infants (Cirelli et al., 2020). Moreover, listeners quickly recognize the emotions being conveyed by music and show high levels of agreement about the emotions that are being expressed through music, regardless of their degree of music expertise (Juslin & Laukka, 2004). Nonetheless, musical expertise is associated with enhanced sensitivity to emotions evoked by music (Castro & Lima, 2014; Lima & Castro, 2011). Developmentally, children as young as 5 years old can recognize different emotions evoked by music at above-chance levels (Stachó et al., 2013), and 11 years old children are as accurate as adults in this task (Hunter et al., 2011). Perceived and felt emotions through music tend to be associated with each other (Swaminathan & Schellenberg, 2015). Beyond emotional expressiveness, there is extensive research showing that music induces emotions (Scherer, 2004). For example, listening to sad music might induce a negative emotional state (Egermann & McAdams, 2012), and music has been shown to engage several brain networks related to emotional processing and reward (e.g., amygdala, auditory cortex, and anterior cingulate cortex), underlining that listeners respond affectively to music (Blood & Zatorre, 2001; Koelsch, 2020). Furthermore, music listening is used to regulate emotions and mood (e.g., relieve anxiety, Lonsdale & North, 2011), and has been reported to be the most important personal use of music across different cultures (Boer & Fischer, 2012; Koelsch, 2020). The question how music aptitude relates to socio-emotional skills remains unexplored.

Considering emotion recognition, most studies compare musicians' and non-musicians' abilities in their ability to recognize vocal emotions (Martins et al., 2021). Some theories propose that music evolved from ancestral vocalizations, serving adaptative purposes like territorial defense (Mehr et al., 2021). For instance, angry speech is characterized by high vocal intensity, and angry sounding music tends to be loud (Swaminathan & Schellenberg, 2015). Furthermore, research suggests that the more melodies resemble speech in specific acoustic characteristics (e.g., pitch-interval distribution), the more these melodies are preferred by listeners (measured by melodicity ratings; Beauvois, 2007).

Some cross-sectional studies have found improved emotion recognition in musicians across different prosodic emotions in sentences (e.g., Lima & Castro, 2011; Toh et al., 2023), and non-verbal vocalizations (e.g., Correia et al., 2022; Parsons et al., 2014), when compared to non-musicians. Nonetheless, there is also null evidence for an advantage of musicians in emotion recognition. For example, musicians and non-musicians were found to be equally adept in recognizing emotions in emotional prosody (Trimmer & Cuddy, 2008). Fewer studies focus on emotion recognition in facial expressions, and the findings overall show that there is no advantage for musicians in this skill (e.g., Correia et al., 2022). Considering other socio-emotional processes beyond emotion recognition, some studies have found heightened skills in musicians, such as emotional regulation (Athali & Kilis, 2020) and self-reported emotional awareness (Ros-Morente et al., 2019). In children, those who spent more time in musical activities showed more instrumental helping (i.e., assisting another person to achieve an action-oriented goal), and those who received higher prosocial ratings from their parents were reported to be more musically active (Ilari et al., 2020).

Although it is reasonable to hypothesize that music training could be predictive of improved socio-emotional skills, the evidence coming from longitudinal studies is scarce and mostly focus on childhood (Martins et al., 2021). Considering emotion recognition, one study has found that children who received music training showed improved emotional prosody recognition, as compared to a passive control group, but not as compared to an active control group that received drama training (Thompson et al., 2004). The fact that the music training group did not significantly differ from the drama training suggests that the observed effects in emotional prosody recognition do not reflect a specific advantage of music training. Furthermore, children were tested only once on the emotional prosody task (after training), thus, these findings do not allow to establish causality. As for broader aspects of socio-emotional processing, the few available studies yield mixed findings. For example, Schellenberg et al. (2015) found positive effects of music training in children self-reported prosocial skills and sympathy, but only for those who had lower scores on these measures before training. On the other hand, some studies found null effects of music training on prosocial skills, such as sharing and helping (Alemán et al., 2017; Ilari et al., 2021). Moreover, positive effects of music training were found in emotion comprehension skills, but these effects either disappeared when IQ scores were held constant (Schellenberg & Mankarious, 2012) or were found only in a specific age range (Boucher et al., 2021). Therefore, the effects of music training on children's socio-emotional skills remain to be determined. Examining whether music training promotes transfer to children's socio-emotional skills would allow to inform debates on transfer of learning and plasticity (e.g., Wan & Schlaug, 2010), and the use of music as a tool in clinical and educational contexts (e.g., Stegemann et al., 2009; Váradi, 2022).

## The present thesis

In the sections, we have reviewed research focusing on several key points that lay the foundation for the empirical part of this thesis. In the following paragraphs, we briefly outline these key points and the three studies that were conducted, including the specific goals, hypotheses, and research methods.

First, we introduced the notion of music training as a well-known framework to investigate plasticity and transfer of learning (Herholz & Zatorre, 2012). We highlighted the ongoing debate on the extent to which music abilities are determined by preexisting differences (nature) or by music practice (nurture), and the type of approaches typically employed to inform this debate (cross-sectional and longitudinal designs).Studies employing longitudinal designs with random assignment of participants are presumed to provide a more direct examination of the contributions of nature and nurture (Schellenberg, 2020). While transfer to domains tightly related to music is frequently overlooked (e.g., auditory processing - near transfer), most longitudinal studies focus on the possibility that music training benefits substantially different domains from music (e.g., linguistic processing - far transfer). We described how the available evidence on this topic is mixed and emphasized the ongoing debate on the existence of transfer from music training (Bigand & Tillman, 2022).

The first goal of this thesis was to conduct a systematic review and meta-analysis to inform the debate on the existence of transfer through music training. As we previously underlined, a few meta-analyses focusing on music training effects have been conducted in recent years, but these mostly focus on general cognitive abilities (far transfer) and the findings are heterogeneous (e.g., Cooper, 2020; Román-Caballero et al., 2022). Comprehensive reviews that focus on transfer effects of music training to specific domains, namely auditory and linguistic processing, are scant. Examining near transfer is important to inform theories of plasticity and transfer. Moreover, a comprehensive analysis of music training effects on linguistic skills was lacking. Because language is extensively examined in music training studies (e.g., Tervaniemi et al., 2022), evaluating this domain informs debates on far transfer, both from behavioral and brain perspectives. **Chapter II** presents a systematic review and meta-analysis summarizing the findings of longitudinal studies assessing the neuronal and behavioral effects of music training on auditory and linguistic processing.

*Does music training enhance auditory and linguistic processing?*
*A systematic review and meta-analysis of behavioral and brain evidence.*

Sixty-two longitudinal studies were included in this study. Behavioral data were summarized through multivariate meta-analytic models and brain data through a narrative synthesis. In the meta-analysis, we also asked whether training effects depend on the outcome measure (auditory vs. linguistic skills), type of music training (instrumental vs. non-instrumental), participants' age, publication year, aspects of the study design (type of control group, randomization, risk of bias), aspects of the training programs (total months of training, hours per week), and baseline differences. We also assessed the presence of publication bias.

Following the ongoing debate on the existence of transfer effects of music training, another important key point outlined is that the potential transfer of music training to socio-emotional processing remains underinvestigated (Martins et al., 2020). Socio-emotional processing is a multi-dimensional construct that includes a wide range of abilities, spanning from emotion recognition skills to broader aspects of socio-emotional functioning (e.g., prosociality). We focused on emotion recognition skills, as these start to develop early in life and are presumed to play an important role in socio-emotional adjustment (Besel & Yullie, 2010). However, evidence for this assumption remains scarce. Furthermore, we called attention to the fact that although most research on emotion recognition is focused on the visual domain (i.e., facial expressions), the human voice is a pivotal source of emotional information (Grandjean, 2021). We described two vocal communication channels: emotional prosody and non-verbal vocalizations. Research on vocal emotions is primarily focused on its´ basic, acoustic, perceptual, and neurocognitive aspects (e.g., Schirmer & Kotz, 2006).

The second goal of this thesis was to shed light on possible associations between children's vocal emotion recognition skills and socio-emotional adjustment. Children, like adults, make a significant use of vocal emotions, and it is important to understand how this relates to their socio-emotional adjustment, given that childhood is a crucial period for socio-emotional development (Edwards & Denham, 2018). Moreover, examining associations between vocal emotion recognition skills and socio-emotional functioning might contribute to debates on the functional role of vocal emotional expressions, and might even inform interventions aimed at fostering socio-emotional skills in childhood. **Chapter III** presents a cross-sectional study analyzing associations between children's vocal emotion recognition and socio-emotional adjustment.

### *Associations between vocal emotion recognition and socio-emotional adjustment in children.*

The sample included 141 6- to 8-year-old children. We hypothesized that higher vocal emotion recognition accuracy would be associated with better socio-emotional functioning. If children with a greater ability to recognize emotions from vocal cues are better at interpreting social information, this could favour everyday socio-emotional functioning outcomes (e.g., sociability). Children completed forced-choice emotion recognition tasks focused on the two types of vocal emotional cues (emotional prosody and non-verbal vocalizations). Additionally, children also completed an emotion recognition task that focused on facial expressions. The inclusion of this task allowed us to understand if associations between emotion recognition and social-emotional functioning are specific to the auditory domain, or are similarly seen across sensory modalities. The teachers were asked to evaluate children's socio-emotional adjustment using a multidimensional questionnaire that allows for an analysis of several socio-emotional dimensions. Moreover, we tested if results remained significant when individual differences in age, sex, cognitive ability, and parental education are accounted for.

What about the possible effects of music training on socio-emotional skills? In the general introduction we described how music and socio-emotional processing are fundamentally linked (Swaminathan & Schellenberg, 2015). Several theories posit that music evolved to serve socio-emotional purposes (Savage et al., 2021), and that music evolved from ancestral vocalizations (Mehr et al., 2021). Indeed, some cross-sectional studies have found improved vocal emotion recognition in musicians (as compared to non-musicians), but other studies did not find significant advantages of musicians in these emotion recognition skills. We highlighted that longitudinal studies examining effects of music training on socio-emotional skills are scarce. Furthermore, we called attention to the fact that from the few available longitudinal studies on this topic, the results found are mixed and do not allow to reach decisive conclusions.

The third goal of this thesis was to examine whether music training benefits children's socio-emotional processing. Examining possible effects of music training on children's socio-emotional skills is important to clarify the ongoing debate on the existence of far transfer effects of music training, as well as to inform transfer of learning and plasticity theories. Moreover, investigating this research topic might inform music interventions aimed at fostering socio-emotional skills. **Chapter IV** describes a longitudinal study inspecting the effects of music training on children's socio-emotional abilities.

*How does music training affect children socio-emotional abilities?*
*A longitudinal study.*

The sample included 110 6- to 8-year-old children (the same children that participated in the cross-sectional study). This study included pre-test, training, and pos-test phases, in three conditions: an experimental music training condition (Orff-based training, *n* = 37), an active control condition (basketball training, *n* = 40), and a passive control condition (no training, *n* = 33). The training programs were conducted over two school years (2019-2020, 2020-2021). Children were assessed before and after training regarding auditory and motor skills (near transfer), as well as a wide range of far transfer measures: emotion recognition in auditory (emotional prosody, non-verbal vocalizations) and visual modalities (faces), authenticity recognition (laughter and crying), and broader aspects of socio-emotional abilities (empathy, emotion comprehension, and social functioning). Moreover, measures of global cognition and executive functions were included. As previously mentioned, examining near transfer is important to inform theories of plasticity and transfer. We hypothesized that music training would improve auditory and motor skills, considering that these are critical skills during music training (Zatorre et al., 2007). Given the close link between music and socio-emotional processing, we also expected that music training would enhance socio-emotional skills. We analyzed the longitudinal effects of training by using mixed effects modelling The subsequent chapters will delve into each study in detail.

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# CHAPTER II | SYSTEMATIC REVIEW & META-ANALYSIS[1]

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[1] This chapter is published in ***Neuroscience & Biobehavioral Reviews***:

Neves, L., Correia, A. I., Castro, S. L., Martins, D., & Lima, C. F. (2022). Does music training enhance auditory and linguistic processing? A systematic review and meta-analysis of behavioral and brain evidence. *Neuroscience & Biobehavioral Reviews*, 104777.

# Abstract

It is often claimed that music training improves auditory and linguistic skills. Results of individual studies are mixed, however, and most evidence is correlational, precluding inferences of causation. Here, we evaluated data from 62 longitudinal studies that examined whether music training programs affect behavioral and brain measures of auditory and linguistic processing (*N* = 3928). For the behavioral data, a multivariate meta-analysis revealed a small positive effect of music training on both auditory and linguistic measures, regardless of the type of assignment (random vs. non-random), training (instrumental vs. non-instrumental), and control group (active vs. passive). The trim-and-fill method provided suggestive evidence of publication bias, but meta-regression methods (PET-PEESE) did not. For the brain data, a narrative synthesis also documented benefits of music training, namely for measures of auditory processing and for measures of speech and prosody processing. Thus, the available literature provides evidence that music training produces small neurobehavioral enhancements in auditory and linguistic processing, although future studies are needed to confirm that such enhancements are not due to publication bias.

*Keywords:* Music training, Longitudinal, Auditory processing, Linguistic processing, Plasticity, Transfer, Neuroimaging, Electrophysiology, Meta-analysis, Systematic review, Narrative Synthesis

# 1. Introduction

Understanding how experience changes our brain and behavior is a fundamental question in cognitive neuroscience. This phenomenon is referred to as *plasticity*, and research on this topic often focus on individuals with training on specific domains, such as juggling (Draganski et al., 2004), spatial navigation (e.g., Woollett & Maguire, 2011), and bilingualism (e.g., Van de Putte et al., 2018). Over the past two decades, there has been a widespread interest in the idea that music training might be a useful framework for studying brain and behavioral plasticity (e.g., Herholz & Zatorre, 2012; Moreno and Bidelman, 2014; Münte et al., 2002; Wan & Schlaug, 2010). This idea remains contentious, though (Sala and Gobet, 2020, Swaminathan & Schellenberg, 2021).

Many correlational studies report differences between musicians and musically untrained individuals in brain structure and function (e.g., Bianchi et al., 2017; Gaser and Schlaug, 2003; Krause et al., 2010; Magne et al., 2006), and associations between music training and enhanced performance in abilities such as executive functioning (e.g., Zuk et al., 2014), speech-in-noise perception (e.g., Parbery-Clark et al., 2009), and emotional prosody recognition (e.g., Lima & Castro, 2011). It is typically presumed that the benefits are *caused* by musical experience (Schellenberg, 2020a), and therefore reflect plasticity, but correlational designs cannot exclude the possibility that the benefits are the cause rather than the consequence of training. This possibility is plausible because musically trained and untrained individuals differ in many ways in addition to training. Pre-existing cognitive, personality and socioeconomic factors might determine who takes music lessons (Schellenberg, 2020b), and twin studies show that genetic factors account for many aspects of musical behavior and achievement, including propensity for music practice, musical abilities, choice of musical instrument and genre, and associations between music practice and musical abilities (McPherson, 2016, Mosing et al., 2014, Mosing and Ullén, 2018, Ullén et al., 2016).

A growing number of studies implement longitudinal designs to address the issue of causality. Participants are assessed before and after a music training program, and compared to a control group that either does nothing – passive control (e.g., Hyde et al., 2009; James et al., 2020) – or takes part in a different form of training such as painting – active control (e.g., Martins et al., 2018; Moreno et al., 2009). Active control groups and random assignment to the groups allow for stronger inferences of causality (Schellenberg, 2020b). Active control groups minimize the possibility that music-related benefits stem from nonmusical aspects of the training (e.g., time spent in a learning environment), and random assignment minimizes self-selection effects (e.g., pre-existing motivational differences). Design features vary across studies, but a commonly asked question is whether music training produces *transfer* effects, i.e., has consequences that generalize beyond the trained skills. Due to potential theoretical and practical implications, there is particular excitement about the possibility that music promotes transfer of skills to substantially different nonmusical domains, such as mathematics, IQ, or language. Transfer to domains like these is called *far* transfer (Barnett & Ceci, 2002), and whether it exists is an ongoing debate (e.g., Bigand & Tillmann, 2022; Sala & Gobet, 2017a; Sala & Gobet, 2017b; Swaminathan & Schellenberg, 2021). Transfer to domains tightly related to music is called *near* transfer.

The processing of fine-grained acoustic features of sounds is a near transfer domain of music training (e.g., Bigand & Tillmann, 2022; Kraus & Chandrasekaran, 2010). Auditory skills are critical for music, and music training requires high precision in the processing of subtle acoustic differences, for instance in pitch or timing, which can be present in a range of sounds, from single-frequency tones to complex ones such as melodic or rhythmic patterns. There is evidence of cortical and subcortical plasticity in the auditory pathway (e.g., Herholz & Zatorre, 2012; Pantev & Herholz, 2011), and this plasticity can relate to improved auditory and musical abilities (e.g., Habibi et al., 2016; Hyde et al., 2009). In a study with children, however, Kragness et al. (2021) found that individual differences in music discrimination are stable over time, and when prior performance is held constant (measured five years earlier), the association between music training and music discrimination disappears. Even for near transfer domains, music training effects can therefore be weak.

Language is one of the far transfer domains most extensively examined in the music training literature. Many studies examine transfer to linguistic abilities including phonological awareness (e.g., Vidal et al., 2020), reading (e.g., Carioti et al., 2019), speech-in-noise perception (e.g., Hennessy et al., 2021), speech-in-quiet perception (e.g., Tierney et al., 2015), or prosody perception (e.g., Moreno et al., 2009). Although results from individual studies vary (e.g., Boebinger et al., 2015; Mehr et al., 2013), the mechanisms underlying associations between music and linguistic processing have been discussed. Both music and language are forms of human communication, rely on auditory learning and on a hierarchical organization of elements (e.g., from sounds/phonemes to melodies/sentences), and share auditory pathways (e.g., Peretz et al., 2015; Tervaniemi et al., 2022; Zatorre et al., 2002). According to the 'OPERA' hypothesis (Patel, 2011, Patel, 2012, Patel, 2014), music training induces plasticity in speech and language networks when five conditions are met: music engages sensory and cognitive networks that Overlap with those engaged by speech (e.g., encoding of periodicity; auditory working memory); music places higher demands on these networks than speech, requiring more Precision of processing; and musical activities occur in a context that involves positive Emotion, extensive Repetition, and focused Attention. In short, music training would enhance speech and language processing because it places higher demands on shared neural networks, elicits emotional rewards, and requires repetition and attention.

Several meta-analyses examine longitudinal evidence for music training effects, all focused on far transfer and behavioral measures (Cooper, 2020, Gordon et al., 2015, Román-Caballero et al., 2018, Román-Caballero et al., 2022, Sala and Gobet, 2017a, Sala and Gobet, 2020, Vaughn, 2000). The emphasis is on general cognitive and academic skills, such as IQ and mathematics, and results reveal a small positive effect. The effect is heterogeneous across individual studies, however, and potentially related to the study design. For instance, Gordon et al. (2015) reviewed 13 studies ($N = 901$) assessing music training effects on phonological awareness and reading fluency. There was a small effect of training on phonological awareness ($d = 0.20$), which was larger when the training was longer. The effects on reading fluency were not significant. More recently, Cooper (2020) reviewed 21 studies ($N = 5612$) and found an overall significant effect of $g = 0.28$ for measures of verbal and nonverbal cognitive abilities. The effect remained significant for studies with active control groups, but only when they were conducted in a natural setting (e.g., a classroom). Another meta-analysis, by Sala and Gobet (2020), reviewed 54 studies ($N = 6984$) focusing on transfer to cognitive and academic skills, in an update of a previous meta-analysis on the same topic (Sala and Gobet, 2017a). The new analysis revealed a small significant effect of music training ($g = 0.18$), consistent with the previous one, but also heterogeneity across studies. The effect was observed for studies with passive control groups, but not for those with active control groups. Moreover, for the studies with passive control groups the effect was only found when assignment was not random. Thus, when design quality was optimal, including active control groups and random assignment, the benefits of music training were null. However, a reanalysis of Sala and Gobet's data indicated that randomization was not a robust moderator, and that there would be evidence for transfer if near transfer effect sizes had been excluded in the control groups, as they were in the music groups (e.g., phonological awareness when the group received phonological training; Bigand & Tillmann, 2022). Sala and Gobet's findings were also not replicated in the meta-analysis by Román-Caballero et al. (2022), which revealed significant music training effects on children's cognitive and academic abilities, regardless of randomization and type of control group $\bar{(}_{\Delta} = .26$; 32 studies, 34 independent samples, $N = 5998$). Only studies that involved learning how to play a complex instrument were included, though. It could be that a more demanding training produces larger effects, and that inconsistencies across meta-analyses result from not accounting for the type of music training. Whether music training enhances nonmusical abilities remains unclear, as does the role of study design features.

Two other aspects remain poorly explored. Despite the increasing number of studies of music training effects on brain structure and function, particularly regarding linguistic processing (e.g., Carpentier et al., 2016; Fleming et al., 2019; Hennessy et al., 2021), no systematic reviews have covered brain data. This will be crucial to understand behavior in the context of brain plasticity, and the neurobiological bases of associations between music and nonmusical domains. Moreover, because the primary focus has been on far transfer, meta-analytic evidence for near transfer remains unexplored, and this is crucial for a mechanistic understanding of plasticity and transfer effects. For example, existing hypotheses suggest that sharper auditory processing is required to explain far transfer from music to language (e.g., Besson et al., 2011; Goswami, 2011; Patel, 2014).

The present review and meta-analysis examines the neurobehavioral effects of music training in healthy individuals, focusing on auditory processing (near transfer) and linguistic processing (far transfer). Examining near transfer is necessary to inform theories of plasticity and transfer, and although previous meta-analyses explored far transfer to general cognitive abilities, a comprehensive analysis of effects on linguistic skills is lacking. Because language is extensively examined in music training studies, evaluating this domain will illuminate debates on far transfer, both from behavioral and brain perspectives. Sixty-two longitudinal studies were included, and we asked whether music training effects are observed at the behavioral and brain levels. Behavioral data were summarized through multivariate meta-analytic models and brain data through a narrative synthesis. In the meta-analysis, we also asked whether training effects depend on the outcome measure (auditory vs. linguistic skills), type of music training (instrumental vs. non-instrumental), participants' age, publication year, aspects of the study design (type of control group, randomization, risk of bias), aspects of the training programs (total months of training, hours per week), and baseline differences.

## 2. Methods

We followed the PRISMA guidelines for systematic reviews and meta-analyses (Liberati et al., 2009). The PRISMA checklist is presented in Table S1 (supplementary material), and Fig. 1 depicts a PRISMA flowchart. The protocol for this review was registered on PROSPERO (CRD42020201243).

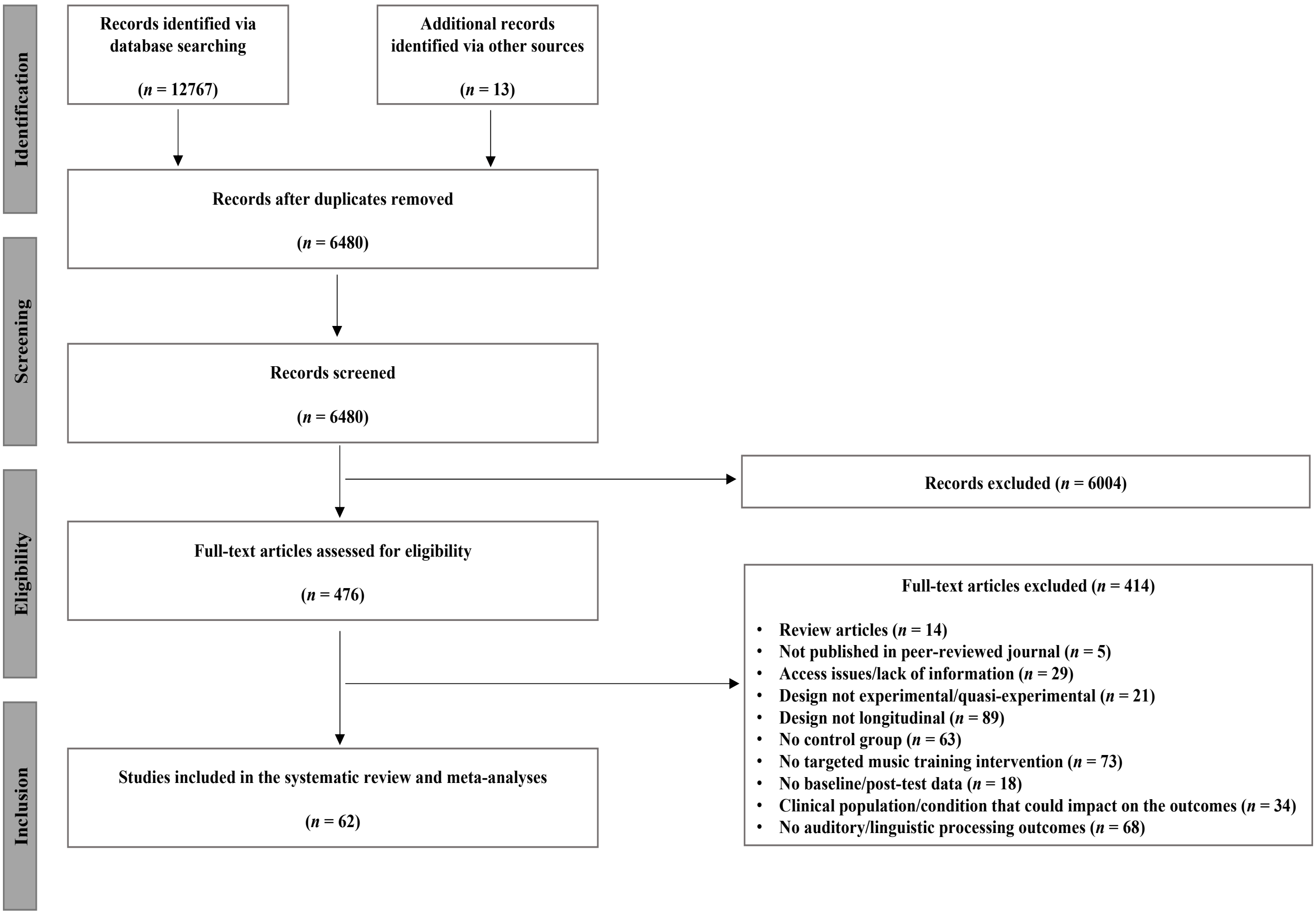

***Figure 1***. Flowchart showing the process of selection of studies for the systematic review and meta-analysis according to the PRISMA guidelines.

## 2.1. Literature search

The first search was conducted in July 2019, using the Web of Science Core Collection, EBSCOhost, Scopus, and PubMed databases to identify longitudinal studies examining effects of music training on auditory and linguistic processing in healthy individuals. We used the query: "music training" OR "music practice" OR "music intervention" OR "music lesson* " OR "music instruction" OR "music program* " OR "music group". This query was adapted according to the specifications of each database (Table S2). By relying on several databases and on a broad query, we aimed to minimize search bias and avoid missing relevant studies, such as those that included linguistic and auditory processing outcomes but had a distinct primary focus (e.g., studies focused on IQ, Schellenberg, 2004; or mathematics, Holmes and Hallam, 2017). Two additional search rounds were conducted, in June 2020 and June 2021, to identify more recent eligible articles. Table S3 presents the total number of studies identified in each database and in each of the searching dates. We also screened the reference lists of the included studies and reviews on the topic to identify additional studies that might have not been captured by our search.

## 2.2. Selection criteria

Studies met the following criteria to be selected: written in English and published in a peer-reviewed journal; full-text available; sample of healthy individuals; longitudinal design; inclusion of a music training group and at least one control group (passive, active or both); and at least one measure of auditory and/or linguistic processing.

Reasons for exclusion: review articles; studies comparing professional musicians with untrained participants (i.e., correlational studies); lack of pre-training and/or post-training data; and studies with clinical populations (e.g., amusia; cochlear implant users).

Titles and abstracts were independently screened by two reviewers (L.N. and A.I.C.) for eligibility using Rayyan (Ouzzani et al., 2016). The same process was repeated for full-texts of all potentially eligible studies, where eligibility was assessed against inclusion criteria (reasons for exclusion are detailed in Table S4). Discrepancies were adjudicated by a third reviewer. We assessed inter-rater reliability (IRR) for the initial and full-text screening phases using Cohen's Kappa. IRR ranged from moderate (Cohen's K, 1st screening = 0.59) to substantial agreement (Cohen's K, 2nd screening = 0.73; Cohen's K, 3rd screening = 0.66) in the initial screenings. The IRR was almost perfect in the full-text screenings (Cohen's K, 1st screening = 0.85; Cohen's K, 2nd screening = 0.84; Cohen's K, 3rd screening = 0.85; Table S5; Landis and Koch, 1977).

## 2.3. Data extraction

The two reviewers who screened the studies for eligibility also independently extracted the following information from each study: authors, title, year, journal, participants' age, design and methodology (i.e., groups, randomization process, music training method [e.g., Suzuki], total months of training, and hours of training per week), type of measurement (i.e., auditory and/or linguistic), means and standard deviations for performance on each task per group (before and after training), and information to assess risk of bias, as specified below (Section 2.4). For studies that included brain outcomes, they additionally extracted information on the measure (e.g., EEG; MRI) and main findings.

When relevant data were missing, we contacted the authors by email (*n* = 24). Eight replied and provided the requested data. In case they could not provide exact means and standard deviations but graphic information was available (*n* = 4), we estimated the values from the graphs using the software WebPlotDigitizer (Rohatgi, 2020). When the required data were neither available nor could be obtained from the authors, the study was either excluded (n = 7), or kept if it provided useful information (e.g., relevant data could be missing for behavioral measures, but not for brain measures; *n* = 4).

## 2.4. Quality assessment

We used the revised Cochrane Risk of Bias tool (RoB 2) to assess the risk of bias in each of the included studies (Higgins et al., 2011). We judged whether each study had a high risk of bias, low risk of bias, or some concerns regarding the following domains: randomization process, deviations from intended intervention, missing outcome data, measurement of the outcome, and selection of the reported results. The overall risk of bias of a given study was considered low if all the domains were rated as low risk, or if only one was rated as "some concerns" and the reviewers did not consider it worrisome. If the studies did not meet criteria for low risk, and no more than three domains were rated as "some concerns", the risk of bias was classified as "some concerns". The other studies were considered to have a high risk of bias. The risk of bias was assessed independently by two reviewers and any disparity was resolved by consensus. The evaluations were based on information provided in the article and in supplementary material. No study was discarded because of risk of bias.

## 2.5. Data synthesis

### 2.5.1. Meta-analysis of behavioral data

### 2.5.2. Calculation of effect sizes and respective variance

To estimate the effects of music training on behavioral measures, we used the formula proposed by Morris (2008) for standardized mean change difference: Hedges´ g (hereafter referred to as $g_\Delta$). This allows not only to compare music training and control groups, but also to control for possible differences in the pre-training values. The formula is:

$$g_\Delta = \mathrm{J} \text{ x } d \quad (1)$$

where:

$$d = \frac{\left(M_{\text{post, } m} - M_{\text{pre, } m}\right) - \left(M_{\text{post, } c} - M_{\text{pre, } c}\right)}{SD_{\text{pooled, pre}}} \qquad (2)$$

The indices $M_{\text{post}}$ and $M_{\text{pre}}$ indicate the scores for different measurement times (e.g., pre- and post-training), for the music group (*m*) and control group (*c*). $SD_{\text{pooled, pre}}$ is the pooled standard deviation for the pre-training scores of both groups. The correction factor to achieve an unbiased estimator is defined as:

$$J = 1 - \frac{3}{4 \text{ x } (\mathrm{N_m} + \mathrm{N_c}) - 9} \quad (3)$$

The indices $N_m$ and $N_c$ are the number of participants in the music and control groups. Positive $g_\Delta$ indicates improvement from pre- to post-training in the music group compared to control group. The variance of $g_\Delta$ was calculated following the formula by Borenstein et al. (2009):

$$V_{g\Delta} = \left(\frac{N_m + N_c}{N_m \text{ x } N_c} + \frac{d^2}{2 \text{ x } (N_m + N_c)}\right) \text{x } J^2 \quad (4)$$

We also calculated the traditional Hedges´ *g* only with pretest scores (hereafter referred to as $g_{pre}$), to compare the performance of music and control groups at baseline:

$$g_{\text{pre}} = J \text{ x } \frac{M_{\text{pre, } m} - M_{\text{pre, } c}}{SD_{\text{pooled, pre}}} \quad (5)$$

$$V_{g_{pre}} = \left(\frac{N_m + N_c}{N_m \text{ x } N_c} + \frac{g^2{}_{pre}}{2 \text{ x } (N_m + N_c)}\right) \text{x } J^2 \quad (6)$$

### 2.5.3. Meta-analysis

The meta-analysis was conducted using the *"metafor"* package (version 2.0.0) from R (Viechtbauer, 2010). Because we frequently included more than one effect size coming from the same participants, a multilevel random-effects model was used to account for this dependency. Applying multivariate meta-analytic models can be challenging when the covariance structure is unknown and cannot be estimated based on previous literature, which was our case. To overcome this, we estimated the variance-covariance matrix from the data using the *"clubSandwich"* package from R (version 0.5.0).

### 2.5.4. Heterogeneity

Because studies differ in many respects, including experimental design, sample size, measures, and training schemes, it is likely that there is heterogeneity in the obtained effects (Xu et al., 2008). Statistical heterogeneity occurs when the true effects of the different studies show larger variation than expected due to random error or by chance. Assessing heterogeneity is therefore important for better evaluating the conclusions that can be drawn from a meta-analysis. We assessed between-studies heterogeneity using the Cochran's *Q* test (Kulinskaya and Dollinger, 2015) and the $I^2$ statistics (Higgins and Thompson, 2002, Higgins et al., 2003).

### 2.5.5. Influential studies and leave-one-out robustness analysis

We assessed the presence of influential studies by calculating Cook's distances. A conservative approach was adopted, considering as influential any study with a Cook's distance greater than three times the mean (Cook, 1977). To assess the robustness of our findings (i.e., to exclude the possibility that our results were driven by one specific study), we also repeated the meta-analysis excluding one study at a time.

### 2.5.6. Moderators

Meta-regression models were used to evaluate the potential influence of ten moderators on the behavioral outcomes:

(1) Domain of outcome measure: auditory or linguistic processing (dichotomous variable). This moderator tested whether the magnitude of transfer effects differed for near transfer (auditory processing) vs. far transfer (linguistic processing) domains.

(2) Type of training: instrumental or non-instrumental (dichotomous variable). This moderator accounted for the diversity of music training programs across studies, considering evidence that effects might be larger when the training involves learning how to play a complex musical instrument compared to other types of training (e.g., programs of music education such as Orff, listening programs, or computerized training of musical skills; Román-

Caballero et al., 2022). We followed the same classification criteria as Román-Caballero et al. (2022).

(3) Baseline differences: measured as gpre (continuous variable). This moderator asked whether between-group differences before training determined the magnitude of training effects. Previous studies raise the possibility that baseline differences determine the likelihood of taking music lessons (e.g., Swaminathan et al., 2017), and this could be a concern particularly for studies with non-randomized group assignment. Recent meta-analyses examined this moderator also to account for potential regression toward the mean in participants who had more extreme differences before training (Román-Caballero et al., 2022, Sala and Gobet, 2020).

(4) Publication year: published before 2000, between 2000 and 2009, or between 2010 and 2022. This variable was transformed into a categorical variable because the data was not uniformly distributed over time (95.16% of the studies were published after 2000). This moderator examined temporal trends in the magnitude of the reported effects.

(5) Age: mean age of the participants – less than 11 years old (children), between 11 and 17 years (adolescents), between 18 and 59 years (adults), and ≥ 60 years (older adults). Age was transformed into a categorical variable because the data was not uniformly distributed over the range of ages (70.97% of the sample are children). The age at which music training begins might influence the magnitude of the effects (e.g., White et al., 2013).

(6) Randomization: randomized or non-randomized group assignment (dichotomous variable). Random assignment is an important methodological aspect to establish causation, as it prevents self-selection effects, thereby minimizing the effects of potential pre-existing differences between groups (e.g., Ilari, 2020; Schellenberg, 2020a).

(7) Type of control group(s): active, i.e., another type of intervention (e.g., sports), or passive, i.e., no intervention (dichotomous variable). This moderator controlled for the possibility that the benefits of music training result from nonmusical aspects of the training.

(8) Duration of training: number of months (continuous variable). The length of music training has been associated with the level of proficiency achieved (e.g., Wilson et al., 2011).

(9) Hours of training per week (continuous variable). Similarly, the frequency of training can be associated with the magnitude of the effects (e.g., Kraus et al., 2014).

(10) Risk of bias: low risk, some concerns or high risk of bias (categorical variable). This moderator reflects the extent to which methodological flaws might have affected the results (Higgins et al., 2011).

### 2.5.7. Publication bias

In addition to the methods-related risk of bias, the risk of publication bias is an important issue to consider. If effects that are “significant” and large, or consistent with the authors’ expectations, are more likely to be published than those that are null or inconclusive, inferences from individual studies and meta-analyses will be biased (e.g., Francis, 2012; Van Aert et al., 2019). Publication bias can lead to exaggerated average effect sizes, which might appear significant and important when there is no underlying ‘true’ effect. We assessed the potential presence of publication bias, and corrected for its consequences, using the trim-and-fill method and meta-regression methods, namely the precision-effect test and precision-effect estimate with standard errors (PET-PEESE; Stanley and Doucouliagos, 2014). Trim-and-fill is a non-parametric method used to estimate the number of studies missing from a meta-analysis due to suppression of most extreme results on one side of the funnel plot. If missing studies are detected, this method augments the observed data to increase the symmetry of the funnel plot (Duval and Tweedie, 2000). This approach assumes independence of effect sizes, and it is therefore not compatible with data like ours where effect sizes cluster around the study from which they originated. To account for dependence, we estimated aggregated effect sizes for each study by generating average estimates using the agg function from the MAd package in R. PET-PEESE tests for selective reporting and adjusts for small-study effects using a measure of precision as a covariate in the meta-analytic model (standard error of the effect size in the case of PET, and sampling variance in the case of PEESE). The procedure involves first testing whether the PET estimate is significant, using PEESE if it is or PET otherwise. The regression coefficient tests for publication bias, and the intercept of the model indicates the average effect size estimate from a study with zero sampling variance, taken as a ‘bias-corrected’ or true average effect.

The usual estimator of the sampling variance of the standardized mean differences includes the effect size itself in the formula. This is problematic when using PET-PEESE, as these test for the independence between $d$ and $V_{g\Delta}$, and the fact that $V_{g\Delta}$ is calculated from $d$ generates an artefactual correlation among them. To overcome this, we followed Pustejovsky and Rodgers (2019) recommendation and modified the conventional variance formula so that it does not rely on the effect size for the estimation. As an alternative to d, we calculated h, whose variance does not involve the effect size:

$$h = \sqrt{2} \times \text{sign}(g_\Delta) \times \left[ ln\left( |g_\Delta| + \sqrt{g_\Delta^2 + a^2} \right) - ln(a) \right] \quad (5)$$

where,

$$a = \sqrt{2 \times \frac{N_m + N_c}{N_m \times N_c} \times (N_m + N_c - 2)} \quad (6)$$

and the sampling variance of the estimate is calculated as:

$$V_h = \frac{1}{N_m + N_c - 2} \quad (7)$$

### 2.5.8. Brain outcomes (narrative synthesis)

Studies on brain outcomes would hardly allow for a quantitative synthesis because of their heterogeneity (e.g., functional versus structural outcomes; magnetic resonance imaging versus electrophysiological measures; task-based versus resting-state measures). We summarized these findings using narrative synthesis. Section 3.4., Table 3 and Fig. 4 summarize the characteristics of the brain studies and their main findings.

# 3. Results

## 3.1. Overview

Table 1 presents an overview of all included studies. We reviewed 62 studies, published between 1974 and 2022. Forty-four of them reported effects of music training on behavioral measures and 27 on brain measures (nine report both behavioral and brain findings). Nineteen studies reported effects on auditory processing, 34 on linguistic processing, and nine on both. Forty-four included a passive control group, 32 an active control group, and 14 included both. Sixteen studies had random assignment and 46 did not. Twenty-six studies had instrumental training programs, and 36 were non-instrumental.

The omnibus sample size was 3928 participants (*M* = 63.35 per study, *SD* = 53.16, range = 12–345). They were distributed across a range of ages: 3034 were children ($M_{age}$ = 6.63 years, *SD* = 1.61, range = 3.60 – 10.30), 326 adolescents ($M_{age}$ = 12.56, *SD* = 1.75, range = 10.80 – 14.69), 269 adults ($M_{age}$ = 28.56, *SD* = 14.59, range = 20.90 – 58.29), and 331 older adults ($M_{age}$ = 67.25, SD = 1.86, range = 63.50 – 68.45). From the total sample, 1845 participants were assigned to music training groups (*M* = 29.76 per study, *SD* = 27.07, range = 6 – 192), 1244 to passive control groups (*M* = 28.27 per study, *SD* = 18.03, range = 6 – 85), and 839 to active control groups (*M* = 26.22 per study, *SD* = 27.37, range = 6 – 153). The music training programs had a mean duration of 9.77 months (*SD* = 9.89, range = 0.66 – 48 months), and a mean frequency of 3.09 h per week (*SD* = 3.16, range = 0.50 – 15h).

| | | | | | Characteristics | | | | Behavioral Measures | | | Brain Measures | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Study | N | Mean Age (years) | Groups (*n* per group) | Random Assignment | Training Duration (months) | Hours of Training (per week) | Type of Music Training | Instrumental Training* | Auditory | Language | MRI | EEG | MEG |
| Tervaniemi et al., 2022<br>(Cereb. Cortex) | 85 | 9.3 | Music (29)<br>Language (38)<br>Passive Control (18) | No | 5.8 | 1.7 | Kodály music theory and solfeggio | | | | | ✓ | |
| Hennessy et al., 2021<br>(Aging) | 41 | 58.3 | Music (18)<br>Passive Control (23) | Yes | 2.8 | 2 | Group choir singing | | ✓ | ✓ | | ✓ | |
| Wiener & Bradley, 2020<br>(Lang. Teach. Res.) | 20 | 20.9 | Music (10)<br>Language (10) | No | 1.8 | 3.5 | Computer-based program (identifying structural elements of music, e.g., chords) | | ✓ | ✓ | | | |
| Habibi et al., 2020<br>(Brain Struct. Funct.) | 23 | 7 | Music (12)<br>Passive Control (11) | No | 48 | NR | Ensemble and group performances<br>(string instruments) | ✓ | | | ✓ | | |
| James et al., 2020<br>(Front. Neurosci.) | 63 | 10.2 | Music (31)<br>Passive Control (32) | Yes | 24 | 1.5 | Orchestra in class (string instruments) | ✓ | ✓ | | | | |
| Li et al., 2020<br>(IEEE Trans. Neural Syst. Rehabilitation Eng.) | 56 | 23.2 | Music (29)<br>Passive Control (27) | Yes | 5.5 | 4.75 | Piano training | ✓ | | | ✓ | | |
| Vidal et al., 2020<br>(Appl. Pscycholingist.) | 44 | 3.6 | Music (23)<br>Visual Arts (21) | Yes | 6.9 | 0.75 | Mixed music activities (e.g., joint singing and rhythm exercises) | | | ✓ | | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dubinsky et al., 2019<br>(Front. Neurosci.) | 63 | 67.6 | Music (34)<br>Passive Control (29) | No | 2.3 | 3 | Choir singing (pitch and vocal training) | | ✓ | ✓ | | ✓ |
| Bugos, 2019<br>(Front. Integr. Neurosci.) | 135 | 68.4 | Music (49)<br>Music (38)<br>Passive Control (48) | No | 3.7 | 3.75 | Piano training;<br>Percussion training | ✓ | | ✓ | | |
| Fleming et al., 2019<br>(Brain Cogn.) | 33 | 67.9 | Music (12)<br>Video Games (8)<br>Passive Control (13) | No | 6 | 2.5 | Piano training | ✓ | | | ✓ | |
| Zendel et al., 2019<br>(Neurobiol. Aging) | 34 | 67.8 | Music (13)<br>Video Games (8)<br>Passive Control (13) | Yes | 6 | 2.5 | Piano Training | ✓ | | ✓ | | ✓ |
| Carioti et al., 2019<br>(Front. Psychol.) | 74 | 11.4 | Music (30)<br>Passive Control (44) | No | 12 | 4 | Ensembles and individualized training (instrument of their choice) | ✓ | | ✓ | | |
| MacCutcheon et al., 2020<br>(Front. Psychol.) | 41 | 6.3 | Music (26)<br>Sports (15) | No | 8.7 | 0.75 | Kodály and Orff | | | ✓ | | |
| Cohrdes et al., 2019<br>(Psychol. Music) | 202 | 5.4 | Music (67)<br>Language (68)<br>Passive Control (67) | No | 6 | 1.5 | Fundamental music competencies<br>(e.g., tonal discrimination) | | ✓ | | | |
| Li et al., 2019<br>(Brain Struct. Funct.) | 56 | 23.2 | Music (29)<br>Passive Control (27) | Yes | 5.5 | 4.75 | Piano Training | ✓ | | | ✓ | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alain et al., 2019<br>(Front. Neurosci.) | 53 | 68.2 | Music (17)<br>Visual Arts (19)<br>Passive Control (17) | No | 3 | 3 | Mixed music activities and basic music theory (e.g., body percussion) | | | ✓ | | ✓ |
| Rose et al., 2019<br>(Psychol. Music) | 38 | 7.8 | Music (19)<br>Passive Control (19) | No | 12 | 3.33 | Individual instrumental playing | ✓ | ✓ | ✓ | | |
| Patscheke et al., 2019<br>(Psychol. Music) | 40 | 5.5 | Music-Pitch (13)<br>Music-Rhythm (13)<br>Sports (14) | Yes | 3.68 | 1 | Pitch training;<br>Rhythm training | | | ✓ | | |
| Jaschke et al., 2018<br>(Front. Neurosci.) | 146 | 6.4 | Music + (38)<br>Music (42)<br>Visual Arts (29)<br>Passive Control (37) | No | 30 | 1.5 | Theoretical and active instrumental lessons | | | ✓ | | |
| See & Ibbotson, 2018<br>(Int. J. Educ. Res.) | 56 | 4.5 | Music (28)<br>Passive Control (28) | Yes | 2.3 | 1 | Kodály approach | | | ✓ | | |
| D’Souza & Wiseheart, 2018<br>(Arch. Sci. Psychol.) | 75 | 7.8 | Music (24)<br>Dance (26)<br>Passive Control (25) | No | 0.7 | 10 | Mixed music activities and instruments | ✓ | | ✓ | | |
| Nan et al., 2018<br>(Proc. Natl. Acad. Sci. U.S.A.) | 74 | 4.6 | Music (30)<br>Reading (28)<br>Passive Control (16) | No | 6 | 2.25 | Piano training | ✓ | ✓ | ✓ | | ✓ |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Li et al., 2018<br>(Hum. Brain Mapp.) | 56 | 23.2 | Music (29)<br>Passive Control (27) | Yes | 5.5 | 4.75 | Piano Training | ✓ |  |  | ✓ |  |  |
| Habibi et al., 2018<br>(Cereb. Cortex) | 47 | 6.9 | Music (15)<br>Sports (15)<br>Passive Control (17) | No | 24 | 6.5 | Ensemble and group performances<br>(string instruments) | ✓ |  |  | ✓ |  |  |
| Degé & Schwarzer, 2018<br>(Music Sci.) | 30 | 10.8 | Music (13)<br>Passive Control (17) | No | 12 | 3 | Mixed music activities and school choir/orchestra |  | ✓ |  |  |  |  |
| Guo et al., 2018<br>(Front. Psychol.) | 40 | 7.5 | Music (20)<br>Passive Control (20) | No | 1.4 | 0.83 | Keyboard harmonica instruction | ✓ |  | ✓ |  |  |  |
| Fujioka & Ross, 2017<br>(Eur. J. Neurosci.) | 14 | 63.5 | Music (7)<br>Passive Control (7) | No | 1.1 | 3 | Piano training | ✓ |  |  |  |  | ✓ |
| Holmes & Hallam, 2017<br>(London Rev. Educ.) | 59 | 5.5 | Music (29)<br>Passive Control (30) | No | 12 | 0.5 | Rhythmic instruction |  |  | ✓ |  |  |  |
|  | 61 | 4.5 | Music (31)<br>Passive Control (30) | No | 12 | 0.5 | Rhythmic instruction |  |  | ✓ |  |  |  |
| Habibi et al., 2016<br>(Dev. Cogn. Neurosci.) | 37 | 6.9 | Music (13)<br>Sports (11)<br>Passive Control (13) | No | 24 | 6.5 | Ensemble and group performance (string instruments) | ✓ |  |  |  | ✓ |  |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carpentier et al., 2016<br>(J. Cogn. Neurosci.) | 30 | 5.6 | Music (14)<br>French (36) | No | 0.7 | 10 | Computer-based program (rhythm, pitch, melody, voice, and basic musical concepts) |  |  |  |  | ✓ |
| Janus et al., 2016<br>(J. Exp. Child. Psychol.) | 57 | 5.5 | Music (29)<br>French (28) | No | 0.7 | 15 | Computer-based program (rhythm, pitch, melody, voice, and basic musical concepts) |  |  | ✓ |  |  |
| Ilari et al., 2016<br>(Front. Psychol.) | 50 | 6.8 | Music (23)<br>Passive Control (27) | No | 12 | 7 | Ensemble practice and group performances (e.g.,violin, choir), musicianship, theory skills | ✓ | ✓ |  |  |  |
| Schellenberg et al., 2015<br>(PLoS One) | 84 | 8.7 | Music (38)<br>Passive Control (46) | No | 10 | 0.67 | Kodály method – ukulele in the classroom | ✓ |  | ✓ |  |  |
| Tierney et al., 2015<br>(Proc. Natl. Acad. Sci. U.S.A.) | 40 | 14.7 | Music (19)<br>Fitness (21) | No | 36 | 2.67 | Learning to play in a large ensemble<br>(e.g., percussion, trumpet) | ✓ |  | ✓ |  | ✓ |
| Moreno et al., 2015<br>(Child Dev.) | 36 | 5.6 | Music (18)<br>French (18) | No | 0.7 | 10 | Computer-based program (rhythm, pitch, melody, voice, and basic musical concepts) |  |  |  |  | ✓ |
| Rautenberg, 2015<br>(J. Res. Read) | 159 | 7.8 | Music (33)<br>Visual Arts (41)<br>Passive Control (85) | No | 8 | NR | Gordon's learning theory of music (rhythmic and tonal skills training, auditory discrimination of timbre and sound intensity) |  |  | ✓ |  |  |
| Slater et al., 2015<br>(Behav. Brain Res.) | 38 | 8.2 | Music (19)<br>Passive Control (19) | Yes | 24 | 2 | Harmony Project (introductory musicianship class and instrumental classes) | ✓ |  | ✓ |  |  |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| Slater et al., 2014<br>(PLoS One) | 42 | 8.3 | Music (23)<br>Passive Control (19) | No | 12 | 4.5 | Harmony Project (introductory musicianship class and instrumental classes) | ✓ |  | ✓ |  |
| Chobert et al., 2014<br>(Cereb. Cortex) | 24 | 8.3 | Music (12)<br>Painting (12) | No | 12 | 1.13 | Kodály and Orff methodologies |  |  | ✓ | ✓ |
| Kraus et al., 2014<br>(J. Neurosci.) | 44 | 8.3 | Music (26)<br>Passive Control (18) | Yes | 12 | 3 | Fundamental skills and group instrumental instruction (strings, woodwinds, brass winds) | ✓ |  |  | ✓ |
| Roden et al., 2014<br>(Appl. Cogn. Pscyhol.) | 345 | 7.9 | Music (192)<br>Natural Science (153) | No | 18 | 0.75 | Lessons of an instrument of their choice | ✓ | ✓ |  |  |
| Kaviani et al., 2014<br>(Cogn. Process.) | 60 | 5.5 | Music (30)<br>Passive Control (30) | No | 2.8 | 1.25 | Orff method (singing, chanting rhymes, clapping, playing and keeping a beat) |  |  | ✓ |  |
| Mehr et al., 2013<br>(PLoS One) | 29 | 4.8 | Music (15)<br>Visual Arts (14) | Yes | 1.5 | 0.75 | Kindermusik, Orff method, Music Together |  |  | ✓ |  |
|  | 45 | 4.7 | Music (23)<br>Passive Control (22) | Yes | 1.5 | 0.75 | Kindermusik, Orff method, Music Together |  |  | ✓ |  |
| François et al., 2013<br>(Cereb. Cortex) | 24 | 8 | Music (12)<br>Painting (12) | No | 12 | 1.13 | Kodály and Orff methodologies |  |  |  | ✓ |
| Rabinowitch et al., 2013<br>(Psychol. Music) | 52 | 10.3 | Music (23)<br>Games (8)<br>Passive Control (21) | Yes | 9 | 1 | Musical group interaction (musical tasks in the form of pre-arranged musical games) |  |  | ✓ |  |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tierney et al., 2013<br>(Front. Psychol.) | 43 | 14.7 | Music (21)<br>Fitness (22) | No | 24 | 3 | Band/Choral class (e.g., sight reading, singing, and playing technique) | | | | | ✓ |
| Rickard et al., 2012<br>(Int. J. Music. Educ.) | 111 | 12.7 | Music (47)<br>Drama (37)<br>Art (27) | No | 6.5 | 1 | Playing and learn about different instruments (improvisation and composition) | | | ✓ | | |
| Bugos & Jacobs, 2012<br>(Res. Stud. Music. Educ.) | 28 | 11.2 | Music (15)<br>Passive Control (13) | No | 4 | NR | Create music while learning compositional and stylistic concepts | | | ✓ | | |
| Moreno et al., 2011a<br>(Psychol. Sci.) | 48 | 5.3 | Music (24)<br>Visual Arts (24) | No | 0.7 | 10 | Computer-based program (rhythm, pitch, melody, voice, and basic musical concepts) | | | ✓ | | |
| Moreno et al., 2011b<br>(Music Percept.) | 60 | 5.3 | Music (30)<br>Visual Arts (30) | No | 0.7 | 10 | Computer-based program (rhythm, pitch, melody, voice, and basic musical concepts) | | | ✓ | | |
| Herdener et al., 2010<br>(J. Neurosci.) | 40 | 22.4 | Music (19)<br>Passive Control (21) | No | 7.5 | 3 | Aural skills training | | | | ✓ | |
| Moreno et al., 2009<br>(Cereb. Cortex) | 32 | 8.4 | Music (16)<br>Painting (16) | No | 6 | 2.5 | Kodály, Orff and Wuytack methodologies | | ✓ | ✓ | | ✓ |
| Hyde et al., 2009<br>(J. Neurosci.) | 31 | 6.1 | Music (15)<br>Passive Control (16) | No | 15 | 0.5 | Individual keyboard lessons | ✓ | | | ✓ | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Piro & Ortiz, 2009<br>(Psychol. Music) | 103 | 6.5 | Music (46)<br>Passive Control (57) | No | 36 | 1.42 | Piano training | ✓ | | ✓ | | |
| Shahin et al., 2008<br>(Neuroimage) | 12 | 4.7 | Music (6)<br>Passive Control (6) | No | 12 | NR | Suzuki method | | | | ✓ | |
| Fujioka et al., 2006<br>(Brain) | 12 | 5.5 | Music (6)<br>Passive Control (6) | No | 12 | NR | Suzuki method | | ✓ | | | ✓ |
| Moreno & Besson, 2006<br>(Psychophysiol.) | 20 | 8.5 | Music (10)<br>Painting (10) | No | 1.8 | 1.33 | Pitch discrimination (e.g., learning the different notes of the scale, musical intervals) | | | | ✓ | |
| Gromko, 2005<br>(J. Res. Music. Educ.) | 103 | 5.5 | Music (43)<br>Passive Control (60) | No | 4 | 0.5 | Bruner's method (e.g., singing, body percussion) | | | ✓ | | |
| Schellenberg, 2004<br>(Psychol. Sci.) | 132 | 6 | Music (30)<br>Music (32)<br>Drama (34)<br>Passive Control (36) | Yes | 8.3 | 0.79 | Keyboard lessons;<br>Kodály voice lessons | ✓ | | ✓ | | |
| Orsmond & Miller, 1999<br>(Psychol. Music) | 42 | 5 | Music (21)<br>Passive Control (21) | No | 4 | NR | Suzuki method | | | ✓ | | |
| Flohr, 1981<br>(J. Res. Music. Educ.) | 156 | 5.3 | Music (29)<br>Passive Control (127) | Yes | 3 | 0.83 | Mixed music activities (e.g., improvisation, playing percussion instruments) | | ✓ | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Young, 1974<br>(J. Res. Music. Educ.) | 64 | 5.5 | Music (32)<br>Passive Control (32) | No | 2 | 1 | Music activities (musical concepts and songs) | ✓ |
| | 64 | 5.5 | Music (32)<br>Passive Control (32) | No | 2 | 1 | Music activities (musical concepts and songs) | ✓ |

[*] This classification of training programs as instrumental or non-instrumental followed the criteria by Román-Caballero et al. (2022).

***Table 1***. Overview of the studies included in the systematic review and meta-analysis (*N* = 62). Abbreviations: EEG – Electroencephalography; MEG – Magnetoencephalography; MRI - Magnetic Resonance Imaging; NR – not reported.

## 3.2. Quality assessment

Table S6 presents an overview of the studies' compliance with the Rob 2 criteria. Twenty-four studies had low risk of bias (38.71%), 18 raised some concerns (29.03%), and 20 had high risk of bias (32.26%). Thus, almost two-thirds of the studies (61.29%) had risk of bias. This was primarily because of the randomization process, a methodological concern for most studies. Forty-seven studies raised some concerns (29) or high risk of bias (18) regarding randomization, and only 15 had low risk.

## 3.3. Meta-analysis of behavioral data

### 3.3.1. Overview

The 44 studies with behavioral measures contributed 161 effect sizes, based on an omnibus sample size of 3241 participants (music groups = 1529; passive control groups = 1029; active control groups = 683). Table 2 shows the distribution of individual studies and number of effect sizes across auditory and linguistic processing domains, as well as across more specific subdomains. Subdomain categories were defined by assigning different tasks to a particular auditory or linguistic skill (e.g., word discrimination and speech-in-noise perception both in the category of speech discrimination). The categories "general auditory discrimination" and "general linguistic skills" refer to studies in which the measures do not discriminate between different types of skills (e.g., rhythm and pitch discrimination; see tables S7 and S8 for details about the tasks).

| **Domain of Outcomes Measure** | **Studies (*n*)** | **Effect Sizes (*n*)** |
|---|---|---|
| **Auditory Processing** | **15** | **34** |
| Rhythm Discrimination | 6 | 8 |
| Pitch Discrimination | 10 | 18 |
| Timbre Discrimination | 1 | 2 |
| General Auditory Discrimination | 5 | 6 |
| **Linguistic Processing** | **36** | **127** |
| Phonological Awareness | 7 | 11 |
| Speech Discrimination | 9 | 19 |
| Reading | 7 | 20 |
| Verbal Fluency | 8 | 17 |
| General Linguistic Skills | 20 | 60 |

***Table 2***. Number of studies and effect sizes within each domain of outcome measure.

### 3.3.2. Meta-analysis

We found a significant positive effect of music training on auditory and linguistic processing ($\overline{g}_{\Delta}$ = 0.31, 95% CI [0.15; 0.47], p < .001; see tables S7 and S8 for individual effect sizes).

### 3.3.3. Heterogeneity

There was evidence for a significant high amount of heterogeneity ($I^2$ = 76.69%, *Q*(160) = 697.05, p < .001), i.e., 76.69% of the between-studies variability in effect sizes was due to true heterogeneity rather than chance (Higgins et al., 2003).

### 3.3.4. Leave-one-out robustness analysis and influential studies

The positive effect of music training was not driven by specific studies, as it was replicated in all leave-one-out sensitivity analyses ($\overline{g}_{\Delta}$ range = 0.25–0.33; ps < .001). We detected two studies with Cook's distance more than three times the mean, though: Jaschke et al. (2018), $\overline{g}_{\Delta}$ = 2.41; and Piro and Ortiz (2009), $\overline{g}_{\Delta}$ = 1.30. The main model was repeated without these studies and the effect of music training remained significant ($\overline{g}_{\Delta}$ = 0.22, 95% CI [0.10; 0.34], p < .001). Removing these outliers also reduced heterogeneity ($I^2$ = 57.97%, *Q*(154) = 441.36, p<.001.They were therefore removed from the subsequent analyses.

### 3.3.5. Baseline differences

To examine whether there were differences between the music and control groups prior to training, we conducted a meta-analysis of gpre. There were no group differences ($\overline{g}_{\Delta\ \mathrm{pre}}$ = 0.01, 95% CI [−0.07; 0.09], *p* = .808), including when the analyses considered separately studies with random assignment ($\overline{g}_{\Delta\ \mathrm{pre}}$ = −0.09, 95% CI [−0.24; 0.05], *p* = .173) and non-random assignment ($\overline{g}_{\Delta\ \mathrm{pre}}$ = 0.05, 95% CI [−0.05; 0.15], *p* = .298). These findings confirmed that randomization was successful, and highlighted that non-random assignment is not necessarily related to advantages in the music groups before training.

### 3.3.6. Moderators

Most moderators did not explain a significant amount of variance in the effect sizes, namely domain of outcome measure (auditory vs. linguistic processing), type of training (instrumental vs. non-instrumental), year of publication, randomization (randomized vs. nonrandomized group assignment), type of control group (passive vs. active), duration of training (months), hours of training per week, age, and risk of bias (ps > .145; see Table S9 for statistical details).

The only significant moderator was baseline differences: the larger the baseline difference between groups, the smaller the observed effect of training (F[1,40] = 15.61; $\bar{g}_{\Delta}$ = −0.87, 95% CI [−1.31;−0.42], $p < .001$). After accounting for this moderator, heterogeneity was slightly reduced, $I^2$ = 48.73%, $Q(153) = 322.04$, $p < .001$. The moderating effect of baseline differences survived corrections for multiple comparisons considering the number of moderators (Bonferroni-corrected $p = .003$. see Fig. 2 for a meta-analytic scatter plot.

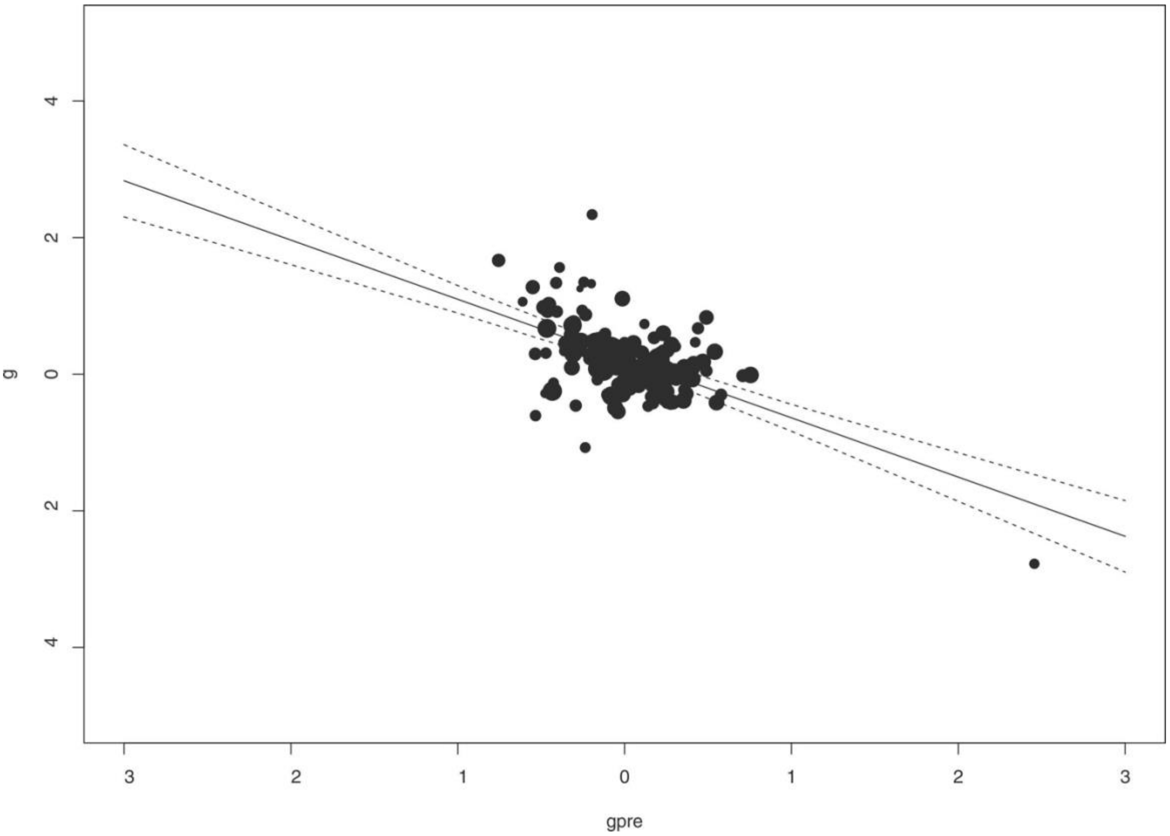

***Fig. 2***. Meta-analytic scatter plot showing the effect sizes of the included studies in the y-axis (Hedges' g) plotted against the predictor in the x-axis (baseline differences between groups, measured as the Hedges' g with the pretest scores). Larger baseline differences between groups led to smaller music training effects in auditory and linguistic processing. Each dot represents an effect size. The bold line corresponds to the regression line of the meta-regression model, and the dashed lines show the 95% confidence interval bounds (note: the moderating effect of baseline differences remains significant when the extreme value observed in the scatter plot is removed from the analysis).

### 3.3.7. Publication bias

The trim-and-fill method with the L0 estimator did not detect any missing studies. But when the same analysis was performed with the R0 estimator, we found evidence in favor of eight missing studies on the left side of the funnel plot (see Fig. 3), a finding compatible with the presence of publication bias. After including these missing studies in a univariate model on the aggregated effect sizes to estimate a corrected effect of music training, the effect was much smaller and became non-significant ($\bar{g}_{\Delta}$ = 0.09, 95% CI [−0.06; 0.24], $p = .221$). Regarding the PET-PEESE correction, the regression coefficient was not significant neither for the standard error in the PET meta-regression (*SE* = 0.74, $p = .280$), nor for the sampling variance in the PEESE meta-regression (*Vh* = 1.53, $p = .223$). Similar findings were obtained in separate analyses for auditory and linguistic processing (auditory processing, PET, SE = 0.60, $p = .629$, PEESE, *Vh* = 2.65, $p = .465$; linguistic processing, PET, *SE* = 0.76, $p = .318$; PEESE, *Vh* = 2.37, $p = .366$). In short, trim-and-fill is suggestive of the presence of publication bias, but PET-PEESE methods are not.

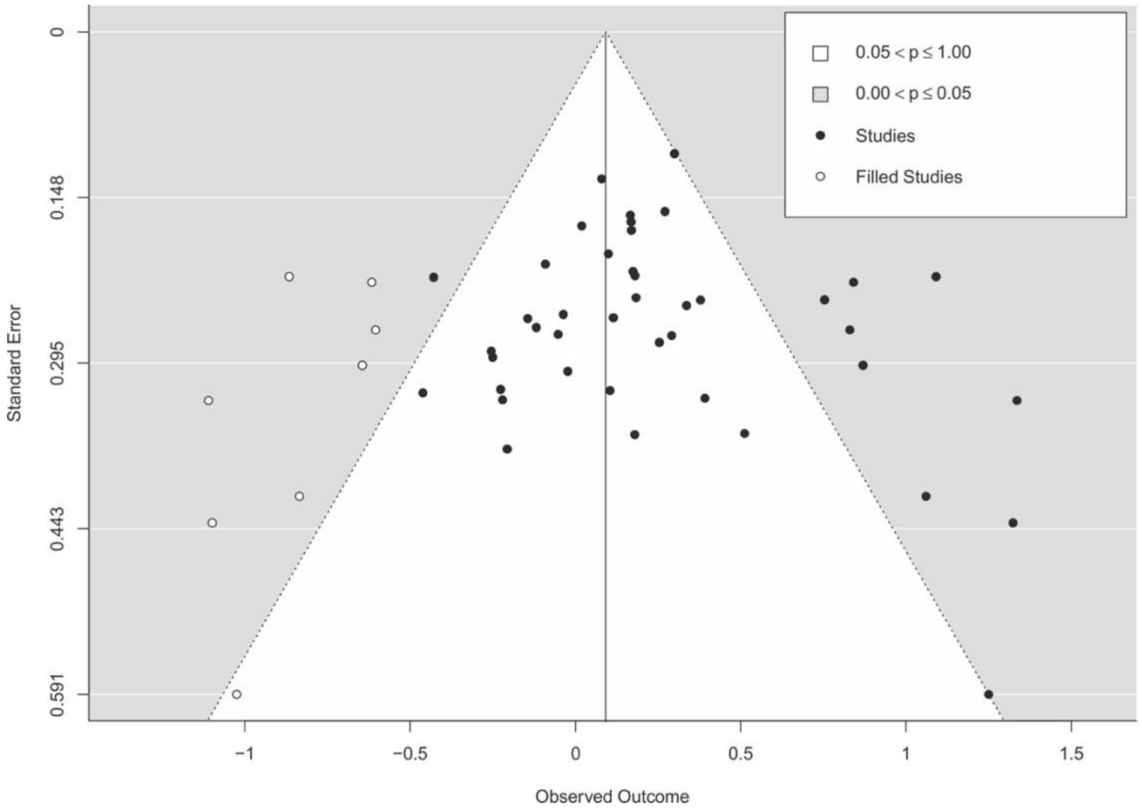

***Fig. 3***. Funnel plot with trim-and-fill of the aggregate effects of the studies. The y-axis represents the standard error of the aggregate effects, and the x-axis represents the magnitude of the effects (observed outcome). The vertical line represents the estimated common effect, and the black dots represent the aggregate effects of the studies included in the meta-analysis. The white dots represent eight missing studies imputed by the trim-and-fill using the *R0*estimator. The contour lines mark different standard levels of statistical significance (95% confidence interval).

## 3.4. Synthesis of brain data

### 3.4.1. Overview

Table 3 and Fig. 4 present an overview of the studies including measures of brain structure and/or activity in relation to auditory and linguistic processing. The omnibus sample size is 1059 participants (music groups = 481; passive control groups = 318; active control groups = 260). Out of the 27 identified studies, 18 investigated effects of music training on auditory processing and 15 on linguistic processing (six studies focused on both). Seventeen used electroencephalography (EEG), eight magnetic resonance imaging (MRI), and two magnetoencephalography (MEG). Most evidence comes from children (*n* = 15; adolescents, *n* = 2; adults, *n* = 5; older adults, *n* = 5). Twelve studies included a passive control group, eight an active control group, and seven included both.

| Study | *N* | Mean Age (years) | Groups (*n* per group) | Random Assignment | Instrumental Training | Primary Focus | Measure(s) | Task | Is There a Benefit of Music Training (*vs*. Control)? |
|---|---|---|---|---|---|---|---|---|---|
| Tervaniemi et al., 2022<br>(Cereb. Cortex) | 85 | 9.3 | Music (29)<br>Language (38)<br>Passive Control *(*18) | No | No | Processing of auditory novelty | EEG - ERP | Oddball paradigm<br>(multi-feature with tones and melodies) | ↑ MMN amplitude during tone frequency deviants (but not for tone location, duration and intensity deviants)<br>No significant effects for P3a amplitude (multi-feature with tones & melodies) |
| Hennessy et al., 2021<br>(Aging) | 41 | 58.3 | Music (18)<br>Passive Control (23) | Yes | No | Speech-in-noise discrimination | EEG - ERP | Oddball paradigm (pure tones) and speech-in-noise perception (active & passive task with syllables) | ↓ N1 latency in the active speech-in-noise discrimination task (but not for the passive speech-in-noise and oddball tasks)<br>↑ N1 amplitude in the passive speech-in-noise discrimination task (but not for the active speech-in-noise task)<br>↑ N1 amplitude for standard trials in the oddball task (but not distractor trials)<br>No significant effects for P1, P2 and P3-like amplitude and latency (active & passive speech-in-noise tasks; oddball task) |
| Alain et al., 2019<br>(Front. Neurosci.) | 53 | 68.2 | Music (17)<br>Visual Arts (19)<br>Passive Control *(*17) | No | No | Processing of auditory novelty | EEG – ERP | Oddball paradigm<br>(piano tones & vowels) | ↑ N1 and P2 amplitude for the piano tones, as compared to the passive control group (but not as compared to visual arts group)<br>No significant effects for vowels<br>No significant effects in the MMN (piano tones & vowels) |
| Dubinsky et al., 2019<br>(Front. Neurosci.) | 63 | 67.7 | Music (34)<br>Passive Control (29) | No | No | Speech perception | EEG - FFR | Passive perception of syllables | No significant effects (FFR strength at fundamental frequency) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Zendel et al., 2019<br>(Neurobiol. Aging) | 34 | 67.8 | Music (13)<br>Video Games (8)<br>Passive Control *(*13) | Yes | Yes | Speech-in-noise discrimination | EEG – ERP | Speech-in-noise perception (active & passive tasks with words) | ↑ N1 amplitude during passive listening to words (but not for the active task)<br>No significant effects for N1 latency<br>↑ Positive-going electrical brain activity during word repetition (but not for the passive task)<br>↑ Negative-going activity (700-1000ms) during passive listening |
| Nan et al., 2018<br>(Proc. Natl. Acad. Sci. U.S.A.) | 74 | 4.6 | Music (30)<br>Reading (28)<br>Passive Control (16) | No | Yes | Processing of auditory novelty | EEG – ERP | Oddball paradigm<br>(piano tones & words) | ↑ pMMR for both words and piano tones<br>Word discrimination based on consonants correlated with ↑ pMMR for piano tones (but not vowels)<br>No significant effects in the MMN and LDN (piano tones & words) |
| Carpentier et al., 2016<br>(J. Cogn. Neurosci.) | 30 | 5.6 | Music (14)<br>French (36) | No | No | Processing of auditory novelty | EEG – ERP | Oddball paradigm<br>(piano tones & vowels) | ↑ Multiscale entropy for piano tones and vowels<br>No significant effects for power spectrum density (piano tones & vowels) |
| Habibi et al., 2016<br>(Dev. Cogn. Neurosci.) | 37 | 6.9 | Music (13)<br>Sports (11)<br>Passive Control (13) | No | Yes | Processing of tones and auditory discrimination | EEG – ERP | Passive perception of tones (violin, piano & pure) and melody/rhythm discrimination | ↓ P1 amplitude during passive listening to piano tones (but not violin and pure tones)<br>↑ P3 amplitude in response to detected melody deviations, as compared to the passive control (but not as compared to sports group)<br>No significant effects in the P2 and N2 amplitude |
| Moreno et al., 2015<br>(Child Dev.) | 36 | 5.6 | Music (18)<br>French (18) | No | No | Processing of auditory novelty | EEG – ERP | Oddball paradigm<br>(piano tones & vowels) | ↑ LDN amplitude to piano tones<br>↓ LDN amplitude to vowels<br>No significant effects in the MMN (piano tones & vowels) |
| Tierney et al., 2015<br>(Proc. Natl. Acad. Sci. U.S.A.) | 40 | 14.7 | Music (19)<br>Fitness (21) | No | Yes | Speech perception | EEG – ERP | Passive perception of speech (syllables) | ↑ Response consistency across trials<br>No significant effects in cortical onset response (N1 – P1 amplitude) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Chobert et al., 2014<br>(Cereb. Cortex) | 24 | 8.3 | Music (12)<br>Painting (12) | No | No | Processing of auditory novelty | EEG – ERP | Oddball paradigm (syllables) | ↑ MMN amplitude to duration and voice onset time of deviant syllables<br>No significant effects for syllabic frequency |
| Kraus et al., 2014<br>(J. Neurosci.) | 44 | 8.3 | Music (26)<br>Passive Control (18) | Yes | Yes | Speech perception | EEG – Time Frequency | Passive perception of contrastive speech (syllables) | ↑ Neurophysiological distinction of contrastive syllables<br>More hours of music training predicted larger improvements in neurophysiological function |
| François et al., 2013<br>(Cereb. Cortex) | 24 | 8 | Music (12)<br>Painting (12) | No | No | Speech segmentation abilities | EEG – ERP | Speech discrimination<br>(pseudowords) | ↑ ERP difference between familiar and unfamiliar pseudowords (familiarity Effect in the 450-550ms latency window) |
| Tierney et al., 2013<br>(Front. Psychol.) | 43 | 14.7 | Music (21)<br>Fitness (22) | No | No | Speech-in-noise perception | EEG – Time Frequency | Passive perception of speech-in-noise (syllables) | ↓ Neural transmission delay between stimulus presentation and the neural response |
| Moreno et al., 2009<br>(Cereb. Cortex) | 32 | 8.4 | Music (16)<br>Painting (16) | No | No | Pitch discrimination in music and speech prosody | EEG – ERP | Melody and speech discrimination (sentences) | ↑ N300 amplitude to weak incongruities in melodies (small pitch variations)<br>↑ Amplitude of a long-lasting positivity to weak incongruities in sentences (small pitch variations)<br>↓ Positivity to strong incongruities in sentences (large pitch variations)<br>No significant effects for strong incongruities in melodies (large pitch variations)<br>No significant effects for congruous melodies and sentences |
| Shahin et al., 2008<br>(NeuroImage) | 12 | 4.7 | Music (6)<br>Passive Control (6) | No | No | Timbre-specific oscillatory gamma band activity | EEG – GBA | Passive perception of tones<br>(piano, violin & pure) | ↑ Induced GBA for piano and violin tones (as compared to pure tones)<br>No significant effects on evoked GBA |
| Moreno & Besson, 2006<br>(Psychophysiol.) | 20 | 8.5 | Music (10)<br>Painting (10) | No | No | Pitch discrimination in speech prosody | EEG – ERP | Speech discrimination (sentences) | ↓ Amplitude of a late positive component in response to strong incongruities in sentences (large pitch variations)<br>No significant effects for weak incongruities in sentences (small pitch variations)<br>No significant effects for congruous sentences |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Habibi et al., 2020<br>(Brain Struct. Funct.) | 23 | 7 | Music (12)<br>Passive Control (11) | No | Yes | Cortical thickness of Auditory Cortices | sMRI | - | No significant changes in cortical thickness |
| Li et al., 2020<br>(IEEE Trans. Neural Syst. Rehabil. Eng.) | 56 | 23.3 | Music (29)<br>Passive Control (27) | Yes | Yes | Dynamic integration of functional systems | Resting-state fMRI | - | ↑ flexible integration of primary functional systems, including the auditory system |
| Fleming et al., 2019<br>(Brain Cogn.) | 33 | 67.9 | Music (12)<br>Video Games (8)<br>Passive Control (13) | No | Yes | Speech-in-noise discrimination | fMRI | Speech-in-noise discrimination (sentences) | ↑ Responses to speech in left Middle Frontal Gyrus and right Medial Frontal Gyrus, left Supramarginal Gyri and right Superior/Middle Temporal Gyrus<br>↑ Responses to speech (left Middle Frontal and Supramarginal Gyri) were correlated with better speech-in-noise perception |
| Li et al., 2019<br>(Brain Struct. Funct.) | 56 | 23.2 | Music (29)<br>Passive Control (27) | Yes | Yes | Modularity in functional brain networks | Resting-state fMRI | - | ↑ Flexibility and intersystem connections of the auditory system |
| Habibi et al., 2018<br>(Cereb. Cortex) | 47 | 6.9 | Music (15)<br>Sports (15)<br>Passive Control (17) | No | Yes | Cortical thickness and volume of Auditory Cortices | sMRI | - | No significant effects (volume and cortical thickness) |
| Li et al., 2018<br>(Hum. Brain Mapp.) | 56 | 23.2 | Music (29)<br>Passive Control (27) | Yes | Yes | Functional and structural connectivity within and between auditory and sensorimotor regions | Resting-state fMRI & DTI | - | No significant changes in connectivity within auditory regions<br>↑ Functional and structural connectivity between auditory and motor regions |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Herdener et al., 2010<br>(J. Neurosci.) | 40 | 22.4 | Music (19)<br>Passive Control (21) | No | No | Processing of auditory novelty in the hippocampus | fMRI | Oddball paradigm<br>(tones) | ↑ Activity in the left anterior Hippocampus in response to temporal novelty in tones (stimulus onset asynchrony with different degrees of deviance) |
| Hyde et al., 2009<br>(J. Neurosci.) | 31 | 6.1 | Music (15)<br>Passive Control (16) | No | Yes | Brain structure and auditory skills | sMRI | - | ↑ Volume in the right Primary Auditory Area (Heschl's Gyrus)<br>↑ Volume in the right Auditory Area related to improvements on a melodic/rhythm discrimination test |
| Fujioka & Ross, 2017<br>(Eur. J. Neurosci.) | 14 | 63.5 | Music (7)<br>Passive Control (7) | No | Yes | Timing processing abilities | MEG - AEF | Passive perception of tones<br>(metronome beats) | ↑ Change of beat-induced beta modulation in the right auditory cortex (ERD & ERS) |
| Fujioka et al., 2006<br>(Brain) | 12 | 5.5 | Music (6)<br>Passive Control (6) | No | No | Processing of tones and noise | MEG - AEF | Passive perception of tones<br>(violin) and noise burst | ↑ N250 latency peak in response to the violin tone<br>↑ N250 amplitude in the left hemisphere to the violin tone<br>No significant effects for noise burst |

***Table 3.*** Overview of the studies included in the systematic review and narrative synthesis of music training effects on brain measures of auditory and linguistic processing (*N* = 27). The main findings are reported for statistically significant results (*p* < .05) comparing music training with control group(s). Abbreviations: AEF – Auditory Evoked Magnetic Field; BOLD – blood oxygen level-dependent imaging; DTI – diffusion tensor imaging; ERD – event-related desynchronization; ERP – event-related potential; ERS – event-related synchronization; FFR – frequency following response; fMRI – functional magnetic resonance imaging; GBA – gamma-band activity; ICA – independent component analysis; ICN – intrinsic connectivity networks; LDN – late discriminative negativity; MMN – mismatch negativity; pMMR – mismatch positivity; ROI – region of interest; sMRI - structural magnetic resonance imaging; ↑ – increased/enhanced/larger; ↓ – decreased/smaller

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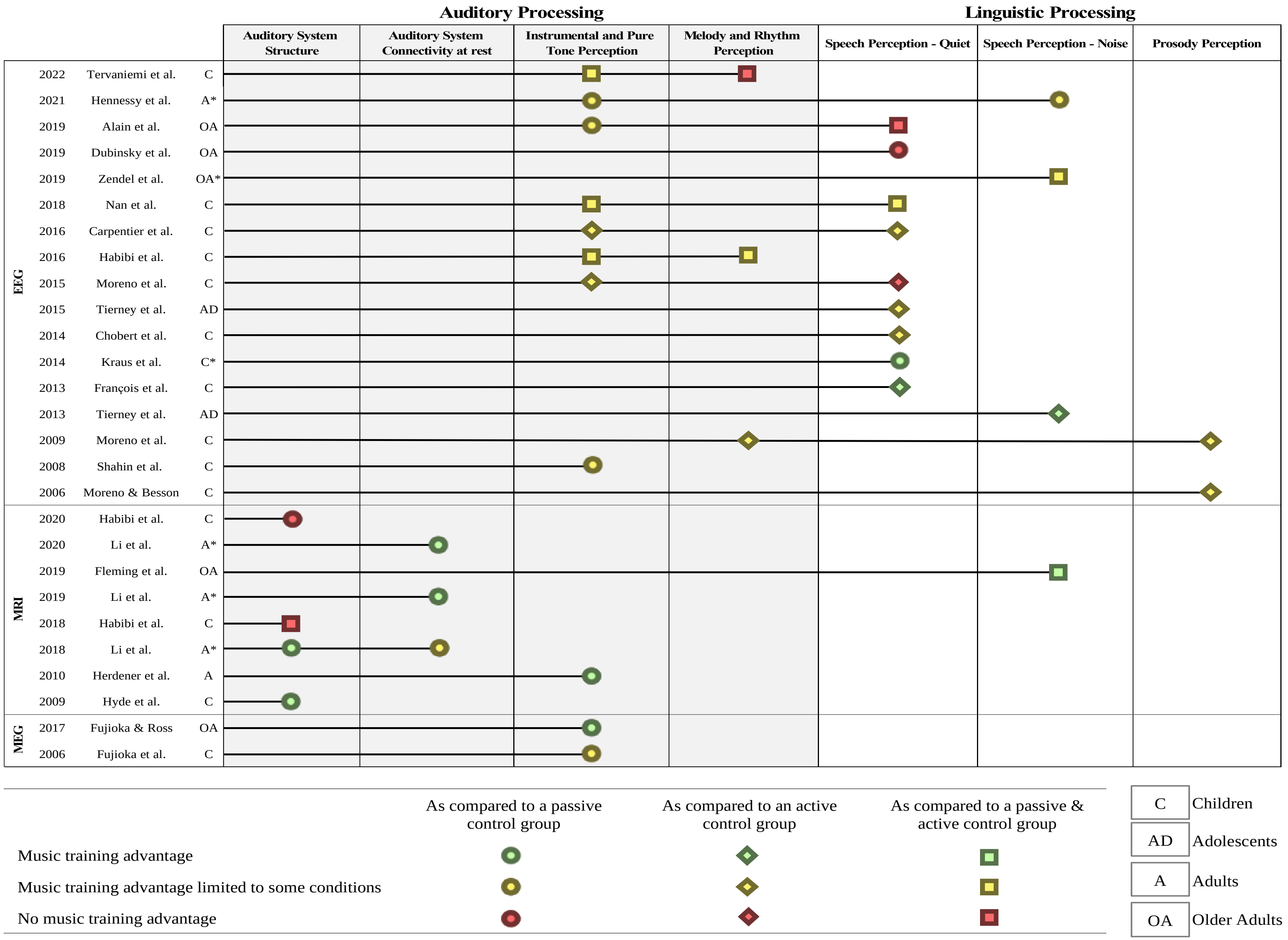
Auditory Processing
Linguistic Processing
Auditory System Structure
Auditory System Connectivity at rest
Instrumental and Pure Tone Perception
Melody and Rhythm Perception
Speech Perception - Quiet
Speech Perception - Noise
Prosody Perception
EEG
2022 Tervaniemi et al. C
2021 Hennessy et al. A*
2019 Alain et al. OA
2019 Dubinsky et al. OA
2019 Zendel et al. OA*
2018 Nan et al. C
2016 Carpentier et al. C
2016 Habibi et al. C
2015 Moreno et al. C
2015 Tierney et al. AD
2014 Chobert et al. C
2014 Kraus et al. C*
2013 François et al. C
2013 Tierney et al. AD
2009 Moreno et al. C
2008 Shahin et al. C
2006 Moreno & Besson C
MRI
2020 Habibi et al. C
2020 Li et al. A*
2019 Fleming et al. OA
2019 Li et al. A*
2018 Habibi et al. C
2018 Li et al. A*
2010 Herdener et al. A
2009 Hyde et al. C
MEG
2017 Fujioka & Ross OA
2006 Fujioka et al. C
As compared to a passive control group
As compared to an active control group
As compared to a passive & active control group
Music training advantage
Music training advantage limited to some conditions
No music training advantage
C Children
AD Adolescents
A Adults
OA Older Adults

***Figure 4.*** Synthesis of the studies examining music training effects on brain measures of auditory and linguistic processing. The studies are organized according to domain (auditory or linguistic processing) and technique (EEG, MRI, or MEG). Green symbols indicate that the study reported an advantage of music training over passive and/or active control group(s); yellow ones indicate that the advantage was limited to some conditions (e.g., reduction of cortical thickness but not cortical volume); and red ones indicate that no advantage of music training was found. Circles indicate that the control group was passive, rhombuses that it was active; and squares that the study had passive and an active control group. “C” indicates studies with children, “AD” with adolescents, “A” with adults, and “OA” with older adults. The asterisks indicate that assignment to the groups was random.

### 3.4.2. Auditory processing

Studies of music training effects on auditory processing have focused on instrumental and pure tone perception (*n* = 11), and on melody and/or rhythm perception (*n* = 3). EEG was the technique used more often (*n* = 11), followed by MEG (*n* = 2) and fMRI (*n* = 1). Instrumental and pure tone perception was examined in eight EEG, one fMRI and two MEG studies, and all asked participants to passively listen to streams of tones (e.g., piano, violin, or pure tones). Seven of these studies used oddball tasks, which examine participants' responses to deviant tones (e.g., A#), presented rarely among more frequent standard tones (e.g., A). The remaining four studies presented a stream of tones but without deviants. Melody and rhythm perception were examined in three EEG studies. One examined participants' responses to deviant melodies using an oddball task (Tervaniemi et al., 2022), and the remaining two asked participants to make same/different judgments on pairs of musical stimuli (Habibi et al., 2016, Moreno et al., 2009). Our synthesis also included six MRI studies that had no task or stimuli but focused on auditory systems and/or their connectivity. Four of them examined music training effects on structural aspects of auditory systems, including connectivity (Li et al., 2018), and cortical thickness and volume (Habibi et al., 2018, Habibi et al., 2020, Hyde et al., 2009). Three focused on functional connectivity of auditory (Li et al., 2019, Li et al., 2020) and auditory-motor networks (Li et al., 2018; this study included both sMRI and fMRI). One MRI study also examined associations between the volume of auditory areas and behavioral performance in a melody/rhythm discrimination task (Hyde et al., 2009).

Most studies on auditory processing were conducted with children (*n* = 11; adults, *n* = 5; older adults, *n* = 2), and compared music training groups with passive control (n = 11) and/or active control groups (*n* = 7). Moreover, most studies have not used random assignment of participants (*n* = 14), and an equal number of studies had instrumental and non-instrumental training programs (*n* = 9 for each). Sixteen out of 18 studies (88.89%) reported some significant benefit of music training on auditory processing (see Fig. 4). This was observed across age groups, regardless of the type of control group, use of random assignment, and type of training program. It was often the case, however, that the benefits were limited to some of the included measures (*n* = 11 out of 16, 68.75%). For example, in an EEG study with children, Moreno et al. (2009) found significant effects in the amplitude of N300 in response to weak incongruities in melodies (small pitch variations), but not in response to strong incongruities (large pitch variations). The two studies that did not find significant effects of music training were sMRI studies focused on children's cortical thickness and volume of auditory cortices (Habibi et al., 2018, Habibi et al., 2020).

### 3.4.3. Linguistic processing

Studies of music training on linguistic processing have focused on speech perception, both in typical/quiet conditions (*n* = 9) and in noise (*n* = 4), as well as on speech prosody perception (*n* = 2). EEG was the technique used in all studies, except for the fMRI study of speech-in-noise perception by Fleming et al. (2019). In the studies examining speech perception in quiet, participants were asked to passively listen to streams of spoken stimuli, which consisted of vowels (e.g., Alain et al., 2019), words (Nan et al., 2018), or syllables (e.g., Kraus et al., 2014), for instance. Five of these studies have used an oddball task, and the remaining four did not include deviant stimuli. There was only one study that included an active task, asking participants to make familiarity judgments (familiar vs. unfamiliar) on pseudowords, which could be new to them or previously presented in a familiarization phase (François et al., 2013). The studies that examined speech-in-noise perception also varied in the type of stimuli (e.g., syllables, Hennessy et al., 2021; sentences, Fleming et al., 2019) and task. One study used passive listening (Tierney et al., 2013), while the remaining three included active tasks. For example, Zendel et al. (2019) asked participants to repeat words aloud. The two studies that examined prosody perception focused on the detection of pitch violations inserted at the end of spoken sentences (e.g., the fundamental frequency of the last word was increased by 120%). Specifically, children were asked to decide whether the last word seemed normal or strange (Moreno and Besson, 2006, Moreno et al., 2009).

Most studies on linguistic processing were conducted with children (n = 8; adolescents, n = 2; adults, n = 1; older adults, n = 4), and compared music training groups with passive control (n = 3) and/or active control groups (n = 12). Moreover, most studies have not used random assignment of participants (n = 12) and had non-instrumental training programs (n = 10). Twelve out of 15 studies (80%) reported some significant benefit of music training on linguistic processing. The effects were observed across age groups, regardless of the type of control group, use of random assignment, and type of training program. Nonetheless, these benefits were also often limited to some of the included measures (n = 8 out of 12, 66.67%). For instance, Hennessy et al. (2021) found significant effects for adults' N1 amplitude during passive listening to speech-in-noise, but not for the active speech-in-noise task (participants were asked to press a button when they could hear a target syllable). Moreover, three studies reported null results (e.g., cortical processing changes in older adults during the perception of deviant vowels; Alain et al., 2019).

### 3.4.4. Summary

The reviewed studies provide initial evidence that music training changes brain responses to auditory and linguistic stimuli, and the structure and functional dynamics of auditory systems. The benefits appear to be similar across age groups, but most evidence comes from children (55.56%), and therefore conclusions for the other groups remain tentative or non-existent. For example, no studies examined auditory processing in adolescents, and there was only one study examining linguistic processing in adults. Benefits seem to be observed slightly more often for auditory compared to linguistic processing (88.89% vs. 80% of the studies, respectively), but the type of control group did not make a difference (the percentage of studies reporting at least some positive effects of music training was 84.21% in the case of passive control groups, and 86.67% in the case of active control groups). Although random assignment did not seem to make a difference in the observed benefits (all studies using random assignment reported at least some positive effects), most studies did not have random assignment (77.78%). The role of randomization therefore remains an open question. Additionally, the number of studies with instrumental and non-instrumental training was relatively balanced (48.15% vs. 51.85%, respectively), and the percentage of studies that reported at least some positive effects was high in both cases (92.31% for instrumental training, and 85.71% for non-instrumental training).

Although the percentage of studies reporting positive effects was high, in many of them the effects were restricted to some of the measures or conditions (auditory domain: 68.75%, linguistic domain: 66.67%), and six studies reported null results. For both auditory and linguistic processing, the effects seem roughly similar across the covered subdomains.

## 4. Discussion

We examined evidence for behavioral and brain effects of music training on auditory and linguistic processing. For the behavioral data, a multivariate meta-analysis revealed a small benefit of music training ($\bar{g}_{\Delta}$ = 0.31), which remained significant after the exclusion of outliers ($\bar{g}_{\Delta}$ = 0.22). The effect was observed regardless of the domain (auditory vs. linguistic), type of music training (instrumental vs. non-instrumental), type of control group (active vs. passive), or strategy of assignment to the groups (random vs. non-random). We found no overall differences between the music and control groups at baseline, but variation in the magnitude of baseline differences moderated music training effects: the larger the differences prior to training, the smaller the improvements. Moreover, meta-regression methods provided no evidence of publication bias (PET-PEESE), but trim-and-fill did, and the music training effect became non-significant after bias correction using this method. For the brain data, a narrative synthesis also provided evidence for a positive effect of music training, both for auditory and linguistic processing. In many of the included studies, effects were restricted to some of the included measures or conditions, though. Thus, the available literature provides evidence that music training causes small improvements in auditory and linguistic processing, but future studies will need to confirm that effect size estimates are not being inflated by publication bias.

### 4.1. Behavioral data

Previous meta-analyses examined far transfer effects of music training (e.g., Cooper, 2020; Román-Caballero et al., 2022; Sala & Gobet, 2020) but, to our knowledge, none has focused on near transfer. Empirical studies also show that there is more interest in far compared to near transfer: in our meta-analysis, 36 studies examined linguistic skills, and only 15 examined auditory skills. Perhaps near transfer effects are taken for granted and thought to require less attention, but examining them is central considering recent evidence that they might be weak or non-existent (Kragness et al., 2021, Schellenberg, 2020c). Moreover, if transfer from music to linguistic processing results from sharper auditory processing (e.g., Besson et al., 2011; Goswami, 2011; Patel, 2014), we need to establish that music training changes auditory skills. We provide meta-analytic evidence that music training can enhance aspects such as rhythm, pitch, and timbre discrimination. The fact that the study design did not play a role suggests that the benefits are unlikely to result from self-selection or nonmusical aspects of the training. Furthermore, we did not find differences between music and control groups at baseline, even when conducting separate analyses for studies with random vs. non-random assignment, which reinforces the idea that the benefits are unlikely to reflect self-selection. Benefits in auditory abilities are consistent with the notion that the auditory system is altered by music training (e.g., Herholz & Zatorre, 2012), and with correlational evidence of advantages in these abilities in musicians (e.g., Rammsayer & Altenmüller, 2006; Schellenberg & Moreno, 2010; Tervaniemi et al., 2005).

Along with general cognitive abilities such as IQ, language is the most studied domain of far transfer from music training, and the one that attracts more theorizing (e.g., Besson et al., 2011; Patel, 2014). Previous meta-analyses covered language-related outcomes (e.g., Gordon et al., 2015; Román-Caballero et al., 2018; Sala & Gobet, 2020), but because their scope was broader, a comprehensive analysis of different aspects of linguistic processing was missing. Moreover, meta-analytic findings are mixed. For instance, Gordon et al. (2015) found significant benefits for phonological awareness in children, but not for reading fluency. Román-Caballero et al. (2018) found significant benefits for phonological verbal fluency in older adults, but not for semantic verbal fluency. Three meta-analyses found small-to-moderate benefits for general cognitive and academic outcomes in children, including aspects of verbal abilities such as vocabulary and phonological processing (Cooper, 2020, Román-Caballero et al., 2022, Sala & Gobet, 2020). Here we conducted the most extensive review of longitudinal data on music training and linguistic abilities, covering studies from all age groups, and found that the benefits are significant and similar across a range of domains, including phonological awareness, speech discrimination, reading, verbal fluency, and general linguistic skills (e.g., verbal IQ). These benefits were comparable to those observed for auditory abilities, and are also unlikely to reflect self-selection effects or nonmusical aspects of the training. That random assignment and type of control group did not play a role is consistent with recent meta-analyses on far transfer (Bigand and Tillmann, 2022, Román-Caballero et al., 2022; but see Sala and Gobet, 2020). More work will be needed to reconcile the benefits observed in longitudinal data with the pattern that emerges from correlational data. Many correlational studies report advantages of musicians in linguistic abilities, such as prosody perception (Lima and Castro, 2011, Marques et al., 2007), but these advantages are not always replicated (e.g., Trimmer and Cuddy, 2008), and the pattern of results for abilities such as speech-in-noise perception is mixed (Boebinger et al., 2015, Kaplan et al., 2021, Madsen et al., 2019, Parbery-Clark et al., 2009). Because correlation does not imply causation, but causation implies correlation, future studies need to uncover the sources of variability in the literature. Crucially, by documenting experience-dependent effects, we do not mean to overlook pre-existing factors. Recent evidence indicates that music training is not necessary to account for enhancements in linguistic abilities: musically untrained individuals with good musical abilities show a more efficient neural encoding of speech (Mankel & Bidelman, 2018), enhanced performance in tasks of speech perception (Swaminathan and Schellenberg, 2017, Swaminathan and Schellenberg, 2020), and better emotion recognition in speech prosody (Correia et al., 2020), mirroring the benefits observed in musicians. Both nature and nurture seem to account for associations between music and nonmusical domains.

The amount of heterogeneity in effect sizes across studies was high (76.38%), in line with meta-analyses based on pre-post intervention effect sizes (Cuijpers et al., 2017). In previous meta-analyses of music training effects, I2 values ranged from 34% (Cooper, 2020) to 96% (Román-Caballero et al., 2018). However, the high levels of unexplained heterogeneity here were partially explained by influential effect sizes, as indicated by Cook's distance values. After removing two influential studies, heterogeneity remained significant but decreased (57.75%). The sources of the remaining variability are unclear. Although we considered ten moderators, only the baseline difference between groups was significant. The larger the differences at baseline, the smaller the effect of music training. This moderator accounted for 9.24% of the heterogeneity, which decreased from 57.75% to 48.51%. A moderating role of baseline differences has also been found by Román-Caballero et al. (2022) and Sala and Gobet (2020). Participants with lower abilities before training could have more room for improvement, or there might be regression toward the mean when samples differ markedly at baseline. The potential role of baseline performance levels in how much participants benefit from music training is an interesting avenue for future research.

Recent work suggests that the type of music training (instrumental vs. non-instrumental) could account for discrepancies across studies (Román-Caballero et al., 2022), but that was not observed here. Instrumental and non-instrumental training programs seem to have comparable effects in auditory and linguistic processing. Future studies could ask whether the putative advantage of instrumental training is more salient for transfer domains less reliant on auditory skills – auditory skills (which are important for auditory but also for many language tasks) are typically an important focus of both instrumental and non-instrumental training programs. Other characteristics of the training could also be a source of variability (e.g., individual vs. group training; vocal vs. instrumental training), and the same applies to the tasks and stimuli used to assess transfer.

## 4.2. Brain data

The present work provides the first systematic synthesis of electrophysiological and neuroimaging data on how music training shapes auditory and linguistic processing. The fact that most studies reported positive effects in at least some of the conditions (88.89% for auditory processing, 80% for linguistic processing) suggests that the observed behavioral benefits can be traced to plastic changes in brain structure and function. Most evidence comes from EEG studies with children (e.g., Carpentier et al., 2016; Moreno et al., 2015), but the number of those using MRI has been increasing (e.g., Habibi et al., 2020; Li et al., 2020).

Consistent with the behavioral data, EEG studies provide evidence that music training can shape several aspects of cortical auditory processing, including those related to instrumental and pure tone perception, and melody and rhythm perception. Positive effects are observed regardless of whether the control groups were passive or active. Tervaniemi et al. (2022), for example, found that music training led to higher MMN amplitude during passive listening to tone frequency deviants in an oddball paradigm. These findings arguably reflect an effect of music training at relatively automatic stages of auditory processing, but task-based studies indicate that effects can be seen at more controlled stages of processing too. Using a melody discrimination task, Moreno et al. (2009) found that music training was associated with a higher N300 amplitude during the perception of small pitch variations in melodies. MRI studies suggest that, in addition to effects on brain responses to auditory stimuli, music training can change the morphology, structural connectivity, and intrinsic functional connectivity of auditory systems. For instance, Hyde et al. (2009) found that music training increased cortical volume in the right primary auditory region in children, and Li et al. (2018) found enhanced structural connectivity between auditory and motor regions in adults. Li et al. (2019) also found that music training enhanced flexibility and intersystem connectivity of the auditory system. Moreover, a literature review suggests that music training might counteract age-related changes in auditory perception and cognition that manifest in late adulthood (Alain et al., 2014). Thus, there is evidence for music training effects on auditory processing at the levels of behavior and brain structure and function.

Our review also highlights that most neuroscientific evidence for music training effects on linguistic processing comes from studies on spoken language perception in quiet (60% of the studies). These studies have often used a passive listening approach. For example, Chobert et al. (2014) found that music training increased the MMN amplitude during passive listening to deviant syllables, and Nan et al. (2018) found increased pMMR amplitude during the perception of words (oddball paradigms). Although fewer, there are also studies that reported promising results for speech-in-noise perception and prosody perception. Zendel et al. (2019) found that music training increased N1 amplitude during speech-in-noise perception, and enhanced a positive-going electrical brain activity during word repetition. Furthermore, Moreno et al. (2009) found that music training was associated with increased amplitude of a long-lasting positivity in response to small pitch variations in sentences. Not only these findings are consistent with those obtained in the meta-analysis of behavioral data, but they are also in line with the notion that music and speech share neurocognitive pathways (e.g., Peretz et al., 2015; Zatorre et al., 2002). A potential explanation for the effects is that music training demands high precision on these shared pathways, leading to neurobehavioral plastic changes that also result in benefits for speech (Patel, 2014).

Both for auditory and for linguistic processing, positive effects of music training were often limited to some of the measures and/or conditions included in the studies. This might reflect true specificity of the effects, but it also raises concerns regarding potential false positives, particularly when no corrections for multiple comparisons are implemented. The small number of participants in many of the published studies adds to these concerns (n < 20 in the music training groups for 18 of the 27 identified studies, 66.67%), precluding definitive conclusions before the findings are replicated in larger samples. More well-powered studies, along with stricter statistics and more explicit hypotheses (regarding which measures are expected to improve and which ones are not), will shed light on the observed variability across studies. For example, in studies with children, while Moreno et al. (2009) reported that music training increased the amplitude of a long-lasting positivity in response to small pitch variations in sentences, Moreno and Besson (2006) found no effects using the same task on a different sample. This variability might additionally relate to the characteristics of music training programs, stimuli and tasks, which remain poorly explored. Moreover, because most available evidence is based on children, future work will be crucial to determine whether similar findings are observed for older participants. Finally, we were unable to perform a quantitative meta-analysis of the brain data because of the small number of studies and heterogeneity in the outcome measures. But, as the number of existing studies grows, it will be important to revisit these findings quantitatively.

## 4.3. Clinical implication and future directions

By documenting positive effects of music training, the present review suggests that musical activities could be an effective, safe, and comfortable tool to improve auditory and linguistic skills. These skills are crucial for everyday communication and social interactions (e.g., Neves, Martins et al., 2021; Parbery-Clark et al., 2011), and they are impaired in conditions such as dyslexia, specific language impairment, and hearing impairment treated with cochlear implantation. We note that the benefits of training were small, though, raising questions regarding their practical significance. There are some studies directly examining whether music training improves auditory and linguistic processing in clinical conditions (e.g., Cheng et al., 2018; Frey et al., 2019; Fuller et al., 2018), but this research is in its infancy and shares some of the problems observed in the music training literature, including small sample sizes, non-random assignment, and lack of active control groups. Additionally, although musical activities can have a unique motivational component, learning to play a musical instrument requires effort and time. It remains unclear whether shorter and focused interventions targeting specific auditory and linguistic impairments could be more efficient than music training. This would not mean that there is no value in engaging in musical activities. Music is fundamentally linked with positive emotions, mood regulation, and social bonding, and these are arguably the primary motives for the ubiquity of musical behaviors (e.g., Koelsch, 2014; Tarr et al., 2014).

We have also identified several limitations in the existing literature on music training that will need to be addressed in future work, as we summarize in Table 4. Improving aspects such as sample size, design quality, and unbiased reporting of findings will be crucial to reach firmer conclusions regarding near and far transfer effects. Publication bias is a particularly important issue. Meta-regression methods showed no evidence of bias, but the trim-and-fill method suggested that we cannot be sure that the music training effects truly exist beyond the reach of selective reporting of positive findings. To further complicate things, the available bias-correction methods have limitations, which might under- or over-correct meta-analytic estimates for biases (e.g., Stanley, 2017). In any event, future longitudinal studies on music training should adopt strategies to counteract publication bias, such as preregistration (see Table 4).

| Concerns | Suggestions |
|---|---|
| Variability and lack of detailed information about the training programs | ● Reporting details about the amount of training, including total duration, number of sessions per week, and whether participants are encouraged to practice at home or not<br>● Providing a rationale and detailed description of the contents of training programs, including the covered skills and how they will be trained<br>● Being explicit about the mechanistic links between the trained skills and the expected transfer effects<br>● Linking the hypotheses to the specific features of training as much as possible |
| Evidence mostly limited to children | ● Focusing on other age groups to determine whether the effects are age-dependent or more general across the life span |
| Small sample sizes | ● Including larger samples, ideally informed by power analyses<br>● Optimizing the reliability and validity of the measures (e.g., by using validated measures and/or running pilot studies) |
| Suboptimal designs | ● Allocating participants randomly to the groups<br>● Including active control groups<br>● Controlling for confounding variables such as personality, cognitive abilities and socioeconomic status |
| Selective reporting and emphasis on findings favoring the music group | ● Preregistering the studies, specifying details such as the full list of measures, hypotheses and plans for analyses<br>● Reporting null results and consider them when discussing significant ones<br>● Distinguishing between confirmatory and exploratory analyses<br>● Data sharing |

***Table 4.*** Identified concerns and suggestions for future longitudinal studies on music training effects.

## 4.4. Conclusions

The present review provides evidence that music training has a small positive effect on auditory and linguistic processing. A multivariate meta-analysis showed that the benefits can be observed across a range of behavioral tasks, and a narrative synthesis of neuroscientific studies showed that they can also be observed at the level of brain function and structure. A causal role of music training can be inferred because we focused exclusively on longitudinal evidence, the effects were observed regardless of whether the assignment to the groups was random or not, and there were no differences between the music and control groups before training. These findings are suggestive of both near and far transfer, and have implications for debates on plasticity and on the use of music as an intervention tool in educational and clinical contexts. Because current evidence is often based on small samples, further well-powered studies are needed to establish the reliability of the findings. We have also obtained some evidence that publication bias might be inflating the true effect of music training, an issue that should be considered in future work.

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# CHAPTER III | CROSS-SECTIONAL STUDY[2]

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[2] This chapter is published in ***Royal Society Open Science***:

Neves, L., Martins, M., Correia, A. I., Castro, S. L., & Lima, C. F. (2021). Associations between vocal emotion recognition and socio-emotional adjustment in children. *Royal Society Open Science*, *8*(11), 211412.

# Abstract

The human voice is a primary channel for emotional communication. It is often presumed that being able to recognize vocal emotions is important for everyday socioemotional functioning, but evidence for this assumption remains scarce. Here, we examined relationships between vocal emotion recognition and socio-emotional adjustment in children. The sample included 141 6- to 8-year-old children, and the emotion tasks required them to categorize five emotions (anger, disgust, fear, happiness, sadness, plus neutrality), as conveyed by two types of vocal emotional cues: speech prosody and non-verbal vocalizations such as laughter. Socio-emotional adjustment was evaluated by the children's teachers using a multidimensional questionnaire of self-regulation and social behaviour. Based on frequentist and Bayesian analyses, we found that, for speech prosody, higher emotion recognition related to better general socio-emotional adjustment. This association remained significant even when the children's cognitive ability, age, sex and parental education were held constant. Follow-up analyses indicated that higher emotional prosody recognition was more robustly related to the socio-emotional dimensions of prosocial behaviour and cognitive and behavioural self-regulation. For emotion recognition in non-verbal vocalizations, no associations with socio-emotional adjustment were found. A similar null result was obtained for an additional task focused on facial emotion recognition. Overall, these results support the close link between children's emotional prosody recognition skills and their everyday social behaviour.

*Keywords:* Emotion Recognition, Vocal Emotions, Speech Prosody, Socio-Emotional Adjustment, Children

## 1. Introduction

We perceive emotional information through multiple communication channels, including vocal and facial expressions. These channels offer a window into the emotions of others, and the ability to recognise the conveyed states is an integral part of everyday communication. Although most research has focused on facial expressions, the human voice is a major source of emotional information that reflects a primitive and universal form of communication (Ghazanfar & Rendall, 2008; Latinus & Belin, 2011). We can communicate vocal emotions via linguistic information but also via nonverbal cues. Hearing a scream, for instance, might indicate that someone needs help or that there is a threat nearby. Nonverbal emotional cues in the human voice can be divided into two domains: inflections in speech, so-called emotional prosody; and purely nonverbal vocalisations, such as laughter and crying, often called affective bursts (e.g., Grandjean, 2021).

Emotional prosody corresponds to suprasegmental and segmental modifications in spoken language during emotion episodes. Prosodic cues include pitch, loudness, *tempo*, rhythm, and timbre, as embedded in linguistic content (Grandjean et al., 2006; Schirmer & Kotz, 2006). Purely nonverbal vocalisations, on the other hand, do not contain any linguistic information (e.g., screams, laughter), and they represent a more primitive form of communication, sometimes described as the auditory equivalent of facial expressions (Belin et al., 2004). Prosody and nonverbal vocalisations rely on partly distinct articulatory and perceptual mechanisms (Pell et al., 2015; Scott et al., 2010). Based primarily on studies with adults, we know that listeners can accurately identify several positive and negative emotions from the two types of vocal emotional cues, even when they are heard in isolation and without contextual information (e.g., Castro & Lima, 2010; Cowen et al., 2019; Lima et al., 2013a; Sauter et al., 2010). But it has also been shown that emotion recognition accuracy is higher for nonverbal vocalisations compared to prosody (Hawk et al., 2009; Kamiloglu et al., 2020; Sauter et al., 2013).

In development, soon after birth, infants can discriminate emotional expressions in nonverbal vocalisations (e.g., Soderstrom et al., 2017) and prosodic cues (e.g., Flom & Bahrick, 2007). Emotion recognition abilities improve throughout childhood and adolescence, although it is still not established when they peak (Amorim et al., 2019; Grossmann et al., 2010; Morningstar et al., 2018; Sauter et al., 2013). Infants and young children also show a general preference for auditory over visual information (e.g., tones *vs*. lights, Nava & Pavani, 2013; natural sounds *vs.* pictures, Wille & Ebersbach, 2016), which might extend to emotional cues. For instance, Ross et al. (2021) observed that children under the age of eight find it challenging to ignore vocal emotional cues in multimodal stimuli, even if explicitly asked to base their judgment on body cues alone.

Even though it is typically presumed that vocal emotion recognition skills are crucial for communication at any age, research has primarily focused on more basic acoustic, perceptual and neurocognitive aspects of these expressions (e.g., Grandjean, 2021; Schirmer & Kotz, 2006). Evidence for associations with broader aspects of everyday socio-emotional functioning remains relatively scarce, particularly in normative samples. Socio-emotional functioning has been defined as a multidimensional and broad concept (Edwards & Denham, 2018). It includes the ability to understand our own and others' emotions, to regulate our own behaviour, and to establish and maintain relationships (Denham et al., 2015; Murray et al., 2015). These processes start to develop early in life and are linked to health outcomes and well-being (Nelis et al., 2011; Ogren & Johnson, 2020).

Studies on clinical populations are suggestive of a link between vocal emotional processing and socio-emotional functioning, both in adult (e.g., Amminger et al., 2012; Jaywant & Pell, 2009; Lima et al., 2013b) and paediatric samples (Deveney et al., 2012; Morningstar et al., 2019; O'Nions et al., 2017). For instance, youth with severe mood dysregulation and bipolar disorder (Deveney et al., 2012), and with depressive symptoms (Morningstar et al., 2019), show impaired recognition of emotional prosody. There are fewer studies on healthy samples, but they point in the same direction. Carton et al. (1999) showed that better emotional prosody recognition was associated with better self-reported relationship well-being in healthy adults, even after controlling for depressive symptoms. Terracciano et al. (2003) also found that better emotional prosody recognition correlated with self-reported openness to experience, a trait linked to social behaviour engagement (e.g., Cabrera et al., 2006; Saef et al., 2018). We have shown that the ability to recognise laughter authenticity is associated with higher empathic concern and trait emotional contagion in adults (Neves et al., 2018). However, there are also null results regarding vocal emotion recognition and traits associated with social behaviour, such as agreeableness and extraversion (Furnes et al., 2019).

Children, like adults, make use of vocal emotions in social interactions, and it is important to understand how this relates to their socio-emotional adjustment, given that childhood is a pivotal period for socio-emotional development (Edwards & Denham, 2018; Denham et al., 2015). Studies with pre-schoolers found that higher emotional prosody recognition correlates with higher peer-rated popularity and lower teacher-rated emotional/behavioural problems (Nowicki & Mitchell, 1998), as well as with lower parent-rated hyperactivity and conduct problems (Chronaki et al., 2015). Studies with school-age children have also documented associations between emotional prosody recognition and socio-emotional variables including self-reported social avoidance and distress (McClure & Nowicki, 2001), teacher-rated social competence (Leppänen & Hietanen, 2001; Rothman & Nowicki, 2004) and emotional and behavioural difficulties (Nowicki et al., 2019), and peer-rated popularity (Leppänen & Hietanen, 2001; see also Baum & Nowicki, 1998). However, some of the identified associations are limited to particular groups (e.g., observed for girls, but not for boys; Leppänen & Hietanen, 2001; Nowicki & Mitchell, 1998), and null results have been reported too. For instance, pre-schoolers' emotional prosody recognition did not correlate with teacher-rated externalising problems (Nowicki & Mitchell, 1998) and parent-rated internalising behaviour (Chronaki et al., 2015). Additionally, inferences have often been based on relatively small samples, typically less than 80 children, and the focus has been on prosody, leaving the other domain of vocal emotional cues – purely nonverbal vocalisations – unexplored. To our knowledge, only one study included nonverbal vocalisations, and the emphasis was on how children matched vocal with facial information (Scheerer et al., 2020). Other poorly understood questions are whether associations between vocal emotion recognition and socio-emotional functioning are specific and direct, or a consequence of general differences in cognitive abilities and socio-economic background. These general factors correlate with emotion recognition abilities (e.g., Erhart et al., 2019; Izard et al., 2000) and social functioning (e.g., Bellanti & Bierman, 2000; Dearing et al., 2006; Gilman et al., 2003), and they are often not considered as potential confounds (e.g., Chronaki et al., 2015; Leppänen & Hietanen, 2001).

In the current study, we asked whether vocal emotion recognition relates to socio-emotional adjustment in six- to eight-year-old children. We covered emotional speech prosody and nonverbal vocalisations, and hypothesized that higher emotion recognition accuracy would be associated with better socio-emotional functioning. If children with a greater ability to recognise emotions from vocal cues are better at interpreting social information, this could favour everyday socio-emotional functioning outcomes, such as the willingness to be friendly and helpful with others, and the ability to stay calm and focused. Participants completed forced-choice emotion recognition tasks focused on the two types of vocal emotional cues. Their teachers were asked to evaluate children's socio-emotional functioning using The Child Self-Regulation and Behaviour Questionnaire (CSBQ; Howard & Melhuish, 2017). This is a multidimensional measure, which allows for an analysis of several socio-emotional dimensions (e.g., sociability, prosocial behaviour, emotional self-regulation), and it correlates with outcomes such as peer relationship problems and emotional symptoms (Howard & Melhuish, 2017). We predicted that children scoring higher on vocal emotion recognition would be rated by their teachers as more socio-emotionally competent in general. We also examined whether this putative association was limited to a particular group of participants (e.g., girls), or driven by general cognitive and socio-economic factors. In other words, we tested if results remained significant when individual differences in age, sex, cognitive ability, and parental education are accounted for. This is relevant, considering the reviewed evidence that results can be distinct as a function of sex and age, and that cognitive and socio-economic factors can be associated with emotion recognition and social functioning, therefore being potential confounds.

More exploratory questions asked which socio-emotional functioning dimensions are more clearly linked to vocal emotion recognition, and whether associations between emotion recognition and social-emotional functioning are specific to the auditory domain, or are similarly seen across sensory modalities. In addition to the two vocal emotion recognition tasks, children also completed an emotion recognition task that focused on facial expressions. There is some evidence that better facial emotion recognition relates to fewer behavioural problems (Chronaki et al., 2015; Nowicki & Mitchell, 1998; Nowicki et al., 2019) and better self-regulation skills in children (Rhoades et al., 2009; Salisch et al., 2015). But null results have also been reported, namely regarding social avoidance and distress (McClure & Nowicki, 2001) and peer popularity (Leppänen & Hietanen, 2001). Moreover, studies that include the two sensory modalities (i.e., vocal and facial emotions) are relatively rare, and they have also reported mixed findings (e.g., McClure & Nowicki, 2001).

## 2. Method

### 2.1. Participants

One hundred forty-eight children were recruited from elementary public schools in a metropolitan area in Northern Portugal (Porto). Seven were excluded due to neurological diseases (*n* = 2), atypically low general cognitive ability (Ravens' score < 25th percentile; *n* = 4), or lack of data regarding the socio-emotional measure (*n* = 1). The final sample included 141 children (73 boys) between six and eight years of age (*M* = 7.14 years, *SD* = 0.51, range = 6.34 - 8.89). They were 2nd graders from seven different classes, each with one teacher assigned for the entire year. All children were Portuguese native speakers and, according to parent reports, had normal hearing and no neurological/neurodevelopmental disorders (e.g., autism spectrum disorders). Parents' education varied from four to 19 years (*M* = 10.98; *SD* = 3.46). Participants were tested as part of a longitudinal project looking at the effects of music training on emotion recognition and socio-emotional behaviour.

An *a priori* power analysis with G*Power 3.1 (Faul et al., 2009) indicated that a sample size of at least 138 would be required to detect correlations of *r* = .30 or larger between variables, considering an alpha level of .05 and a power of .95. For regression models including five predictors (age, sex, parental education, general cognitive ability, and emotion recognition), a sample of at least 134 participants would be required to detect partial associations of *r* = .30 or larger between each predictor variable and socio-emotional adjustment.

This study was approved by the local ethics committee, Iscte – University Institute of Lisbon (reference 28/2019), and it was conducted in agreement with the Declaration of Helsinki. Written informed consent was obtained for all participants from a parent or legal guardian, and children gave verbal assent to participate.

## 2.2. Materials

### 2.2.1. Emotion recognition tasks

The children completed three emotion recognition tasks. Two of them were focused on vocal emotions, speech prosody and nonverbal vocalisations, and the third one on facial expressions. Each task included 60 trials, with 10 different stimuli for each of the following categories: anger, disgust, fear, happiness, sadness, and neutrality. The stimuli were part of validated corpora (speech prosody, Castro & Lima, 2010; nonverbal vocalisations, Lima et al., 2013a; facial expressions, Karolinska Directed Emotional Faces database, Goeleven et al., 2008) that have been frequently used (e.g., Agnoli et al., 2012; Correia et al., 2019, 2020; Lima & Castro, 2011; Lima et al., 2016; Lima et al., 2013b; Safar & Moulson, 2020). Speech prosody stimuli were short sentences (*M* = 1473 ms, *SD* = 255) with emotionally neutral semantic content (e.g., "O quadro está na parede", *The painting is on the wall*), produced by two female speakers to communicate emotions with prosodic cues alone. Nonverbal vocalisations consisted of brief vocal sounds (*M* = 966 ms, *SD* = 259) without linguistic content, such as laughs, screams, or sobs, and were produced by two adult female and two adult male speakers. Facial expressions consisted of colour photographs of male and female actors without beards, moustaches, earrings, eyeglasses, or visible make-up. Each photograph remained visible until participants responded. Based on validation data from adults, the average recognition accuracy for the stimuli used here was expected to be high (emotional prosody: 78.42%; nonverbal vocalisations: 82.20%; facial expressions: 82.98%).

Participants made a six-alternative forced-choice decision for each stimulus in each of the three tasks. They were asked to identify the expressed emotion from a list that included *neutrality, anger, disgust, fear, happiness, and sadness*. To improve children's engagement throughout the task, an emoji illustrating each emotional category was included on the response pad and on the laptop screen (visible after the stimulus' offset). Visual aids like emojis or pictures are typically used in vocal emotion recognition tasks intended for children (e.g., Amorim et al., 2019; Correia et al., 2019; Sauter et al., 2013). Each task started with six practice trials (one per emotional category), during which feedback was given. After these trials, the stimuli were presented randomly across two blocks of 30 trials each (no feedback was given). Short pauses were allowed between blocks to ensure that children remained focused and motivated. Each task took approximately 12 minutes. The tasks were implemented using SuperLab Version 5 (Cedrus Corporation, San Pedro, CA), running on an Apple MacBook Pro laptop. Responses were collected using a seven-button response pad (Cedrus RB-740). Auditory stimuli were presented via headphones (Sennheiser HD 201).

The percentage of correct answers was calculated for each emotional category and task. Accuracy rates were then corrected for response biases using unbiased hit rates, or *Hu*, which were used for all analyses (Wagner, 1993; for a discussion of biases in forced-choice tasks see, e.g., Isaacowitz et al., 2007). Hu values represent the joint probability that a given emotion will be correctly recognised (given that it is presented), and that a given response category will be correctly used (given that it is used at all), such that they vary between 0 and 1. Hu = 0 when no stimulus from a given emotion is correctly recognised, and Hu = 1 when all the stimuli from a given emotion are correctly recognised (e.g., sad prosody), and the corresponding response category (sadness) is always correctly used (i.e., when there are no false alarms). Primary analyses were conducted using average scores for each task because we had no predictions regarding specific emotions.

### 2.2.2. Socio-emotional adjustment

The Child Self-Regulation and Behaviour Questionnaire (CSBQ) is a 33-item educator-report (or parent-report) questionnaire that assesses children's socio-emotional behaviour (Howard & Melhuish, 2017). Scale items cover seven subscales: sociability (seven items, e.g., *Chosen as a friend by others*), externalising problems (five items, e.g., *Aggressive to children*), internalising problems (five items, e.g., *Most days distressed or anxious*), prosocial behaviour (five items, e.g., *Plays easily with other children*), behavioural self-regulation (six items, e.g., *Waits their turn in activities*), cognitive self-regulation (five items, e.g., *Persists with difficult tasks*), and emotional self-regulation (six items, e.g., *Is calm and easy-going*). Items are rated on a scale from 1 (*not true*) to 5 (*certainly true*). Individual item scores are then summed to produce total scores for each subscale (Howard & Melhuish, 2017). A global socio-emotional functioning score was also computed by averaging the means of the seven subscales, hereafter referred to as *general socio-emotional index*. For this purpose, scores for the externalising and internalising problems subscales were reversed so that higher scores indicated better socio-emotional adjustment across all subscales.

The CSBQ translation to European Portuguese followed the guidelines for adapting tests into multiple languages (e.g., Hambleton, 2005). Two European Portuguese native speakers independently translated the items of the original English CSBQ. They were fluent in English, and one of them (C.F.L.) is experienced in the adaptation of questionnaires and an expert in emotion processing. A single version of the questionnaire was obtained by sorting out the disagreements between the two translators. This version was then shown to two lab colleagues for a final check on language clarity and naturalness, and to discuss the matching between the original and the translated version.

The original CSBQ has sound psychometric properties (Howard & Melhuish, 2017), and in the current dataset internal consistency values were good-to-excellent (Cronbach's $\alpha = 0.85$ for general socio-emotional index, ranging from $\alpha = 0.80$ for externalising/internalising problems to $\alpha = 0.91$ for cognitive self-regulation).

### 2.2.3. General cognitive ability

The Raven's Coloured Progressive Matrices were used as a measure of general non-verbal cognitive ability (Raven, 1947). All participants of the final sample performed within the normative range (≥ 14 out of 36, *M* = 22.63, *SD* = 4.53, range = 14 – 33; norms for Portuguese 2nd graders; Simões, 1995).

## 2.3. Procedure

Children were tested individually in a quiet room at their school, in two experimental sessions lasting about 45 minutes in total. General cognitive ability was assessed in the first session and emotion recognition in the second one. The order of the emotion recognition tasks was counterbalanced across participants. Before the sessions, a parent completed a background questionnaire that asked for information about parental education and employment, and the child's history of health issues, such as psychiatric, neurological/neurodevelopmental disorders, and hearing impairments.

The CSBQ questionnaire was completed by the children's teacher. Having the teacher completing the questionnaire, instead of a parent, allowed us to maximize sample size, as it could be difficult to get all the 141 parents to return the questionnaire in a timely manner, and to minimize social desirability (for a similar approach, e.g., Leppänen & Hietanen, 2001; Nowicki et al., 2019). Additionally, many of the CSBQ items focus on interactions with peers and behaviours in the school context, which can be best documented by teachers. The teachers were blind to the hypothesis of the study. They had known the children for about one and a half years when they filled the questionnaire, having had the opportunity to interact with them and observe their behaviour on a daily basis.

## 2.4. Data analysis

The data were analysed using standard frequentist *and* Bayesian analyses conducted with JASP Version 0.14.1 (JASP Team, 2020). A repeated-measures analysis of variance (ANOVA) with task (speech prosody, nonverbal vocalisations, and facial expressions) as within-subjects factor was performed to examine differences in emotion recognition across tasks. Pearson correlations and multiple regression analyses were used to test for associations between our variables of interest. Holm-Bonferroni corrections for multiple comparisons were applied to *p* values, except in the case of follow-up exploratory analyses (focussed on specific emotions and specific dimensions of socio-emotional adjustment), for which uncorrected *p* values are reported. In addition to *p* values, a Bayes Factor ($BF_{10}$) statistic was estimated for each analysis using the default priors (correlations, stretched beta prior width = 1; *t*-tests, zero-centred Cauchy prior with scale parameter 0.707; linear regressions, JZS prior of *r* = .354; repeated-measures ANOVAs, zero-centered Cauchy prior with a fixed-effects scale factor of *r* = .5, a random-effects scale factor of *r* = 1, and a covariates scale factor of *r* = .354). Bayes factors consider the likelihood of the observed data given the alternative and null hypotheses. $BF_{10}$ values were interpreted according to Jeffreys' guidelines (Jarosz & Wiley, 2014; Jeffreys, 1961), such that values below 1 correspond to evidence in favour of the null hypothesis: values between 0.33 and 1 correspond to anecdotal evidence, between 0.10 and 0.33 to substantial evidence, between 0.03 and 0.10 to strong evidence, between 0.01 and 0.03 to very strong evidence, and less than 0.01 to decisive evidence. Values above 1 correspond to evidence for the alternative hypothesis: values between 1 and 3 correspond to anecdotal evidence, between 3 and 10 to substantial evidence, between 10 and 30 to strong evidence, between 30 and 100 to very strong evidence, and greater than 100 to decisive evidence. An advantage of Bayesian statistics is that they allow us to interpret null results and to draw inferences based on them.

The full data set can be found here: https://osf.io/qfp83/?view_only=47031990843a48978ca8058e98118805.

# 3. Results

## 3.1. Emotion recognition

Figure 1 shows children's accuracy in the emotion recognition tasks (see Supplementary Table S1 for statistics for each emotion, and Table S2 for confusion matrices). Average Hu scores were .41 for speech prosody (*SD* = .18; range = .04 – .85), .72 for vocalisations (*SD* = .11; range = .35 – .94), and .67 for faces (*SD* = .13; range .35 – .94). Performance was above the chance level (.17) for all three modalities, *p*s < .001, $BF_{10} > 100$, and there was no substantial departure from normality (skewness, range = -1.38 – 0.75; kurtosis, range = -1.36 – 2.64; Curran et al., 1996). A repeated measures ANOVA with task as within-subjects factor showed that performance differed significantly across tasks, *F*(2, 280) = 296.48, $p < .001$, $\eta^2 = .68$; $BF_{10} > 100$. It was lowest for prosody (prosody vs. vocalisations, $p < .001$, $BF_{10} > 100$; prosody vs. faces, $p < .001$, $BF_{10} > 100$) and highest for vocalisations (vocalisations vs. faces, $p < .001$, $BF_{10} > 100$). There was a positive correlation between the two vocal emotion recognition tasks ($r = .32$, $p < .001$, $BF_{10} > 100$), and between these and the faces task (prosody and faces, $r = 0.40$, $p < 0.001$, BF10 > 100; vocalizations and faces, $r = 0.32$, $p < 0.001$, BF10 > 100).

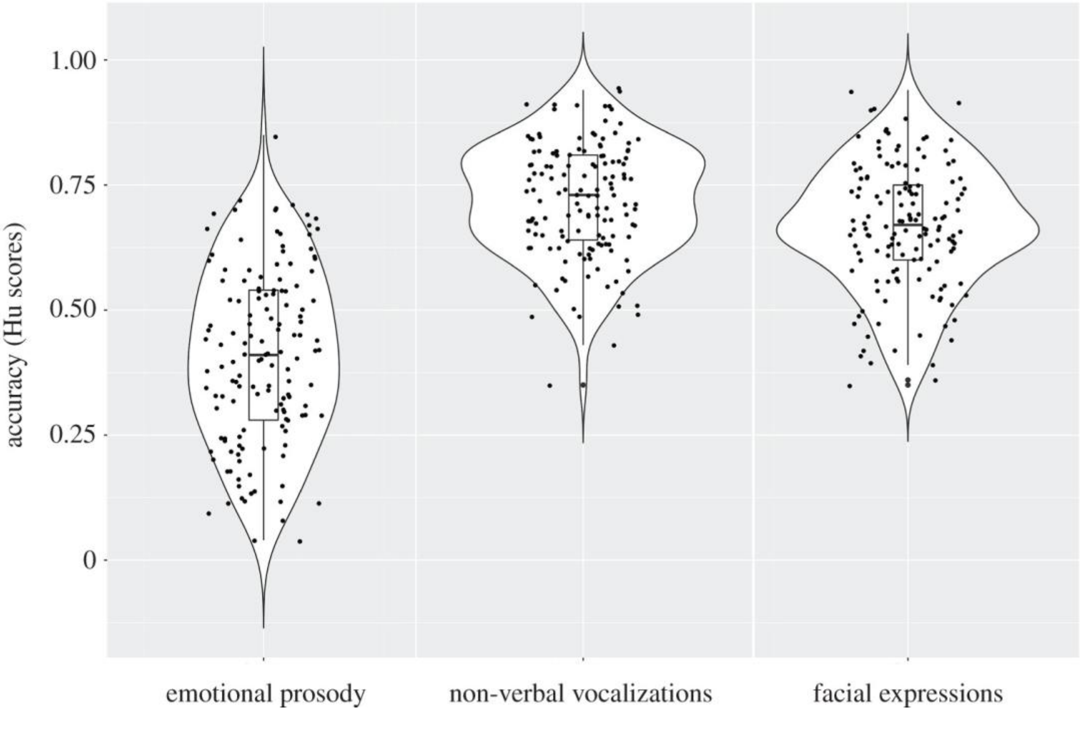

***Figure 1***. Individual results, box plots and violin plots depicting average emotion recognition scores (Hu) for emotional prosody, non-verbal vocalizations and facial expressions.

## 3.2. Socio-emotional adjustment

Scores for the general socio-emotional index and for each CSBQ subscale are presented in Figure 2. The general socio-emotional score was 3.75 on average, and it varied widely among children, from 2.27 to 4.85 (*SD* = 0.55). There was no substantial departure from normality in the CSBQ data (skewness, range = -0.63 – 0.86; kurtosis, range = -0.84 – 0.05; Supplementary Table S3; Curran et al., 1996). There were correlations among the CSBQ subscales (see Supplementary Table S4 and S5), as expected according to the published data (Howard & Melhuish, 2017).

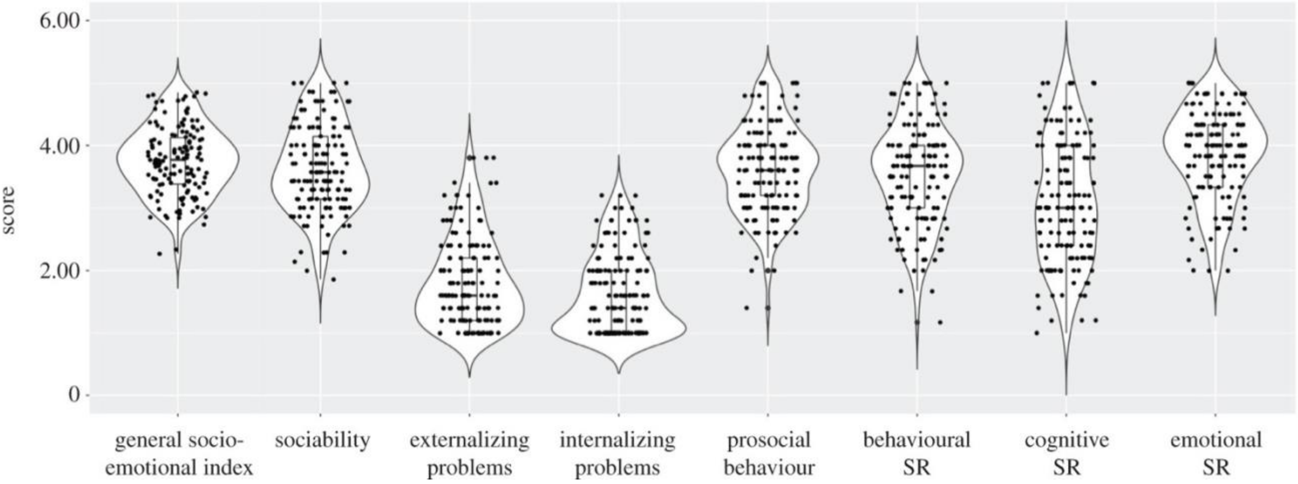

***Figure 2.*** Individual results, box plots and violin plots depicting teacher reports on children's social-emotional adjustment, as assessed with the CSBQ questionnaire. SR = self-regulation.

## 3.3. Cognitive and socio-demographic variables

Table 1 shows correlations between the main study variables—emotion recognition and general socio-emotional adjustment—and age, sex, parental education, and cognitive ability. Emotion recognition was not associated with demographic or cognitive variables, except for small correlations between emotional prosody recognition and parental education and cognitive ability. Socio-emotional adjustment was higher for girls compared with boys, and it was also higher for younger children and for those with higher parental education.

| | Age | Sex | Parental Education (years) | Cognitive Ability |
|---|---|---|---|---|
| Emotion Recognition | | | | |
| Emotional Prosody | .00 | .21 | .25* | .27* |
| | *0.11* | *0.18* | *8.05* | *22.14* |
| Nonverbal Vocalizations | .14 | -.63 | .10 | .02 |
| | *0.43* | *0.22* | *0.21* | *0.11* |
| Facial Expressions | .05 | -1.97 | .10 | .10 |
| | *0.13* | *1.06* | *0.22* | *0.21* |
| General Socio-emotional Index | -.32* | -2.97* | .42*** | .22 |
| | *> 100* | *9.45* | *> 100* | *3.44* |

Note. *N* = 141 for all analyses, except for those involving parental education, where *n* = 139. $BF_{10}$ values are indicated in italics. For Age, Parental Education and Cognitive Ability, values represent Pearson correlation coefficients; for Sex, they represent *t* values (two-tailed independent sample *t*-tests). * $p < .05$; *** $p < .001$ (Holm Bonferroni-corrected).

***Table 1.*** Associations between the main study variables (emotion recognition and general socio-emotional adjustment) and age, sex, parental education, and general cognitive ability.

## 3.4. Emotion recognition and socio-emotional adjustment

In line with our prediction, we found decisive evidence for a correlation between higher emotion recognition in speech prosody and better general socio-emotional adjustment, $r = 0.32$, $p < 0.001$, $BF_{10} > 100$. A similar correlation was not found for emotion recognition in non-verbal vocalizations, however, $r = 0.10$, $p = 0.24$. It was also not found for faces, $r = 0.12$, $p = 0.33$. For both vocalizations and faces, Bayesian analyses provided substantial evidence for the null hypothesis (vocalizations, $BF_{10} = 0.21$; faces, BF10 = 0.27).[3]

To exclude the possibility that the association between emotional prosody recognition and socio-emotional adjustment was due to cognitive or socio-demographic factors, we used multiple regression. We modelled socio-emotional adjustment scores as a function of age, sex, parental education, cognitive ability, and average accuracy on the emotional prosody recognition task. This model explained 30.77% of the variance, $R = 0.58$, $F5{,}133 = 13.26$, p < 0.001, $BF_{10} > 100$. Independent contributions were evident for age, partial $r = -0.30$, $p < 0.001$, BF10 = 49.10; sex, partial $r = 0.22$, $p = 0.01$, $BF_{10} = 3.06$; and parental education, partial $r = 0.28$, $p = 0.001$, $BF_{10} = 28.68$, but not for cognitive ability, $p = 0.34$, $BF_{10} = 0.17$. Crucially, emotional prosody recognition made an independent contribution to the model, partial $r = 0.27$, $p = 0.002$, and the Bayesian analysis provided strong evidence for this contribution, $BF_{10} = 14.25$. We calculated Cook's values and confirmed that this effect was not explained by extreme data points on the regression model (Cook's distance $M = 0.01$, *s.d.* = 0.01, range = 0.00–0.07). The partial association between emotional prosody recognition and socio-emotional adjustment is illustrated in figure 3a.

Although we had no predictions regarding specific emotions, we wanted to ensure that the association between prosody recognition and socio-emotional adjustment was not driven by a single or small subset of emotions. Follow-up multiple regression analyses, conducted separately for each emotion, showed that positive partial correlations could be seen for most emotions, at significant or trend level: happiness, $r = 0.23$, $p = 0.01$, $BF_{10} = 3.81$; anger, $r = 0.22$, $p = 0.01$, $BF_{10} = 3.20$; fear, $r = 0.21$, $p = 0.01$, $BF_{10} = 2.26$; and neutrality, $r = 0.19$, $p = 0.03$, $BF_{10} = 1.24$. For sadness and disgust, the trend was in the same direction but did not reach significance: sadness, $r = 0.12$, $p = 0.16$, $BF_{10} = 0.30$; disgust, $r = 0.13$, $p = 0.12$, $BF_{10} = 0.36$. For completeness, an additional multiple regression was conducted including all emotions simultaneously (see electronic supplementary material, table S6), and none of them contributed uniquely to socio-emotional outcomes ($p_s > 0.34$), probably because of the shared variance across them.

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[3] Because there was no substantial departure from normality in the data, our analyses were based on untransformed Hu values. However, the pattern of results remained similar when the models were repeated on arcsine-transformed values (Wagner, 1993), as can be seen in the electronic supplementary material, Analyses.

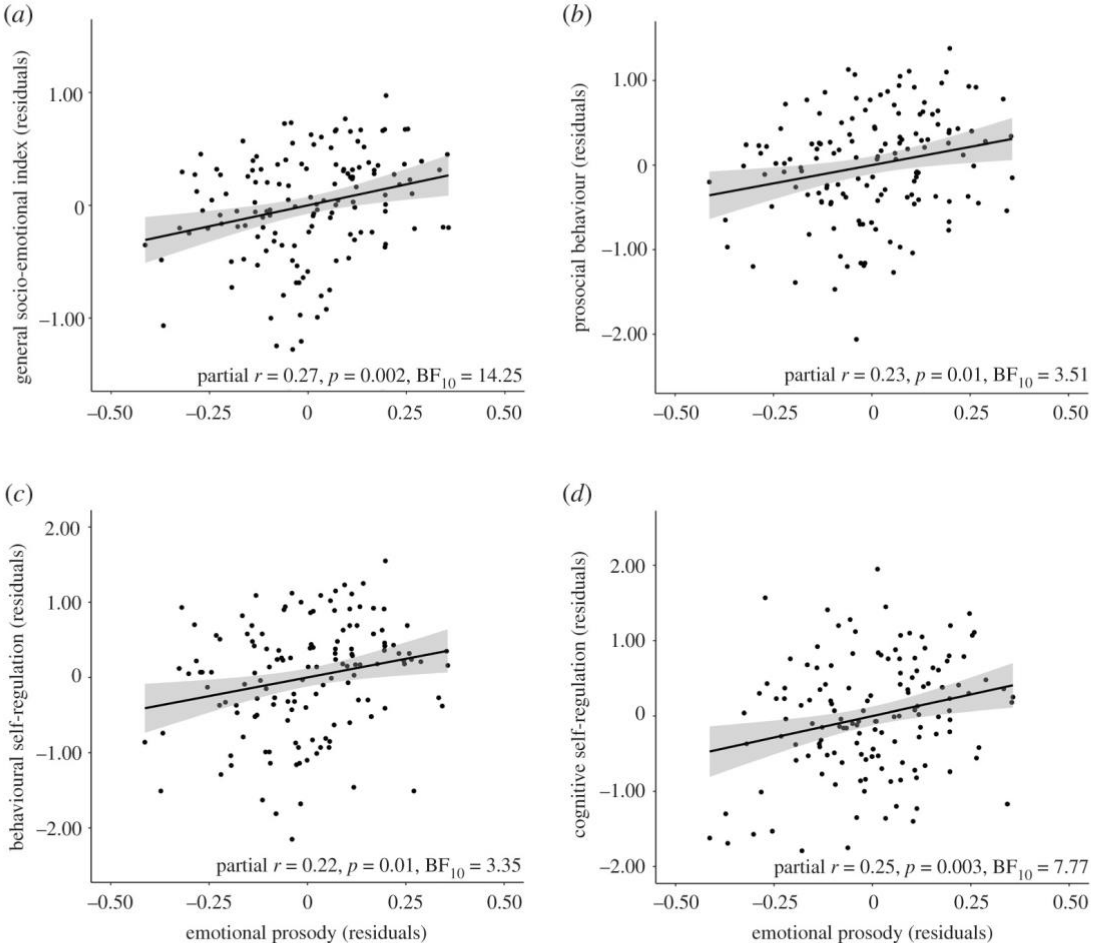

***Figure 3.*** Partial regression plots illustrating the relationship between emotion recognition in emotional prosody and general socio-emotional adjustment scores (*a*), prosocial behaviour (*b*), behavioural self-regulation (*c*) and cognitive self-regulation (*d*), after removing the effects of age, sex, parental education and cognitive ability. Grey shades represent 95% confidence intervals.

## 3.5. Socio-emotional adjustment dimensions

We also explored how emotional prosody recognition related to specific socio-emotional dimensions, considering the CSBQ subscales: sociability, externalizing problems, internalizing problems, prosocial behaviour, behavioural self-regulation, cognitive self-regulation and emotional self-regulation. This was inspected using multiple regressions, modelling scores on each CSBQ subscale as a function of age, sex, parental education, cognitive ability and average accuracy on emotional prosody recognition. Results are detailed in table 2. Associations were particularly clear for prosocial behaviour, cognitive self-regulation and behavioural self-regulation, all supported by substantial evidence ($p$s < 0.02, $3.34 < BF_{10} < 7.78$). We calculated Cook's values and confirmed that the effects were not explained by extreme data points on the regression model: Cook's distance *M*= 0.01, s.d. = 0.01 (Cook's distance range = 0.00–0.06 for prosocial behaviour; 0.00–0.05 for behavioural self-regulation; and 0.00–0.06 for cognitive self-regulation). Partial associations between emotional prosody recognition and these dimensions of socio-emotional adjustment are illustrated in figure 3*b*–*d*.

There were also significant associations between emotional prosody recognition and the dimensions of sociability and emotional self-regulation, but the level of evidence was weaker (*p*s < 0.03, $1.61 < BF_{10} < 2.74$). For the remaining two socio-emotional dimensions, externalizing and internalizing problems, emotional prosody recognition did not uniquely contribute to the models (*p*s > 0.33, $BF_{10} < 0.18$).

| Model | Adj. $R^2$ | *F* (5, 133) | $BF_{10}$ | $b^a$ | *SE* | $B^b$ | *t* | CI 95% | Partial *r* | $BF_{10}$ partial *r* |
|---|---|---|---|---|---|---|---|---|---|---|
| Sociability | .19 | 7.46*** | > 100 | | | | | | | |
| Constant | | | | 5.76 | .86 | | 6.73*** | [4.07, 7.46] | | |
| Age | | | | -.43 | .11 | -.31 | -3.97*** | [-.65, -.22] | -.33 | > 100 |
| Sex | | | | .03 | .11 | .02 | 0.27 | [-.19, .25] | .02 | 0.11 |
| Parental Education | | | | .04 | .02 | .18 | 2.08* | [.00, .07] | .18 | 0.91 |
| Cognitive Ability | | | | .01 | .01 | .06 | 0.69 | [-.02, .04] | .06 | 0.14 |
| Emotional Prosody | | | | .76 | .33 | .19 | 2.34* | [.12, 1.40] | .20 | 1.62 |
| Externalising Problems | .08 | 3.48** | 2.64 | | | | | | | |
| Constant | | | | .96 | .92 | | 1.04 | [-.86, 2.78] | | |
| Age | | | | .21 | .12 | .15 | 1.79 | [-.02, .44] | .15 | 0.53 |
| Sex | | | | -.37 | .12 | -.26 | -3.12** | [-.60, -.13] | -.26 | 12.34 |
| Parental Education | | | | -.02 | .02 | -.08 | -0.86 | [-.05, .02] | -.07 | 0.15 |
| Cognitive Ability | | | | .01 | .01 | .06 | 0.68 | [-.02, .04] | .06 | 0.13 |
| Emotional Prosody | | | | -.28 | .35 | -.07 | -0.79 | [-.97, .41] | -.07 | 0.15 |
| Internalising Problems | .19 | 7.52*** | > 100 | | | | | | | |
| Constant | | | | -.78 | .78 | | -1.00 | [-2.33, .77] | | |
| Age | | | | .46 | .10 | .37 | 4.66*** | [.27, .66] | .38 | > 100 |
| Sex | | | | .03 | .10 | .02 | 0.27 | [-.17, .22] | .02 | 0.11 |
| Parental Education | | | | -.02 | .02 | -.12 | -1.46 | [-.05, .01] | -.13 | 0.31 |
| Cognitive Ability | | | | -.02 | .01 | -.17 | -1.99* | [-.05, .00] | -.17 | 0.77 |
| Emotional Prosody | | | | -.28 | .30 | -.08 | -0.95 | [-.87, .30] | -.08 | 0.17 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Prosocial Behaviour | .19 | 7.31*** | > 100 | | | | | | | |
| Constant | | | | 3.62 | 1.86 | | 4.23*** | [1.93, 5.31] | | |
| Age | | | | -.19 | .11 | -.14 | -1.73 | [-.40, .03] | -.15 | 0.48 |
| Sex | | | | .27 | .11 | .19 | 2.46* | [.05, .48] | .21 | 2.16 |
| Parental Education | | | | .05 | .02 | .24 | 2.79** | [.01, .08] | .24 | 4.93 |
| Cognitive Ability | | | | .00 | .01 | .02 | 0.20 | [-.02, .03] | .02 | 0.11 |
| Emotional Prosody | | | | .86 | .32 | .22 | 2.66** | [.22, 1.51] | .23 | 3.51 |
| Behavioural SR | .19 | 7.56*** | > 100 | | | | | | | |
| Constant | | | | 3.00 | .99 | | 3.03** | [1.04, 4.96] | | |
| Age | | | | -.14 | .13 | -.09 | -1.14 | [-.39, .11] | -.10 | 0.21 |
| Sex | | | | .40 | .13 | .25 | 3.21** | [.16, .65] | .27 | 16.34 |
| Parental Education | | | | .06 | .02 | .24 | 2.87** | [.02, .10] | .24 | 6.11 |
| Cognitive Ability | | | | -.00 | .02 | -.02 | -0.21 | [-.03, .03] | -.02 | 0.11 |
| Emotional Prosody | | | | .99 | .38 | .21 | 2.64** | [.25, 1.74] | .22 | 3.35 |
| Cognitive SR | .43 | 21.47*** | > 100 | | | | | | | |
| Constant | | | | 2.59 | 1.02 | | 2.54* | [.57, 4.62] | | |
| Age | | | | -.26 | .13 | -.18 | -2.78** | [-.62, -.10] | -.23 | 4.76 |
| Sex | | | | .08 | .13 | .04 | 0.61 | [-.18, .34] | .05 | 0.13 |
| Parental Education | | | | .11 | .02 | .37 | 5.13*** | [.07, .15] | .41 | > 100 |
| Cognitive Ability | | | | .06 | .02 | .27 | 3.82*** | [.03, .09] | .31 | > 100 |
| Emotional Prosody | | | | 1.15 | .39 | .20 | 2.96** | [.38, 1.91] | .25 | 7.77 |
| Emotional SR | .09 | 3.82** | 5.05 | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Constant | 4.55 | .92 | | 4.92*** | [2.72, 6.37] | | |
| Age | -.17 | .12 | -.12 | -1.43 | [-.40, .06] | -.12 | 0.30 |
| Sex | .32 | .12 | .23 | 2.74** | [.09, .55] | .23 | 4.34 |
| Parental Education | .01 | .02 | .06 | 0.61 | [-.03, .05] | .05 | 0.13 |
| Cognitive Ability | -.02 | .01 | -.13 | -1.42 | [-.05, .01] | -.12 | 0.29 |
| Emotional Prosody | .90 | .35 | .22 | 2.56* | [.20, 1.59] | .22 | 2.73 |

*Note.* SR - Self-regulation. * *p* < .05; ** *p* < .01; *** *p* < .001 (uncorrected *p*-values). [a] Unstandardized regression coefficient. [b] Standardized regression coefficient.

***Table 2***. Multiple regression analyses for each dimension of socio-emotional adjustment. Predictors were age, sex, parental education, cognitive ability, and emotional prosody recognition accuracy.

## 4. Discussion

In the current study, we asked whether individual differences in vocal emotion recognition relate to socio-emotional adjustment in children. We measured emotion recognition in two types of vocal emotions, speech prosody and nonverbal vocalisations. Socio-emotional adjustment was assessed through a multidimensional measure completed by the children's teachers. We found strong evidence for a positive association between speech prosody recognition and socio-emotional adjustment, based on both frequentist and Bayesian statistics. This association remained significant even after accounting for age, sex, parental education, and cognitive ability. Follow-up analyses showed that prosody recognition was more robustly linked to the socio-emotional dimensions prosocial behaviour, cognitive self-regulation, and behavioural self-regulation. For emotion recognition in nonverbal vocalisations, there were no associations with socio-emotional adjustment. A similar null result was found for the additional emotion recognition task focused on facial expressions.

Some prior studies have reported an association between children's emotional prosody recognition abilities and aspects of socio-emotional adjustment including behavioural problems (e.g., social avoidance and distress; McClure & Nowicki, 2001), peer popularity (e.g., Nowicki & Mitchell, 1998), and global social competence (e.g., Leppänen & Hietanen, 2001). However, results have been mixed (Chronaki et al., 2015; Nowicki & Mitchell, 1998) and often based on relatively small samples. It also remained unclear whether the associations are specific, or a result of factors such as parental education. The present study corroborates the association between emotional prosody recognition and socio-emotional adjustment in a sample of six to eight-year-olds, and it indicates that this association is not reducible to cognitive or socio-demographic variables, namely age, sex, cognitive ability, and parental education. Emotional prosody cues help us build up a mental representation of other's emotional states (Grandjean, 2021), and prosody can convey a wide range of complex and nuanced states, such as verbal irony, sarcasm, and confidence (Cheang & Pell, 2008; Morningstar et al., 2018; Pell & Kotz, 2021). Interpreting prosodic cues might be challenging, as indicated by evidence (that we replicated) that emotion recognition accuracy is lower for emotional prosody compared to nonverbal vocalisations and facial expressions (e.g., Hawk et al., 2009; Kamiloglu et al., 2020; Sauter et al., 2013). This increased difficulty might be because prosodic cues are embedded in speech, which constrains acoustic variability (Scott et al., 2010). These stimuli are also more complex in that they include both lexico-semantic and prosodic cues, while in nonverbal vocalisations and facial expressions lexico-semantic information is not present. Children with an earlier and more efficient development of this complex ability might therefore be particularly well-equipped to navigate their social worlds.

In exploratory analyses focused on specific dimensions of socio-emotional adjustment, we found that children's ability to recognise emotional prosody was particularly related to prosocial behaviour and cognitive and behavioural self-regulation. These findings were based on uncorrected *p* values, but the fact that they were also supported by substantial Bayesian evidence suggest that they are meaningful. Prosociality is associated with positive social behaviours such as cooperation, altruism, and empathy (Jensen, 2016; Lockwood et al., 2014). The ability to recognise fearful facial expressions was found to be linked to adults' prosocial behaviour (Adolphs & Tusche, 2017; Marsh et al., 2007; Marsh et al., 2014). This could be because distress cues are a powerful tool to elicit care, and being able to 'read' them could promote prosocial behaviours, such as helping a crying child (Marsh, 2019). Regarding vocal emotions, decreased cooperative behaviour was observed in adults towards partners displaying emotional prosody of anger, fear and disgust (Caballero & Díaz, 2019). However, this was found in a study focused on decisions to cooperate in a social decision-making paradigm, and participants' ability to recognise emotional prosody was not examined. To our knowledge, the current study is the first to show that emotional prosody recognition is positively linked to prosocial behaviour in school-aged children. It is possible that the ability to accurately interpret the emotional meaning of complex stimuli (such as speech) allows children to more readily deduce when to cooperate, share, or help others, all prosocial behaviours covered by our measure. Future work inspecting how children's vocal emotion recognition relates to their prosocial behaviour will be important to better understand this finding.

Self-regulation includes behavioural and cognitive components, and we found associations with children's prosody recognition abilities for both. The behavioural component refers to the ability to remain on task, to inhibit behaviours that might not contribute to goal achievement, and to follow socially appropriate rules (Murray et al., 2015). The cognitive component is focused on more top-down processes related to problem-solving, focused attention and self-monitoring, which might support autonomy and task persistence. Prior evidence shows that pre-schoolers' recognition of facial expressions correlates with attention processes and behavioural self-regulation (Rhoades et al., 2009; Salisch et al., 2015), but evidence regarding vocal emotion recognition is scant. In view of evidence that attention can contribute to performance in emotional prosody tasks in adults (e.g., Borod et al., 2000; Lima et al., 2013b) and children (e.g., Filipe et al., 2018), it could have been that children who were more able to focus and remain on task were in a better position for improved performance. For instance, emotional prosody recognition requires listeners to maintain temporally dynamic information in working memory to inform interpretation, and self-regulation may covary with this type of attention (Hoffmann et al., 2012). However, although we found a correlation between cognitive ability and prosody recognition, thus replicating previous evidence, the association with self-regulation remained significant after cognitive ability was accounted for, making this explanation less likely. Alternatively, because the ability to decode emotional prosody supports a more efficient understanding of communicative messages (e.g., from parents or teachers), this might allow children to understand more easily the tasks they are expected to perform, the rules to follow, and the goals to achieve. Future studies assessing self-regulatory processes in more detail will be important to delineate the sub-processes driving the general associations uncovered here.

Contrasting with the findings for prosody, for nonverbal vocalisations we observed no associations with socio-emotional adjustment. To our knowledge, ours is the first study that systematically considers the two sources of vocal emotional cues - prosody and nonverbal vocalisations - in the context of associations with socio-emotional functioning. This matters because, despite both being vocal emotional expressions, they differ in their production and perceptual mechanisms (Pell et al., 2015; Scott et al., 2010), and indeed also seem to differ in their correlates. This null result seems unexpected, considering that nonverbal vocalisations reflect a primitive and universal form of communication (e.g., Sauter et al., 2010), thought to play an important role in social interactions. It could have been that our measures of emotion recognition and socio-emotional adjustment were not sensitive enough to capture the effect. But it could also be that variability in the processing of vocalisations does not play a major role for socio-emotional functioning in typically developing school-age children. Previous results indicate that children as young as five years are already proficient at recognizing a range of positive and negative emotions in nonverbal vocalisations, with average accuracy approaching 80%, and there is no improvement from five to 10 years for most emotions (Sauter et al., 2013). Such proficiency is replicated here, and we also found that the range of individual differences is small when compared to prosody (see Figure 1). This could mean that, for most healthy school-age children, the ability to recognise nonverbal emotional vocalisations is already high enough for them to optimally use these cues in social interactions, such that small individual variation will not necessarily translate into measurable differences in everyday behaviour. This result will need to be followed up in future studies, however, to examine whether it replicates across different measures and age groups (e.g., including a broader range of emotions and a more comprehensive assessment of socio-emotional adjustment).

That performance on the additional facial emotion recognition task also did not correlate with socio-emotional adjustment corroborates the findings of some previous studies. McClure and Nowicki (2001) found that eight to 10-year-old children's ability to recognise facial expressions was not associated with dimensions of socio-emotional adjustment, namely social avoidance and distress. Leppänen and Hietanen (2001) also reported null results regarding peer popularity in a sample of seven to 10-year-olds. Moreover, Chronaki et al. (2015) found that pre-schoolers' ability to recognise facial expressions was not associated with parent-rated internalising problems. On the other hand, there is evidence that facial emotion recognition can relate to fewer behavioural problems in school-age children (e.g., Nowicki et al., 2019) and to better self-regulation in preschoolers (e.g., Salisch et al., 2015). These discrepancies across studies might stem from differences in samples' characteristics and measures. For instance, pre-schoolers (Salisch et al., 2015) compared to school-age children (McClure & Nowicki, 2001), and measures of peer-rated popularity (Leppänen & Hietanen, 2001) compared to measures of social avoidance and distress (McClure and Nowicki, 2001). Such possibilities will be clarified as more research is conducted on this topic. In the current study, based on a relatively large sample informed by power analyses, Bayesian statistics provided in fact evidence for the null hypothesis. In line with our reasoning for nonverbal vocalisations, a tentative explanation is that children's proficiency at decoding facial emotions at this age is already high, such that the impact of individual variation in everyday life behaviour might be less apparent.

A limitation of the current study is the correlational approach. We provide evidence for an association between emotional prosody recognition and socio-emotional adjustment, but we cannot exclude the possibility that emotional prosody recognition skills are the result, not the cause, of better socio-emotional adjustment. Having more and better social interactions plausibly provides opportunities for children to learn about emotional expressions, and to hone their emotion recognition skills. Future systematic longitudinal research will be needed to establish causality, for example by testing whether an emotion recognition training program leads to improved social interactions. Another limitation is that we used vocal and facial stimuli produced by adults, and it would be interesting to know if similar results would be obtained with stimuli produced by children. Children can accurately recognise vocal expressions produced by participants of any age, but there is also evidence that they might perform better for stimuli produced by children their age (Amorim et al., 2019; Rhodes & Anastasi, 2012; but see McClure & Nowicki, 2001). Moreover, the emotional prosody task contained stimuli produced by female speakers only, whereas nonverbal vocalisations and facial expressions included both female and male actors. Because there is some previous evidence that the speaker's sex might influence vocal emotion recognition (e.g., Belin et al., 2008; Zuckerman et al., 1975; but see Amorim et al., 2019), we cannot exclude the possibility this might have contributed to the distinct results across tasks. Future studies should also extend our findings to different emotion recognition tasks to establish their generalizability. In line with previous studies (e.g., Amorim et al., 2019; Correia et al., 2019; Sauter et al., 2013), we have used visual aids (emojis) to make the task more engaging and less reliant on linguistic/reading abilities, but at the same time this might have inflated performance and increased the reliance on auditory-visual matching processes. One last point is that we only used a teacher-report socio-emotional measure. Future work combining different socio-emotional measures, such as parent-report and performance-based tasks, would allow us to test these relationships more stringently.

In conclusion, the current study shows that emotional speech prosody recognition is associated with general socio-emotional adjustment in children. We also show that this association is not explained by cognitive and socio-demographic variables, and results were particularly robust for the socio-emotional dimensions prosocial behaviour and self-regulation (cognitive and behavioural components). These findings did not generalize to vocal emotional stimuli without linguistic information - nonverbal vocalisations - and were also not seen for facial expressions. Altogether, these results support the notion that emotional speech recognition skills play an important role in children's everyday social interactions. They also contribute to debates on the functional role of vocal emotional expressions, and might inform interventions aimed at fostering socio-emotional skills in childhood.

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# CHAPTER IV | LONGITUDINAL STUDY[4]

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[4] This chapter describes a longitudinal study that is under preparation for publication in a peer-reviewed international journal.

# Abstract

There is a growing interest in the idea that music training transfers to substantially different domains (far transfer), while transfer to domains closely related to music are often presumed to exist and has attracted less attention (near transfer). Whether and how music training affects socio-emotional skills has been poorly explored. We conducted a longitudinal study with 6- to 8-year-old children to examine possible near and far transfer effects of music training, namely on children's socio-emotional skills. The study was implemented in a regular school environment and included pre-test, training and post-test phases, in three conditions: music training (Orff-based training, *n* = 37), an active control group (basketball training, *n* = 40), and a passive control group (no training, *n* = 33). The training programs were conducted over two school years. Children were assessed in a wide range of socio-emotional skills, namely auditory and visual emotion recognition, authenticity recognition, empathy, emotion comprehension, and social behavior. We also assessed executive functions (far transfer) and near transfer domains, namely auditory skills, fine-motor skills, and gross-motor skills. Additionally, we tested for possible negative effects of the COVID-19 pandemic, and examined if individual differences before training predicted the magnitude of the effects over time. We found significant effects of music training on auditory and motor skills, but for auditory skills this was only true in comparison with the basketball group. The significant effects on fine-motor skills and gross-motor skills were observed in comparisons with both control groups. On the other hand, we found no significant effects of music training on any socio-emotional skill, nor executive functions. Furthermore, children who had lower auditory, motor, and prosody recognition skills at pre-test improved more on these skills, as compared to those who had higher scores at pre-test. However, this effect was similar across groups. Children who did not suffer a negative impact during lockdown had higher auditory skills and better social behavior at post-test, than those who were reported to have suffered a negative impact. These findings might inform debates on the far transfer effects of music training, and the use of music as an intervention tool in clinical and educational settings.

*Keywords:* Transfer effects, Auditory and Motor skills, Socio-emotional processing, Music training, Children

## 1. Introduction

The longitudinal effects of music training have been extensively studied (e.g., Hennessy et al., 2021; Martins et al., 2018; Tervaniemi et al., 2022). Usually, participants are children who are tested before and after a music training program and compared to a control group that either does nothing (passive control) or takes part in a different form of training such as sports (active control). A commonly asked question is whether music training produces transfer effects. Transfer refers to how learning something new affects performing in new situations (Haskell, 2000). Transfer to domains closely related to the trained domain is called *near transfer*. For instance, effects of music training on auditory (Kraus & Chandrasekaran, 2010) and motor skills (Martins et al., 2018). Studying near transfer effects is central to understanding the mechanisms of transfer (Neves et al., 2022). For example, positive effects of music training on auditory processing may lead to improved nonmusical skills that rely on auditory processing, such as speech perception (e.g., Besson et al., 2011; Patel, 2014). There is a particular interest in the *far transfer* of skills, that is, in the possibility that music training benefits substantially different domains, such as language (e.g., Vidal et al., 2020), executive functions (e.g., Moreno et al., 2011) and general cognitive abilities (e.g., IQ - Schellenberg, 2004). There is an ongoing debate whether far transfer of music training exists (Bigand & Tillmann, 2022). A possible underlying mechanism could be that music training induces far transfer of learning by improving executive functions, which in turn generalizes across many cognitive domains (Degé et al., 2021). However, the evidence coming from longitudinal studies is mixed: while some studies have found significant far transfer effects  (e.g., Moreno et al., 2009), other studies have found that far transfer effects of music training are null (e.g., Mehr et al., 2013). Indeed, enhanced skills in musically trained individuals may reflect formal training, but possibly also reflect other factors, such as predispositions (e.g., Correia et al., 2022). Notwithstanding this ongoing debate on the existence of far transfer effects of music training, transfer to socio-emotional skills is a topic particularly underexplored (Martins et al., 2021).

Socio-emotional functioning emerges early in life and childhood is a critical period for its development (Edwards & Denham, 2018). The central aspects of socio-emotional functioning include the ability to understand our own and others' emotions, to regulate our behavior, and to establish and maintain relationships (Denham et al., 2015; Murray et al., 2015). Thus, socio-emotional functioning ranges from more basic perceptual processes (e.g., emotion recognition in voices) to higher-order processes (e.g., empathy). These socio-emotional functioning aspects are pivotal for children's well-being and related to each other. For instance, better vocal emotion recognition was found to be associated with higher socio-emotional adjustment scores in 6- to 8-year-old children (Neves et al., 2021). Socio-emotional processing is inextricably linked to music (Swaminathan & Schellenberg, 2015). We perceive and feel emotions in response to music (e.g., a negative emotional state after listening to sad music; Egermann & McAdams, 2013), and use music to regulate mood (e.g., to relieve anxiety; Lonsdale & North, 2011). Moreover, music is a powerful means of communication (e.g., playing songs to engage infants; Cirelli et al., 2020). Studies that inspect associations between music aptitude and socio-emotional skills are mostly focused on clinical populations. For instance, a developmental music disorder (amusia) was shown to be associated with impairments in visual and auditory emotion recognition, as well as emotional authenticity recognition (Lima et al., 2016). Music therapy interventions are promising tools for developing social-emotional skills across different conditions, such as autism spectrum disorder (e.g., Duffy & Fuller, 2000; LaGlasse, 2014). Studies with healthy populations have generally found heightened socio-emotional skills in musicians, as compared to non-musicians, including higher levels of self-reported emotional awareness (Ros-Morente et al., 2019) and better emotion recognition in prosody (e.g., Lima & Castro, 2011; but see e.g., Dibben et al., 2018; Park et al., 2015). In children, those who spent more time in a music program also displayed more instrumental helping (i.e., assisting another person to achieve an action-oriented goal), but not sharing behaviors, and children who received higher prosocial ratings from their parents were reported to be more musically active (Iari et al., 2020).

Although these cross-sectional studies show positive associations between music training and children's socio-emotional processing, they do not offer causal evidence. Longitudinal designs with random assignment of participants allow for such inferences (Schellenberg, 2020), but there are only a few that investigate this topic, and these have yielded mixed findings. Positive effects of music training were found in children's emotion comprehension skills, but these effects either disappeared when IQ scores were held constant (Schellenberg & Mankarious, 2012), or were found only in a specific age range (4- to 5-year-old, but not 3- to 4-year-old; Boucher et al., 2021). Music training was also found to enhance children's self-report (Alemán et al., 2017) and teacher-report (Yuan-Yang, 2020) self-regulation skills, and Williams and Bertheslen (2019) found enhanced self-report emotional self-regulation in children, but not considering cognitive and behavioral self-regulation. Some studies did not find any effects on children's prosocial skills, such as sharing and helping (Alemán et al., 2017; Ilari et al., 2021), or on teacher-reported empathy (Yuan-Yang, 2020). Schellenberg et al. (2015) found positive effects of music training in 8-year-old self-reported prosocial skills and sympathy, but only for those who had lower scores on these measures before training. This finding aligns with previous studies showing that the magnitude of the effects of training programs aimed at fostering children's social skills is higher for those who had initial lower scores (e.g., Crapara et al., 2015). Importantly, the design quality of these studies was often suboptimal, thus precluding inferences of causation. For example, some studies had a lack of random assignment of participants (e.g., Schellenberg & Mankarious, 2012), lack of a control group (e.g., Boucher et al. 2021), and short training programs (e.g., Yuan-Yang et al., 2020 – 8 weeks). Therefore, the effects of music training on children's socio-emotional skills remain to be clarified.

We conducted a longitudinal training study to examine possible far-transfer effects of music training to socio-emotional skills in 6- to-8-year-old children. The study was implemented in a regular school environment, and included pre-test, training and post-test phases. Before training, children were assigned to one of three groups: music (experimental group), sports (active control), and no training (passive control). Randomization allows to minimize the possibility of self-selection effects (e.g., pre-existing motivational differences). Moreover, the inclusion of an active control group minimizes the possibility that music-related benefits stem from nonmusical aspects of the training (.g., time spent in a learning environment). We assessed a wide array of socio-emotional skills - from basic perceptual processes, that is, emotion recognition (prosody, vocalizations, and facial expressions) and authenticity recognition (laughter and crying), to higher order socio-emotional aspects, namely social behavior, emotion comprehension, and empathy. We also addressed the effects of music training on executive functions (inhibitory control and interference), and on near transfer domains, namely auditory skills (memory, discrimination, and rhythm copying) and motor skills (fine and gross). Considering the near transfer domains, we expected that music training would improve auditory and motor skills, given that these are critical skills during music training (Kraus & Chandrasekaran, 2010; Zatorre et al., 2007), and based on previous longitudinal evidence of enhancements of music training on auditory (e.g., James et al., 2020) and motor skills (e.g., Martins et al., 2021). Furthermore, considering that some authors proposed that the potential far-transfer effects of music training could be explained by enhancements in executive functions (e.g., Degé, 2021; Schellenberg & Peretz, 2008), we included measures of executive functioning (inhibitory control and interference). Even though the findings for music training effects on socio-emotional skills are mixed, music is fundamentally linked to socio-emotional processing (Martins et al., 2021). Therefore, it is reasonable to hypothesize that music training may enhance socio-emotional skills. Additionally, considering that the magnitude of the effects of training programs may be influenced by the initial level of performance (e.g., Schellenberg et al., 2015), we hypothesized that in the music training group, those who had lower predisposition (i.e., lower initial scores before training) improved significantly more than those with higher predisposition (i.e., higher initial scores on the respective skills).

## 2. Method

## 2.1. Participants

A total of 128 participants were recruited to participate in the study. They were all Portuguese 2nd graders from three elementary public schools in the Porto area (Northern Portugal). Eighteen children were excluded due to: school transfer (*n* = 14), neurological disease (*n* = 2), and a score below the 25th percentile in the Raven's Colored Progressive Matrices (RPCM; *n* = 2). The final sample consisted of 110 children (54 girls, *M*age = 7.01 years, *SD* = 0.46, range = 6.34 to 8.89).

The children were randomized at the class level to the music, sports (active control) or no training (passive control) groups (see Table 1). That is, the assignment considered the allocation of entire classes (*n* = 6 classes, 2 classes per group) and ensured that there were no pre-test differences in major demographic and cognitive characteristics. In line with this, the groups did not differ on sex, $\chi^2(2)$ = 1.14, *p* = .566, age, *F*(2,107) = 0.67, *p* = .51, parental education, *F*(2,106) = 0.00004, *p* = 1, and general cognition (RPCM), *F*(2,107) = 0.14, *p* = .87.

| **Characteristics** | **Music**<br>***n* = 37** | **Sports**<br>***n* = 40** | **Passive Control**<br>***n* = 33** |
|---|---|---|---|
| Sex (F/M) | 20/17 | 17/23 | 17/16 |
| Age (in years) | 7.08 (0.59) | 6.96 (0.32) | 6.99 (0.43) |
| Parental education (in years) | 11.14 (3.54) | 11.13 (3.58) | 11.05 (3.72) |
| General cognition (RPCM) | 22.73 (4.45) | 23.28 (4.91) | 23.03 (3.95) |

*SD in parenthesis; F – Female; M – Male; RPCM – Raven's Progressive Colored Matrices*

***Table 1.*** Demographic and cognitive characteristics of children in the music, sports, and passive control group prior to training.

# 3. Design and procedures

## 3.1. Design

This longitudinal training study included a pre-test, training, and post-test. In supplementary figure 1 we provide a timeline and list of all the included measures. The pre-test phase took place in the beginning of the school year 2019/2020. Each child participated in three experimental sessions lasting about two hours in total, in a quiet room of their school[5]. The assessment was conducted by trained researchers. Both training groups started their music and sports programs after the pre-test assessment and finished before the post-test assessment. The parents/legal guardians completed a questionnaire from which we could gather that none of the children had prior formal experience in instrumental music practice nor in basketball practice. There were approximately 13 months of training (ca. 111 hours, over two school years), with two interruptions due to the COVID-19 pandemic and school holidays (first interruption: five and a half months, which including the regular Summer holidays; second interruption: two months). The music and sports groups completed a similar number of training sessions: in the first school year, two sessions per week, lasting 90 minutes each; in the second school year, one session per week, lasting 90 minutes. In the post-test phase (end of the school year 2020/2021), children completed the same assessment protocol.

## 3.2. Procedure

The study was approved by the Ethics Committee of ISCTE - University Institute of Lisbon (reference 28/2019) and the school boards. Written informed consent was obtained from parents/legal guardians of the children, who gave their verbal assent before the start of data collection.

# 4. Training programs

The training programs implemented in the current study are similar to those described in a previous longitudinal study that inspected the effects of Orff-based music training on manual dexterity and bimanual coordination of third graders (Martins et al., 2018). These were adapted to be suitable for second graders. The music and basketball training programs were conducted by two professional teachers specialized in music and basketball, respectively. The programs consisted of structured groups of learning activities and occurred within the children's regular school schedule. Both programs were focused on initiating children into music/basketball technical knowledge and skill. We provide more comprehensive information concerning the training programs in the supplementary table 1.

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[5] We collected sMRI and fMRI data – the statistical analysis is currently in progress and is not included within the scope of this thesis; the restrictions caused by the pandemic prevented the collection of MRI data at post-test.

## 5. Measures

Children completed measures of auditory and motor skills (near transfer), as well as general cognition, executive functions, emotion recognition, authenticity recognition, and broader socio-emotional skills (far transfer). Moreover, the COVID-19 pandemic led to the interruption of the training programs, and recent research has shown that the lockdown affected children's academic performance and well-being (e.g., Cachón-Zagalaz et al., 2020). Therefore, the effects of the pandemic were a confound variable that we attempted to control for (teacher report questionnaire). For the sake of clarity and brevity, we provide more detailed information concerning the measures used in the supplementary table 2.

## 5.1. Control measures

The Raven's Colored Progressive Matrices test (RPCM; Raven, 1947) was used as a control measure of general non-verbal cognitive ability. Furthermore, we measured the impact of COVID-19 lockdown on children's academic achievement, school participation and emotional state, through a teacher report questionnaire.

## 5.2. Near transfer measures

### 5.2.1. Music and auditory skills

We assessed two types of auditory memory: short-term and working memory, as indexed by the Digit Span forward and backwards tasks of the WISC-III (Weschler, 2003), respectively. We also measured auditory discrimination of rhythms and melodies, and recognition of unfamiliar melodies, as indexed by the Montreal Battery of Evaluation of Musical Abilities (MBEMA; Peretz et al., 2013). We measured children's auditory perception and production using the rhythm copy task of the Musical Aptitude Test (MATs; Overy et al., 2003).

### 5.2.2. Motor skills

The Purdue Pegboard test provides a measure of fine motor dexterity and coordination in three conditions: preferred-hand, non-preferred-hand, and both hands simultaneously (Tiffin, 1968). We measured arm-hand dexterity with the preferred-hand and non-preferred hand separately (gross-motor skills), through the Minnesota Manual Dexterity Test (Desrosiers et al., 1997). We also measured arm motor coordination through the Plate Tapping test, with the preferred-hand and non-preferred hand separately (Eurofit, 1993).

## 5.3. Far transfer measures

### 5.3.1. Executive functions

The Go/no-go task measured children's inhibitory control (adapted from Moreno et al., 2011), and the Simon task assessed cognitive interference (adapted from Bialystok, 2006; Simon & Rudell, 1967).

### 5.3.2. Emotion recognition and authenticity recognition

Children completed three forced-choice emotion recognition tasks. Two of them were focused on vocal emotions, speech prosody (Castro & Lima, 2010) and vocalizations (Lima et al., 2013), and the third one on facial expressions (Goeleven et al., 2008). Moreover, children completed two authenticity recognition tasks, one including laughter vocalizations, and the other crying (adapted from Neves et al., 2018).

### 5.3.3. Socio-emotional skills

We included three socio-emotional tasks: the Child Self-Regulation and Behavior Questionnaire (CSBQ), which measures children's social behavior through a parent/educator report questionnaire (Howard & Melhuish, 2017); the Index of Empathy for Children (Bryant, 1982), a self-report questionnaire that measures children's judgements of whether they have an emotional response to other's emotional situations; and the Test of Emotion Comprehension (TEC), a story-telling test of emotional understanding (Pons & Harris, 2000; Rocha et al., 2013).

## 6. Data analysis

## 6.1. Aggregated variables - Principal component analysis

Given that we include auditory memory, rhythm/melodic discrimination, and rhythm copy tasks, we tested whether an aggregate variable could be used as an index of *auditory skills* (separately for pre and post-test) - this allows to reduce collinearity and the contribution of measure-specific error variance. We adopted a similar procedure to fine motor dexterity tasks, which represent *fine-motor skills*, as well as arm-hand dexterity and arm motor coordination tasks, representing *gross-motor skills*. Therefore, we conducted three principal component analysis (PCA) and extracted three components representing near transfer effects of music training: (1) Auditory skills - the ability to discriminate and manipulate auditory information; (2) Fine-motor skills - the ability to coordinate hand and finger movements with the eyes; (3) Gross-motor skills - the ability to coordinate hand-arm movements with the eyes.

Principal component analysis (varimax rotation) revealed a one-factor solution for each domain of near transfer. The solution for auditory skills accounted for 56.92% of the variance (the six tasks loaded highly on the component: discrimination of melodies, discrimination of rhythm, recognition of unfamiliar melodies, rhythm repetition, auditory short-term memory, auditory working memory, rs = .76, .84, .79, .75, .70, .69, respectively). The solution for fine-motor skills accounted for 83.03% of the variance; the three tasks loaded highly on the component: preferred-hand, non-preferred hand, both hands, rs = .89, .92, .92, respectively. The solution for gross-motor skills accounted for 81.87% of the variance; the four tasks loaded highly on the component: arm-hand dexterity with preferred-hand, non-preferred hand, and plate tapping with preferred hand, non-preferred hand, rs = .89, .91, .90, .92, respectively.

We did not aggregate the emotion recognition, authenticity recognition and broader socio-emotional measures because we were interested in how music training might affect different aspects of socio-emotional functioning. That is, the effects of music training on socio-emotional skills are a topic underinvestigated, and the few available longitudinal studies have reported mixed findings. Thus, aggregating the wide range of socio-emotional measures included in this study would not allow to explore the possible differential effects of music training on these measures. Furthermore, we tested an aggregated variable for executive functions (inhibitory control and interference), but the Kaiser-Meyer-Olkin test for sampling adequacy revealed that the data is not suited for principal component analysis (KMO = .50).

## 6.2. Pre-test group comparisons

Before the longitudinal analyses, we conducted one-way ANOVA's to test if there were no group differences prior to training, considering auditory skills, fine- and gross-motor skills, executive functions, emotion recognition, emotional authenticity recognition, and socio-emotional skills.

## 6.3. Longitudinal analysis

We analyzed the effects of training by using mixed effects modelling, as implemented in the lme4 (version 1.1-27.1; Bates et al., 2014) and lmerTest (Kuznetsona et al., 2017) packages for R (version 4.1.3; R Core Team, 2022). Mixed-effects models are suitable to analyze data that are collected according to a repeated measures design, as it explicitly accounts for the inherent within-subject dependency of the data (i.e., multiple measurements are taken on each participant over time). That is, mixed-effects models allow random effects of participants, thus capturing individual variability between subjects and accounting for the correlation structure within the data (Baayen, 2008). We employed linear models for all the variables, that is, near transfer (auditory and motor skills) and far transfer measures (executive functions, emotion recognition, authenticity recognition, social behavior, empathy and emotion comprehension)[6]. Additionally, we calculated individual predisposition scores in order to examine if the initial performance level significantly affected the magnitude of the potential music training effects. Predisposition is a dichotomous variable that was computed based on a median split of the pre-test scores, dividing the participants into low- or high-predisposition. Predisposition was only considered when the model that included a Time*Group interaction was the best fitted.

For each analysis, we started with a baseline model (Model 0) that only included random effects (within-participant variability). Model 0 is a reference model that was compared with more complex models that included fixed effects. In our study, the fixed effects of interest were Time (pre- vs. post-test), Group (music vs. sports vs. control), Predisposition (high vs. low), and COVID-19 impact (with vs. without negative impact). These fixed effects were added one at a time, first to the Model 0 and then to each subsequent model, and held whenever their inclusion improved the model fit (the lower the Akaike Information Criteria [AIC] score, the better the model fit). The fit of each subsequent model was compared to the previous model. As the previous model was nested in the subsequent one, a likelihood ratio test (LR) was conducted to determine whether the models with and without the fixed effects of interest were significantly different (i.e., *p* < .05), and to test the improvement in goodness of fit. The model parameters of improvement in goodness of fit were estimated by the maximum likelihood estimation and BOBYQA optimizer. Significance of the fixed effects and interactions were assessed by means of *F*-test using Satterthwaite approximation (Luke, 2017); Satterthwaites's method was also used for degrees-of-freedom and t-statistics. Pairwise comparisons with Bonferroni correction were conducted when significant main effects or interactions were found in the mixed-effects models (*p* < .05).

## 7. Results

### 7.1. Pre-test group comparisons

There were no pre-test diferences across groups for any of the near transfer measures, namely auditory skills (*F* = 0.36, *p* = .70), fine-motor skills (*F* = 1.41, *p* = .25), and gross-motor skills (*F* = 0.55, *p* = .58). As for the far transfer measures, there were no pre-test differences in executive functions (inhibitory control: *F* = 1.63, *p* = .20; interference: *F* = 0.49, *p* =.62), emotional authenticity recognition (laughter: *F* = 0.56, *p* = .571; crying: *F* = 0.05, *p* = .96), empathy, (*F* = 0.74, *p* = .48), and emotion comprehension, (*F* = 0.53, *p* = .59). There were no pre-test differences in emotion recognition of vocalizations (*F* = 1.49, *p* = .23), and faces (*F* = 2.71, *p* = .07). However, a one-way ANOVA analysis revealed significant pre-test differences in prosody recognition, (*F* = 3.10, *p* = .05; Sports x Passive

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[6] We runned both linear and logistic models for variables whose raw data was categorical and with multiple stimulus items, that is, emotion recognition in prosody, vocalizations, and faces, as well as authenticity recognition. We adopted this procedure to attest that the results were similar across linear and logistic analyses.

control: $p$ = .05; $M_{\text{sports group}} = 0.43$, $M_{\text{control group}} = 0.33$), and social behavior ($F$ = 3.57, $p$ = .03; Sports x Passive control: $p$ = .05; $M_{\text{sports group}}$ = 3.99, $M_{\text{control group}}$ = 3.67). See Table 2 for pre- and post-test descriptives of the measures included.

| **Measures** | **Music Group** | | **Sports Group** | | **Passive Control Group** | | ***F*** | ***p*** |
|---|---|---|---|---|---|---|---|---|
| | **Pre-test** | **Post-test** | **Pre-test** | **Post-test** | **Pre-test** | **Post-test** | | |
| Auditory skills | -0.55 (0.81) | 1.07 (0.81) | -0.67 (0.73) | 0.35 (0.72) | -0.68 (0.60) | 0.48 (0.78) | 0.36 | .697 |
| Fine-motor skills | -0.48 (0.75) | 1.41 (0.68) | -0.70 (0.65) | 0.31 (0.70) | -0.69 (0.57) | 0.12 (0.65) | 1.41 | .249 |
| Gross-motor Skills | 0.62 (0.82) | -0.90 (0.38) | 0.80 (0.99) | -0.70 (0.63) | 0.63 (0.65) | -0.44 (0.62) | 0.55 | .577 |
| **Executive Functions** | | | | | | | | |
| Inhibitory control | 1.64 (0.76) | 2.78 (0.62) | 1.85 (0.60) | 2.85 (0.56) | 1.89 (0.53) | 2.83 (0.45) | 1.63 | .202 |
| Interference | 15.54 (12.94) | 10.47 (10.12) | 15.88 (18.10) | 8.59 (7.78) | 12.42 (16.64) | 9.02 (11.59) | 0.49 | .615 |
| **Emotion Recognition** | | | | | | | | |
| Prosody | 0.41 (0.16) | 0.61 (0.13) | 0.43 (0.20) | 0.56 (0.16) | 0.33 (0.18) | 0.55 (0.16) | 3.10 | **.049** |
| Vocalizations | 0.74 (0.12) | 0.81 (0.10) | 0.71 (0.13) | 0.79 (0.11) | 0.70 (0.10) | 0.79 (0.10) | 1.49 | .231 |
| Faces | 0.70 (0.11) | 0.79 (0.08) | 0.63 (0.13) | 0.72 (0.11) | 0.66 (0.14) | 0.78 (0.12) | 2.71 | .071 |
| **Authenticity Recognition** | | | | | | | | |
| Laughter | 1.25 (0.64) | 1.66 (0.90) | 1.37 (1.05) | 1.62 (0.98) | 1.47 (0.79) | 1.89 (0.79) | 0.56 | .571 |
| Crying | 0.22 (0.74) | 0.28 (0.74) | 0.18 (0.63) | 0.16 (0.79) | 0.22 (0.70) | 0.24 (0.70) | 0.05 | .956 |
| **Socio-Emotional Skills** | | | | | | | | |
| Social behavior | 3.73 (0.56) | 3.92 (0.57) | 3.99 (0.49) | 4.05 (0.49) | 3.67 (0.60) | 3.82 (0.61) | 3.57 | **.032** |
| Empathy | 11.81 (2.94) | 13.38 (3.50) | 11.53 (2.73) | 13.73 (3.09) | 12.39 (3.54) | 14.21 (2.51) | 0.74 | .477 |
| Emotion comprehension | 17.76 (1.38) | 19.32 (1.23) | 17.52 (1.60) | 19.56 (1.12) | 17.88 (1.50) | 19.06 (1.46) | 0.53 | .589 |

*SD in parenthesis.*

***Table 2.*** Pre and post-test scores for each variable, and one-way ANOVA for pre-test differences between groups.

## 7.2. Near transfer effects

For detailed information on the model selection and parameters estimates for the full models of auditory, fine- and gross-motor skills, please see Supplementary Tables 3 and 4, respectively. Figure 1 shows the auditory, fine-motor, and gross-motor patterns of pre- to post-test change in music, sports, and passive control groups.

### 7.2.1. Auditory skills

The best fitted model for auditory skills was: Auditory skills ~ Time * Group * Predisposition + COVID + (1|Participant)] (model A4). We found a significant main effect of Time [$F(1,110) = 271.25$, $p < .001$], showing that all children significantly improved from pre- to post-test, $\beta = 0.60$, $SE = 0.04$, $t(110) = 16.47$, $p < .001$, CI 95% [.53, .67]. We also found a main effect of Group [$F(2,110) = 7.26$, $p = .001$], revealing that the music training group outperformed the sports group, $\beta = -0.30$, $SE = 0.09$, $t(110) = -3.43$, $p = .002$, CI 95% [-.47, -.13], but no differences were found in comparison to the passive control group, $\beta = 0.15$, $SE = 0.12$, $t(110) = 1.21$, $p = .45$, CI 95% [-.09, .39].

There was a significant Time x Group interaction [$F(2,110) = 12.30$, $p < .001$], showing that the music training group had a greater improvement in auditory skills than the sports group, $\beta = -0.15$, $SE = 0.04$, $t(110) = -3.35$, $p = .002$, CI 95% [-.24, -.06]. However, no differences were found in comparison to the passive control group, $\beta = -0.02$, $SE = 0.06$, $t(110) = -0.25$, $p = 1.00$, CI 95% [-.14, .11].

We found a significant Time x Predisposition interaction [$F(1,110) = 4.48$, $p = .04$], with the low-predisposition group improving more than the high-predisposition group in their auditory skills, $\beta = -0.08$, $SE = 0.04$, $t(110) = -2.12$, $p = .04$, CI 95% [-.15, -.01]. However, we did not find a significant Time x Group x Predisposition interaction ($p = .40$). Therefore, this improvement was found regardless of the training group. Additionally, we found a significant main effect of COVID-19 lockdown impact [$F(1,110) = 17.73$, $p < .001$]. Children who have not suffered a negative impact presented better auditory skills at post-test than those who suffered a negative impact, $\beta = 0.21$, $SE = 0.05$, $t(110) = 4.21$, $p < .001$, CI 95% [.11, .31].

### 7.2.2. Fine motor skills

The best fitted model for fine-motor skills was: Fine-motor skills ~ Time * Group * Predisposition (1|Participant)] (model Mf3). A significant main effect of Time [$F(1,110) = 566.30$, $p < .001$] showed that all children improved from pre- to post-test, $\beta = 0.62$, $SE = 0.03$, $t(110) = 23.80$, $p < .001$, CI 95% [.57, .67]. There was a significant main effect of Group, $F(2,110) = 30.43$, $p < .001$, in which the music group presented better fine-motor skills than sports, $\beta = -0.19$, $SE = 0.06$, $t(110) = -3.44$, $p = .001$, CI

95% [-.30, -.08], and the passive control group, *β* = -0.25, *SE* = 0.06, *t*(110) = -4.31, *p* < .001, CI 95% [-.37, -.14].

There was a significant Time x Group interaction [*F*(2,110) = 43.25, *p* < .001], demonstrating that the music group outperformed the sports group, *β* = -0.11, *SE* = 0.04, *t*(110) = -3.16, *p* = .002, CI 95% [-.18, -.04], and the passive control group, *β* = -0.23, *SE* = 0.04, *t*(110) = -5.95, *p* < .001, CI 95% [-.30, -.15]. We found a significant Time x Predisposition interaction [*F*(1,110) = 25.64, *p* < .001], showing that the low-predisposition group improved more than the high-predisposition group in fine-motor skills, *β* = -0.13, *SE* = 0.03, *t*(110) = -5.06, *p* < .001, CI 95% [-.18, -.08]. However, this improvement of the low-predisposition group was found regardless of the training group, as we did not find a significant Time x Group x Predisposition interaction ( *p* = .09).

### 7.2.3. Gross motor skills

The best fitted model for gross-motor skills was: Gross motor skills ~ Time * Group * Predisposition + (1|Participant)] (model Mg3). We found a significant main effect of Time, *F*(1,110) = 785.61, *p* < .001, showing that all children improved from pre- to post-test, *β* = -0.68, *SE* = 0.02, *t*(110) = -28.03, *p* < .001, CI 95% [-.73, -.63]. A significant main effect of Group was found [*F*(2,110) = 3.85, *p* = .02], but no differences were found between the groups after Bonferroni corrections for multiple comparisons (*p*s ≥ .14).

A significant Time x Group interaction [*F*(2,110) = 8.22, *p* < .001] revealed that musically-trained children improved more on gross-motor skills as compared to the passive control group, *β* = 0.14, *SE* = 0.04, *t*(110) = 4.05, *p* < .001, CI 95% [.07, .21], and as compared to the sports group, *β* = -0.07, *SE* = 0.03, *t*(110) = -2.11, *p* = .04, CI 95% [-.14, -.01]. Moreover, a significant Time x Predisposition interaction [*F*(1,110) = 61.90, *p* < .001] revealed that the low-predisposition group had a greater pre- to post-test improvement than the high-predisposition group, *β* = 0.19, *SE* = 0.02, *t*(110) = 7.87, *p* < .001, CI 95% [.14, .24]. However, this improvement of the low-predisposition group was found regardless of the training group, as we did not find a significant Time x Group x Predisposition interaction (*p* = .53).

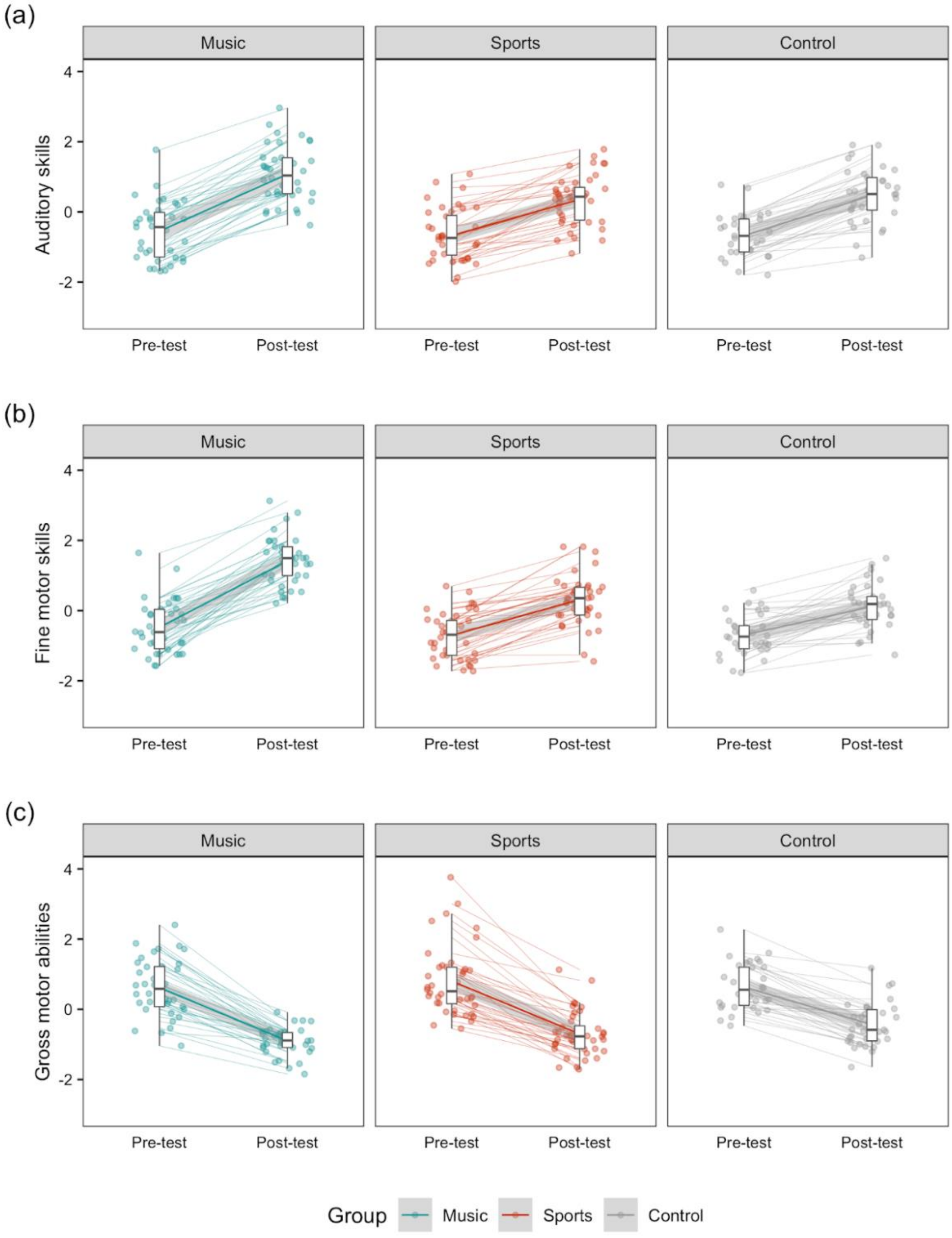

***Figure 1*****.** Mean Scores and Pre- to Post-test Change in Auditory Skills (a), Fine-Motor Skills (b), and Gross-Motor Skills (c), for Music, Sports, and Passive Control Groups.

## 7.3. Far transfer effects

The models selection and parameters estimates of the full models for executive functions, emotion recognition, authenticity recognition, and socio-emotional skills are detailed in Supplementary Tables 3 and 4, respectively. The pattern of pre- to post-test change in music, sports, and passive control groups for executive functions, emotion recognition, emotion authenticity recognition, and socio-emotional skills is shown in Figures 2, 3, 4, and 5, respectively.

### 7.3.1. Executive functions

#### Inhibitory Control

The best fitted model for inhibitory control was: Inhibitory control (*d'*) ~ Time + (1|Participant)] (model IC1). We found a main effect of Time, $F(1,110) = 204.74$, $p < .001$, with all children improving from pre- to post-test, $\beta = 0.52$, $SE = 0.04$, $t(110) = 14.31$, $p < .001$, CI 95% [.44, .59]. Thus, children's performance on the inhibitory control task significantly varied as a function of Time, but not as a function of Group.

#### Interference

The best fitted model for interference was: Interference ~ Time + (1|Participant)] (model I1). We found a main effect of Time, $F(1,109.47) = 11.27$, $p = .001$, with all children improving from pre- to post-test, $\beta = -2.67$, $SE = 0.80$, $t(109.47) = -3.36$, $p = .001$, CI 95% [-4.23, -1.11]. Thus, children's performance on the interference task significantly varied as a function of Time, but not as function of Group.

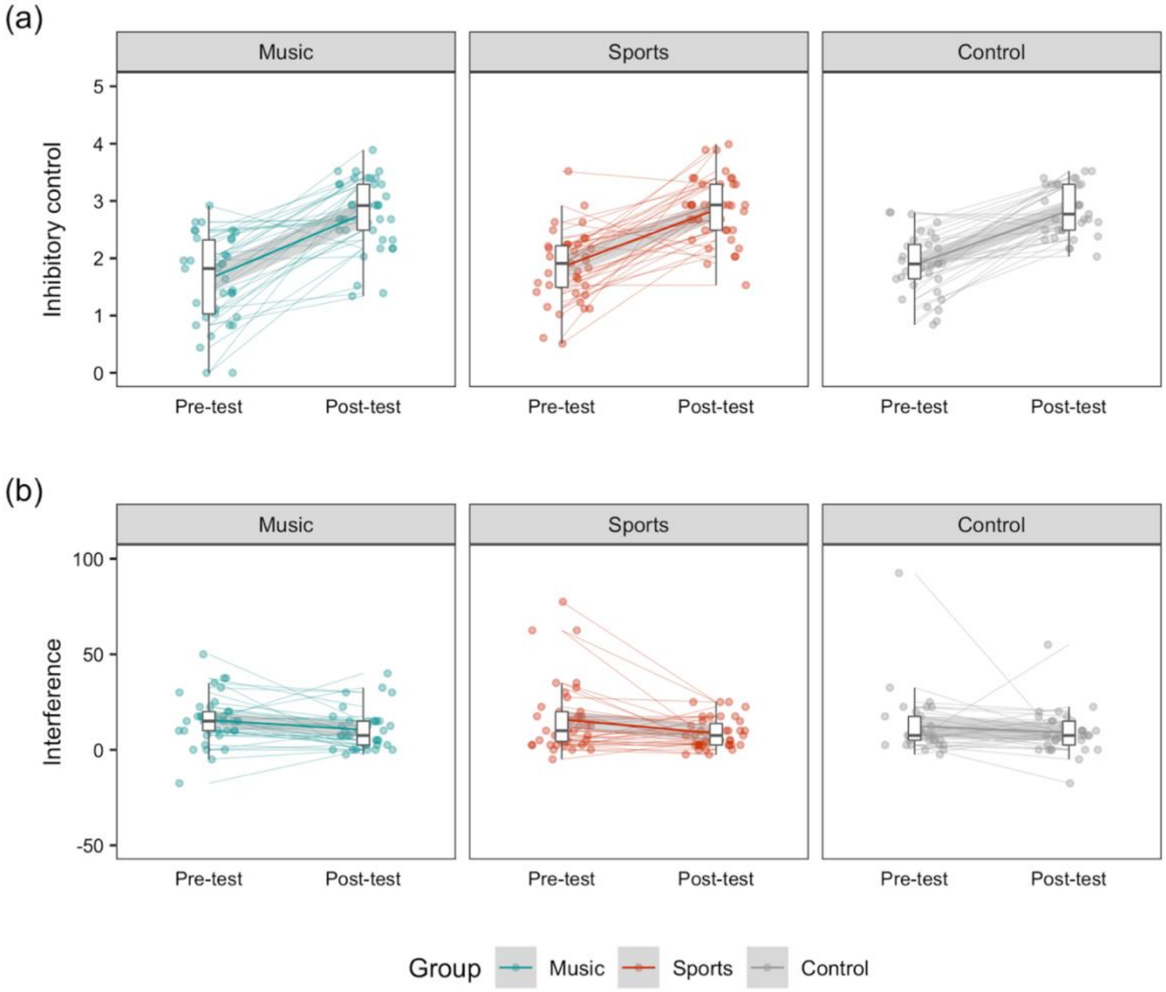

***Figure 2*****.** Mean Scores and Pre- to Post-test Change in Inhibitory Control (a), and Interference (b), for Music, Sports, and Passive Control Groups.

### 7.3.2. Emotion recognition

#### Prosody

The best fitted model for emotion recognition in prosody was: Emotion recognition in prosody ~ Time * Group * Predisposition + (1|Participant)] (model ERp3). We found a significant main effect of Time [*F*(1,110) = 253.56, *p* < .001], with all children improving from pre- to post-test, *β* = 0.09, *SE* = 0.01, *t*(110) = 15.92, *p* < .001, CI 95% [.08, .10]. However, there was no significant main effect of Group [*F*(2,110) = 1.78, *p* = .17], nor a significant Time by Group interaction [*F*(2,110) = 2.49, *p* = .09]. There was a significant Time by Predisposition interaction [*F*(1,110) = 38.46, *p* < .001], with the low-predisposition group improving more than the high-predisposition group, *β* = -0.03, *SE* = 0.01, *t*(110) = -6.20, *p* < .001, CI 95% [-.04, -.02]. This improvement was found regardless of the training group, as we did not find a significant Time x Group x Predisposition interaction (*p* = .68).

#### Vocalizations

The best fitted model for emotion recognition in vocalizations was: Emotion recognition in vocalizations ~ Time + (1|Participant)] (model ERv1). The results showed a main effect of Time, *F*(1,110) = 47.91, *p* < .001, with all children improving from pre- to post-test, *β* = 0.04, *SE* = 0.01, *t*(110) = 6.92, *p* < .001, CI 95% [.03, .05]. Thus, children's performance on emotion recognition in vocalizations significantly varied as a function of Time, but not considering the Group.

#### Faces

The best fitted model for emotion recognition in faces was: Emotion recognition in faces ~ Time + Group + (1|Participant)] (model Erf3). In order to test if music training had a differential effect in emotion recognition in faces, before running the one that proved to be the best fitted model we ran one that included the Time by Group interaction (model ERf2: Emotion recognition in faces ~ Time * Group + (1|Participant)]. We found significant main effects for Time [*F*(1,110) = 85.95, *p* < .001] and Group [*F*(2,110) = 10.07, *p* = .007], but not a significant Time x Group interaction [*F*(2,110) = 1.66, *p* = .436]. Thus, we decided to run a simpler model (i.e., only including the main effects of Time and Group, model ERf3) and tested whether this model had a similar (*p* > .05) or better goodness of fit (*p* < .05 and lower AIC) than model ERf2. This proved to be true (please see Supplementary Table 3).

We found a significant main effect of Time, *F*(1,109.72) = 83.41, *p* < .001, showing that all children improved their ability from pre- to post-test, *β* = 0.05, *SE* = 0.01, *t*(109.72) = 9.13, *p* < .001, CI 95% [.04, .06]. A significant main effect of Group [*F*(2,110.24) = 5.01, *p* < .01] revealed that the music group presented higher scores than the sports group, *β* = -0.04, *SE* = 0.01, *t*(110.54) = -2.91, *p* = .004, CI 95% [-.06, -.01], but not as compared to the passive control group, *β* = 0.01, *SE* = 0.01, *t*(110.07) = 0.40, *p* = .689, CI 95% [-.02, .03].

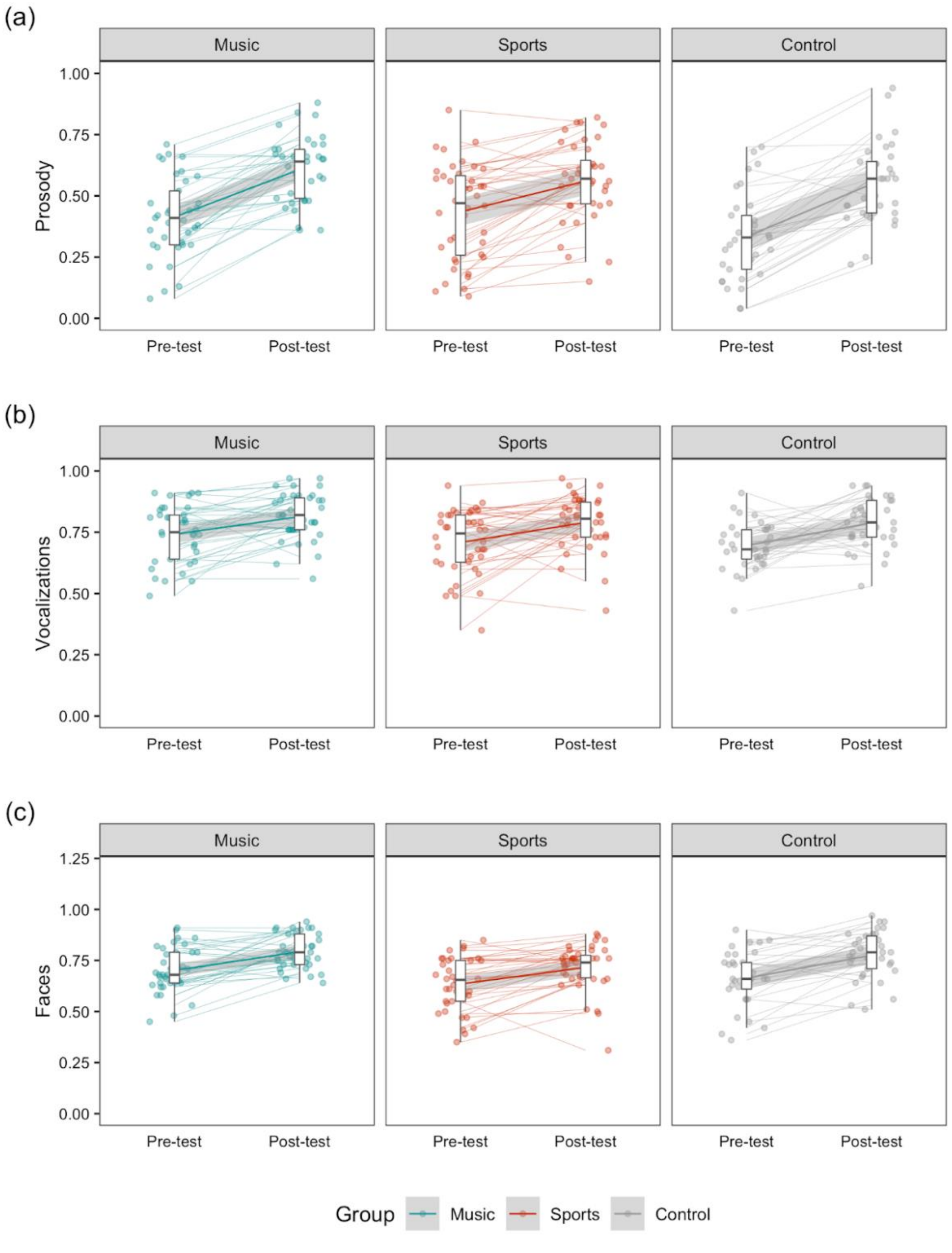

***Figure 3.*** Mean Scores and Pre- to Post-test Change in Emotion Recognition in Prosody (a), Vocalizations (b), and Faces (c), for Music, Sports, and Passive Control Groups.

### 7.3.3. Authenticity recognition

#### Laughter

The best fitted model for recognition of authenticity in laughter was: emotional authenticity recognition in laughter ~ Time + (1|Participant)] (model EARl1). We found a significant main effect of Time, $F(1,109.89) = 15.56$, $p < .001$, with children improving from pre- to post-test, $\beta = 0.18$, $SE = 0.05$, $t(109.89) = 3.95$, $p < .001$, CI 95% [.09, .27]. This result demonstrated that children's performance on authenticity recognition in laughter significantly varied as a function of Time, but not as function of Group.

#### Crying

The best fitted model for recognition of authenticity in crying was: Emotional authenticity recognition in crying ~ (1|Participant)] (model EARc0). This result demonstrated that children's performance on emotional authenticity recognition in crying did not significantly vary as a function of Time nor Group.

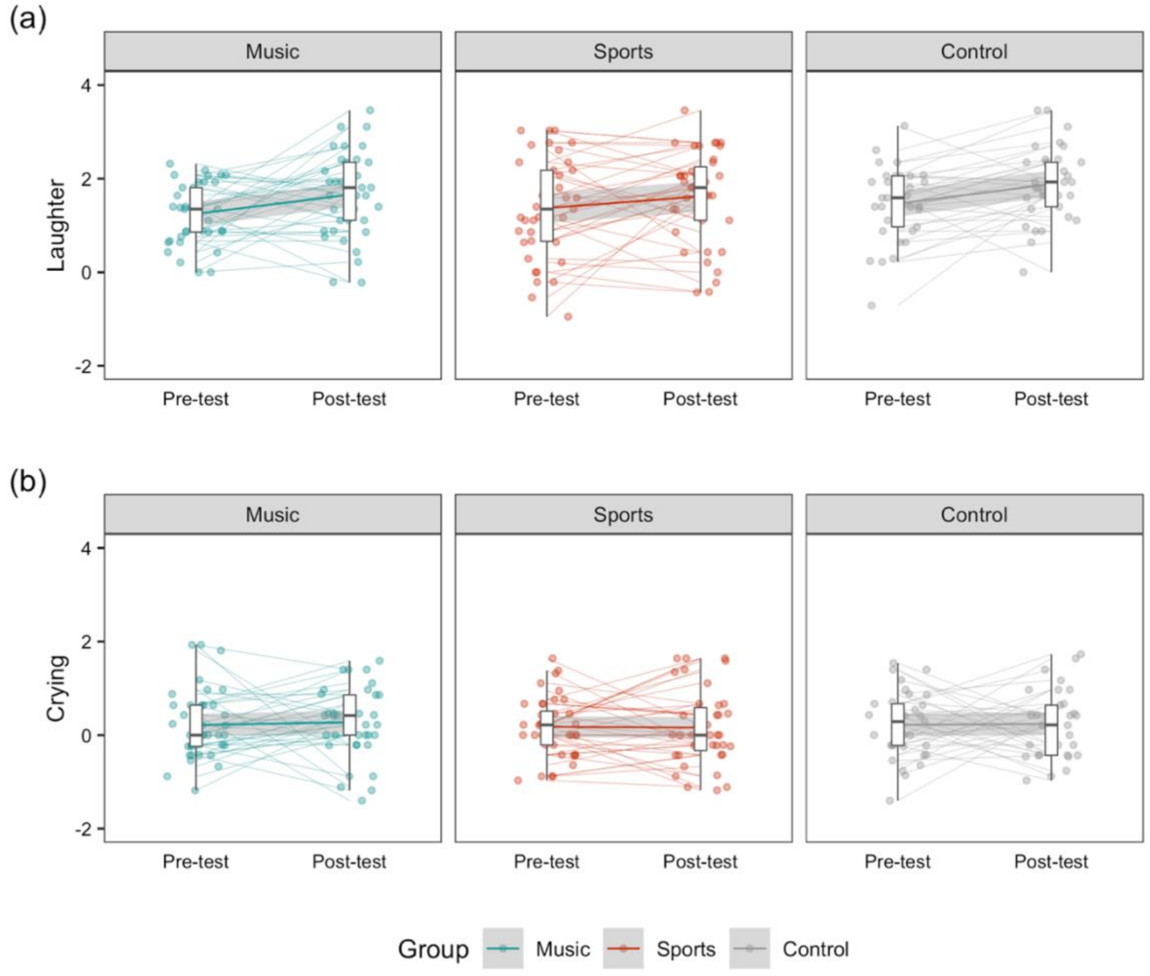

***Figure 4***. Mean Scores and Pre- to Post-test Change in Emotion Authenticity Recognition in Laughter (a), and Crying (b), for Music, Sports, and Passive Control Groups.

### 7.3.4. Socio-emotional skills

#### Social Behavior

The best fitted model for social behavior was: Social Behavior ~ Time + COVID + (1|Participant)] (model SB3). We found a significant main effect of Time, *F*(1,110) = 23.79, *p* < .001, showing that all children improved from pre- to post-test, *β* = 0.07, *SE* = 0.01, *t*(110) = 4.88, *p* < .001, CI 95% [.04, .09]. Additionally, we also found a significant main effect of COVID-19 lockdown impact, *F*(1,110) = 23.38, *p* < .001, evidencing that children who have not suffered a negative impact presented higher social behavior scores than their peers who were reported to have suffered a negative impact, *β* = 0.24, *SE* = 0.05, *t*(110) = 4.84, *p* < .001, CI 95% [.14, .34]. Therefore, children's social behavior varied as a function of Time and COVID-19 impact, but not considering the Group.

#### Empathy

The best fitted model for empathy was: Empathy ~ Time + (1|Participant)] (model E1). We found a significant main effect of Time, *F*(1,110) = 27.10, *p* < .001, with all children improving from pre- to post-test, *β* = 0.94, *SE* = 0.18, *t*(110) = 5.21, *p* < .001, CI 95% [.58, 1.29]. This result demonstrated that children's empathy significantly varied as a function of Time, but not considering Group.

#### Emotion Comprehension

The best fitted model for emotion comprehension was: Emotion Comprehension ~ Time + (1|Participant)] (model EC1). There was a significant main effect of Time, *F*(1,109) = 111.75, *p* < .001, with all children improving from pre- to post-test, *β* = 0.80, *SE* = 0.08, *t*(109) = 10.57, *p* < .001, CI 95% [.66, .96]. However, children's emotion comprehension did not vary as a function of Group.

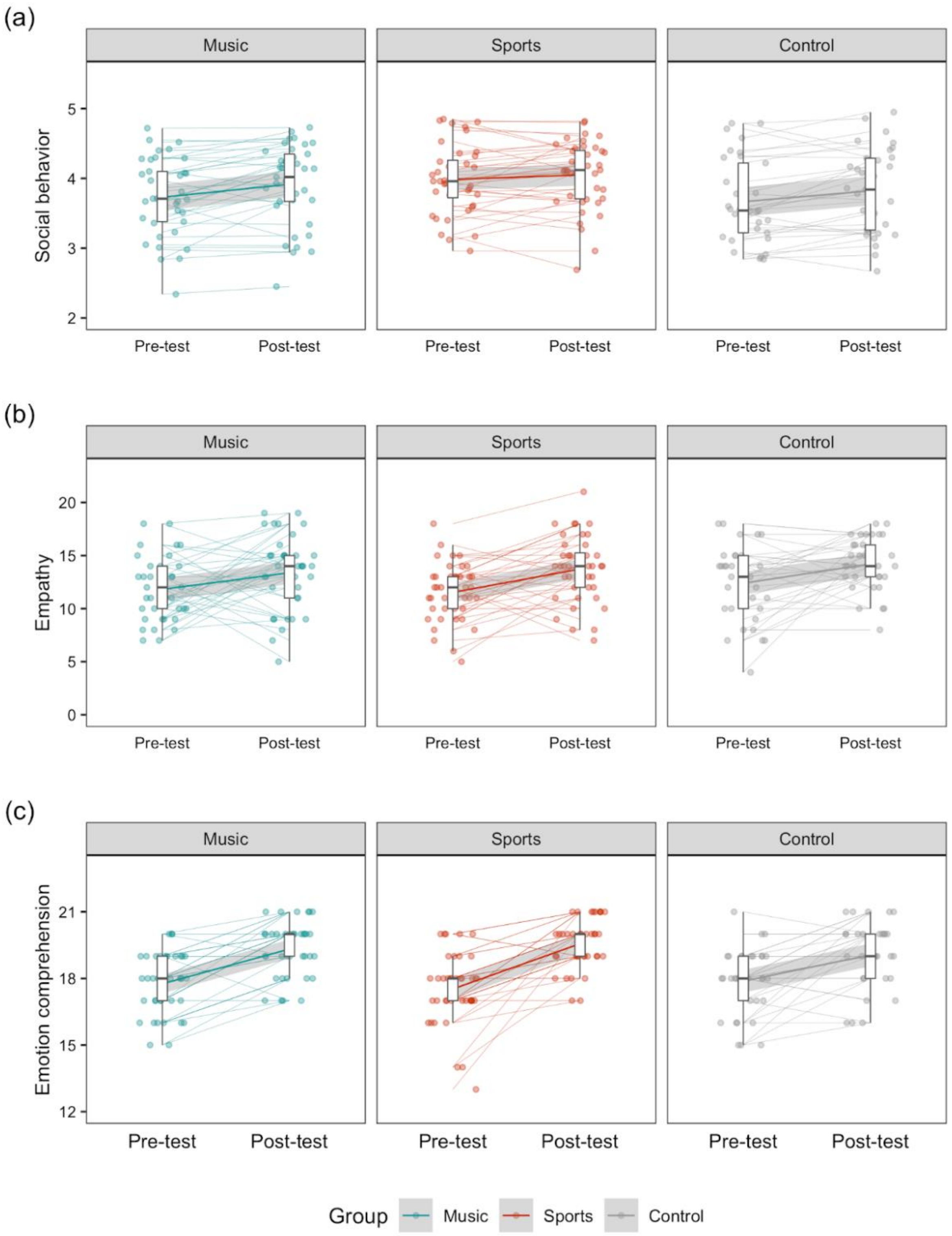

***Figure 5*****.** Mean Scores and Pre- to Post-test Change in Social Behavior (a), Empathy (b), and Emotion Comprehension (c), for Music, Sports, and Passive Control Groups.

## 8. Discussion

In this study we asked whether music training improves children's socio-emotional skills. We conducted a longitudinal study with 6- to 8-year-old children to examine this question. The study was implemented in a regular school environment, and it included pre-test, training and post-test phases. The effects of music training were compared to those of sports training, and to a passive control group. We measured a wide range of socio-emotional skills, namely emotion recognition, authenticity recognition, as well as social behavior, emotion comprehension, and empathy. We also examined the effects of music training on executive functions (inhibitory control and interference), and on near transfer domains, namely auditory and motor skills. We found positive effects of music training on auditory and motor skills (near transfer), but these effects did not extend to any socio-emotional skill, nor executive functions (far transfer). Furthermore, children who had lower auditory, motor, and prosody recognition skills at pre-test improved more on these skills, as compared to those who had higher scores at pre-test – but this effect was similarly observed across groups. Additionally, we examined possible negative effects of the lockdown during the COVID-19 pandemic, and found that children who did not suffer a negative impact had higher auditory skills and better social behavior than those who were reported to have suffered a negative impact during the lockdown.

Considering the close relationship between music and socio-emotional processing (Savage et al., 2021), and the fact that socio-emotional skills have been described to be a strong candidate for transfer through music training (Schellenberg & Lima, 2023), we expected to find significant effects of music training on children's socio-emotional skills. However, the results on this matter proved to be null. As for emotion recognition skills, previous cross-sectional studies have found positive associations between musical abilities and enhanced vocal emotion recognition, such as non-verbal vocalizations (e.g., Correia et al., 2022; Parsons et al., 2014), and one study found a positive association between musical abilities and the ability to recognize authenticity in laughter (Lima et al., 2016). On the other hand, previous studies have found null effects of music training on emotion recognition skills, namely facial expressions (e.g., Correia et al., 2022; Farmer et al., 2020), non-verbal vocalizations (e.g., Weijkamp & Sadakata, 2016), and prosody recognition (e.g., Trimmer & Cuddy, 2008). Our findings agree with this cross-sectional evidence showing null effects of music training on emotion recognition skills. To our knowledge, only one study has inspected effects of music training on children emotion recognition skills (Thompson et al., 2004). This study has reported that children who received music training showed improved prosody recognition, as compared to a passive control group, but not as compared to a drama group. The fact that the music training group did not significantly differ from the drama training suggests that the observed effects in prosody recognition do not reflect a specific advantage of music training. Furthermore, children were tested only at post-test on the prosody recognition task, thus, it could be possible that the groups significantly differed in their prosody recognition skills at pre-test. Therefore, these findings do not allow to establish causality. Considering broader aspects of socio-emotional processing, our results align with previous longitudinal studies showing that music training did not significantly improve children's socio-emotional skills, such as empathy (Yuan-Yang, 2020), prosociality (Alemán et al., 2017) and cognitive and behavioral self-regulation (Williams & Berthelsen, 2019). One possible explanation for the fact that we did not find significant effects of music training on socio-emotional skills is the idea that transfer is much more likely to occur under conditions where trained and untrained activities largely overlap (Barnett & Ceci, 2002). Therefore, the transfer of learning between distant domains rarely happens (Schellenberg, 2020; Schellenberg & Lima, 2023), which would be the case of music and socio-emotional skills. Still in this vein, we included socio-emotional measures that rely to a great extent on higher-level cognitive processing, such as the Test of Emotion Comprehension (Albanese et al., 2010; Schellenberg & Mankarious, 2012). This strong higher-order cognitive component reinforces the idea that there is a significant distance between the domains, that is, music-related skills and higher order socio-emotional skills. Accordingly, Schellenberg and Mankarious (2012) found that the positive association between music training and children's emotion comprehension scores disappeared when IQ was held constant. Nonetheless, while the emotion comprehension test might recruit higher-order cognition, we included socio-emotional measures that rely less on higher-order cognition and the results were still null, namely the emotion recognition tasks, which rely to a great extent on basic perceptual abilities. On the other hand, some longitudinal studies did find significant effects of music training on children's socio-emotional skills, namely in emotion comprehension (Boucher et al., 2021), emotional self-regulation (Williams & Berthelsen, 2019), prosocial skills and sympathy (Schellenberg et al., 2015). One cannot exclude the possibility that the music training program might had significant effects on other socio-emotional skills that were not included here, such as sympathy (Schellenberg et al., 2015) and synchronization skills (Buren et al., 2021). Music activities frequently engage synchronization behaviors, which in turn could promote cooperation and social bonding (Cirelli, 2018). Another plausible explanation for the null effects of music training is the lockdown imposed by the COVID-19 pandemic. Several studies have shown that the socio-emotional development of children was severely disrupted during lockdown (e.g., Egan et al., 2021). Indeed, those children who did not suffer a negative impact of the pandemic showed higher social behavior scores, as compared to children whose teachers reported to have suffered a negative impact during the pandemic. Thus, one cannot rule out the possibility that music training could have had a significant positive effect on children's socio-emotional skills if the pandemic did not exist.

Considering executive functions, we did not find significant effects of music training on cognitive interference and inhibitory control, which are considered to be far transfer domains of music training

(Miendlarzewska & Trost, 2014). This finding aligns well with the previously mentioned argument that transfer of learning between distant domains is rare (Schellenberg, 2020; Schellenberg & Lima, 2023). Moreover, this finding is in accordance with previous longitudinal evidence showing null effects of music training on children's inhibitory control (e.g., Guo et al., 2018) and cognitive interference (e.g., Frischen et al., 2021), as well as with a recent review that concludes that there is no good evidence of causality between music training and executive functions (Schellenberg & Lima, 2023). Therefore, the present results do not allow to test the hypothesis that possible far transfer effects of music training could be explained by enhancements in executive functions (e.g., Degé, 2021; Schellenberg & Peretz, 2008).

We found significant effects of music training on children's auditory skills, as compared to the sports training group, but not the passive control group. Auditory processing is considered to be a near transfer domain of music training (Wang, 2022). Indeed, performing music is a complex and demanding form of auditory expression, requiring high precision in the processing of subtle acoustic cues (Kraus & Chandrasekaran, 2010). Our findings agree with previous longitudinal studies showing that music training enhances children auditory processing. For example, Hyde et al. (2009) found an increased cortical volume in the right primary auditory region in children that received music training, and this increase was positively associated with a rhythm and melody discrimination task. However, the fact that the significant effect of music training on auditory skills was found in comparison to the sports group, but not the passive control group, is intriguing. One plausible explanation is the existence of underlying factors that are not fully understood, or factors that were not accounted for. For example, several studies have explored how different aspects of children and teacher's social environment affect intrinsic motivation. One study has found that the more teachers perceive pressure (e.g., performance standards), the less they are self-determined toward teaching (Pelletier et al., 2002). The presence of unmeasured or uncontrolled factors is frequent and can contribute to puzzling outcomes. A recent systematic review and meta-analysis has shown that music training improves auditory processing at the behavioral and brain level, but this effect was small, and high levels of heterogeneity were found (Neves et al., 2022). This high level of heterogeneity shows that there is a significant source of variability in the effects of music training that is unclear. Additionally, one important aspect is the COVID-19 pandemic. That is, children who did not suffer a negative impact of the lockdown had higher auditory skills than those children who were reported to have suffered a negative impact. Thus, ours results suggest that the lockdown had a negative impact on children's auditory skills, and this could have contributed to this puzzling outcome, even though we found a significant effect of music training on these skills. On the other hand, it is plausible to expect that near transfer effects of music training may not always occur (Schellenberg & Lima, 2023). Previous longitudinal studies did not find significant effects of music training on children's auditory processing. For example, Ilari et al. (2016) did not find significant effects of music training on rhythm perception, as compared to a passive control group. At the brain level, there were no significant effects of music training on children's cortical thickness of auditory cortices, as compared to a passive control group (Habibi et al., 2020). It is possible that to elicit more marked music training effects in auditory processing, the music program requires a higher amount of practice, different time courses, or even different training methodologies, for example.

We found significant evidence for a positive effect of music training on fine and gross-motor skills. Considering fine-motor skills, the significant effect found was in comparison with both the sports group and passive control group. As for gross-motor skills, the significant effect was also found in comparison with the passive control group and sports group. This finding is in accordance with the idea that motor skills are a near transfer domain of music training (Pantev & Herholz, 2011). A possible mechanism for these near transfer effects found might be explained by the high overlap between the trained skills within the music training programs and the measured skills. For example, the music training program involved instrumental performance such as playing a descant recorder, which implies precision in finger dexterity (Martins et al., 2018). Accordingly, some authors propose that near transfer of training often occurs when it involves tasks that are procedural in nature (Subedi, 2004). Music training involves procedural knowledge, as it implies a step of operation in sequence (e.g., playing a song with the xylophone), and the sequence of steps is repeated every time the task is performed (e.g., song rehearsal). Importantly, in previous longitudinal studies, significant effects of music training on children's fine-motor skills were also found (e.g., Costa-Giomi, 2005; Martins et al., 2018), supporting our finding that music training can promote near transfer effects to motor skills. The positive effect of music training on gross-motor skills was found in relation to the passive control group, as well as considering the basketball group. Basketball training involves gross manual dexterity, such as dribbling (e.g., Fotrousi et al., 2012), that resemble some of the gross-motor skills also involved in the music training program, such as body percussion. Therefore, it is surprising that the music group improved significantly more than the sports group in gross-motor skills. Nevertheless, our results show that basketball training was not as effective as music training in improving fine-motor skills, similarly to previous longitudinal evidence with children (Martins et al., 2018).

Additionally, we have found that children who had worse auditory, motor and prosody recognition skills at pre-test improved more on these skills, as compared to those who had higher scores at pre-test. This effect was found among all children, regardless of belonging to the music, sports, or no training group. Therefore, although we found a positive effect of music training on auditory and motor skills, one cannot conclude that music training had the greatest success among the children who scored lower at pre-test. Schellenberg et al. (2015) found positive effects of music training in 8-year-old socio-emotional skills, but only for those who had lower scores on these measures before training. In our study, although we found that those children who had lower scores on prosody recognition before training were the ones that improved more on this task, we did not find significant effects of music training on emotion recognition in prosody. It would be important for future studies to thoroughly investigate whether and how the magnitude of the effects of music training programs are influenced by the initial level of performance, as this could potentially enhance the effectiveness of the training programs (e.g., Caprara et al., 2015).

One limitation of this study is that the allocation of participants at pre-test was not truly random. As this longitudinal study was conducted in a regular school environment, by the time children were recruited to participate in the study they were 2nd graders already allocated to a class. Therefore, we conducted randomization at a class level to either the music, sports, or no training (rather than individual level). Children within the same class participated in the same training program (or no training), and it is reasonable to expect that within classes children interacted and influenced each other throughout the study. For instance, we cannot rule out the possibility that if a few children were not motivated during the music training program, they could have negatively influenced other children in the same class and diminish possible transfer effects. Following this idea, it would have been important to measure children's and teachers' motivation, as several studies have shown how motivation is a powerful mechanism of learning (e.g., Larson & Rusk, 2011). One inevitable limitation of our study is the fact that the training programs were interrupted due to the COVID-19 pandemic, which potentially impacted the consistency of the training programs, as well as children's progress and well-being.

In conclusion, we have documented significant effects of music training on children's auditory and motor skills (near transfer). However, the improvement of the music training group on auditory skills was found to be inconclusive, as it did not significantly differ from the improvement of the passive control group. We also show that there were no significant effects of music training on socio-emotional skills and executive functions (far transfer). Altogether, these results support evidence on the effectiveness of music training on improving motor skills (near transfer), and inform debates on the far transfer effects of music training. Moreover, these results shed light on a poorly explored topic in the literature, that is, longitudinal effects of music training on socio-emotional processing.

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# CHAPTER V | GENERAL DISCUSSION

## 1. Overview of research findings

Does music training provide non-musical benefits? We examined this question by inspecting whether music training transfers to auditory and linguistic processing, as well as to children's socio-emotional processing. Considering socio-emotional processing, we also investigated associations between emotion recognition skills and socio-emotional adjustment.

First, we conducted a systematic review and meta-analysis with the aim of informing ongoing debates on whether music training produces transfer effects. We focused on specific domains that are underexplored in summaries of the literature, namely auditory and linguistic processing. Sixty-two longitudinal studies assessing whether music training programs affect behavioral and brain measures of auditory and linguistic processing were examined. The results pointed to a small positive neurobehavioral enhancement of music training on both domains. However, we found suggestive evidence of publication bias and a high level of heterogeneity.

Second, we conducted a cross-sectional study examining associations between children's emotion recognition skills and their socio-emotional adjustment. The sample included 141 6- to 8-year-old children, and the tasks required them to categorize different emotions as conveyed by two types of vocal emotional cues: prosody and non-verbal vocalizations. Socio-emotional adjustment was evaluated by the children's teachers using a questionnaire of self-regulation and social behavior. Higher emotion recognition in prosody was positively associated with better general socio-emotional adjustment. However, no significant associations were observed for emotion recognition in non-verbal vocalizations and facial expressions.

Third, we conducted a longitudinal study to clarify whether music training transfers to children's socio-emotional processing. We also measured executive functions, and included near transfer measures (auditory and motor skills). The study included pre-test, training, and post-test phases, in three conditions: music training ($n$ = 37), sports training ($n$ = 40), and no training ($n$ = 33). We did not find significant far transfer effects of music training, namely considering socio-emotional processing, and executive functioning. We found evidence for an advantage of music training on near transfer measures (auditory and motor skills). However, the advantage of music training on auditory skills was only significant in comparison with the active control group (sports), but not the passive control group.

Altogether, the findings of the present thesis suggest that music training can transfer to domains tightly related to music, namely auditory, fine and gross-motor skills (i.e., near transfer). However, evidence for transfer effects to substantially different domains is scant (i.e., far transfer). The meta-analysis revealed a small positive effect of music training on linguistic processing, but in the longitudinal study we did not find effects of music training on children's executive functions and socio-emotional processing. Emotion recognition in prosody was found to be associated with higher children's socio-emotional adjustment.

## 2. Transfer of learning through music training

### 2.1. Near transfer

The results reported in the present thesis suggest that music training has the potential to cause behavioral and brain benefits on auditory processing (i.e., near transfer). This statement is supported by the following: (1) our meta-analysis revealed a  small significant effect of music training on a wide range of auditory skills, such as rhythm and pitch discrimination; (2) the narrative synthesis was suggestive that music training changes brain responses to auditory stimuli, as well as the structure and functional dynamics of auditory systems; (3) the longitudinal study revealed a positive effect of music training on children's auditory skills (e.g., auditory memory). Furthermore, in the longitudinal study, we found significant evidence of the benefits of music training in motor skills (fine and gross-motor skills). These findings are aligned with the notion that performing music is a complex and demanding form of auditory expression, requiring high precision in the processing of subtle acoustic cues (Kraus & Chandrasekaran, 2010). Thus, auditory processing is tightly related to music training and is widely accepted as a near transfer domain (Wang, 2022). Benefits of music training in auditory processing are consistent with correlational evidence showing brain and behavioral differences between musicians and non-musicians in these skills. For instance, musicians exhibited superior performance on tests of pitch-processing and discrimination (Schellenberg & Moreno, 2010), as well as bimanual motor sequence timing execution (Kincaid et al., 2002), as compared to non-musicians. Moreover, gray matter volume differences were found in auditory and motor brain regions of musicians, when compared to a group of amateur musicians and non-musicians (Gaser & Schlaug, 2013). Indeed, auditory processing is highly related to motor processing, as music training requires complex auditory-motor interactions (Bailey et al., 2014; Lahav et al., 2005). For example, while playing an instrument, motor systems control the necessary fine motor skills to produce sound. This sound is processed by the auditory system, which in turn is used to adjust motor performance (Zatorre et al., 2007). Thus, motor skills are typically assumed to be a near transfer domain of music training, and our findings agree with this idea.

While correlational evidence does not allow us to infer causation, longitudinal studies inspecting music training effects frequently forsake near transfer domains. This was clearly visible in the meta-analysis, in which we inspected many longitudinal studies examining music training effects on auditory and linguistic processing, and only 34% of the studies included auditory measures. Near transfer effects might be assumed to always occur, thus, one might conclude that they require less attention (Bigand & Tillman, 2022). This idea originally stems from the theory of identical elements, which posits that transfer of learning occurs only to the extent that the new learning task contains elements identical to those in the previous tasks. For example, driving one's car generalizes to other models of cars. Thus, near transfer is believed to be common (Perkins & Salomon, 1992; Thorndike & Woodworth, 1901). In this vein, there is a prevailing assumption that transfer is much more likely to occur under conditions where trained and untrained activities largely overlap (Barnett & Ceci, 2002; Gathercole et al., 2019). Several longitudinal studies conducting training programs have reported results consistent with this view. For example, positive effects of working memory training on performance in working memory tasks (Minear et al., 2016), and positive effects of spatial training in mental rotation skills (Gilligan et al., 2019). The theoretical foundation of the transfer hypothesis through music training is plasticity (Moreno & Bidelman, 2014). That is, extensive music practice is believed to be related to plasticity, as it is accompanied by the acquisition of domain-specific cognitive and sensorimotor skills (Herholz & Zatorre, 2012; Patel, 2021). Accordingly, a possible mechanism for these near transfer effects might come from the overlap between the trained skills within the music training programs and the measured skills (Kraus & Chandrasekaran, 2010; Pantev & Herholz, 2011). For example, in our longitudinal study, children participated in an Orff-based music training program that involved the recognition of pitch and rhythm variations, which are fundamental skills during auditory processing (Kraus et al., 2012). Moreover, the training program involved instrumental performance such as playing a descant recorder, which implies precision in finger dexterity (Martins et al., 2018). Accordingly, some authors proposed that near transfer of training often involves tasks that are procedural in nature (Subedi, 2004). Music training involves procedural knowledge, as it implies a step of operation in sequence (e.g., playing a song with the xylophone), and the sequence of steps is repeated every time the task is performed (e.g., song rehearsal).

On the other hand, the meta-analysis revealed that the music training effects on auditory processing were small, and possibly affected by publication bias. That is, from the few studies that examine music training effect on auditory processing, possibly only the results that were in accordance with the authors' expectations were published, thus, the true effect of music training might be inflated (VanAert et al., 2019). These expectations could be aligned with the prevailing idea that music training invariably transfers to near domains. Following this idea, it is relevant to note that there is evidence showing null findings on near transfer domains of music training. For example, Ilari et al. (2016) found null effects of music training on children's rhythm perception, as compared to a passive control group. At the brain level, there were no significant effects of music training on children's cortical thickness of auditory cortices, as compared to a passive control group (Habibi et al., 2020). Importantly, in our longitudinal study we found significant effects of music training on auditory processing as compared to the sports group, but not as compared to the passive control group. This result is intriguing, and while it does not resonate with the generally recognized notion of the transferability of music training to near domains, this result aligns with previous studies showing that the effects of music training on auditory skills were not significant, as compared to a passive control group (e.g., Ilari et al., 2016).

These null findings could be attributed to many different factors, such as suboptimal designs (Ilari, 2020). Suboptimal designs are common to find within the music training literature. For instance, some studies include short periods of training and do not randomly assign the participants (Schellenberg, 2020). Random assignment is an important methodological practice that reduces the possibility of self-selection effects (e.g., motivational differences), as it randomly allocates participants to the respective experimental groups before training. In our longitudinal study, the allocation of participants was not truly random – we conducted randomization at a class level to either the music, sports, or no training (rather than at the individual level). Children within the same class participated in the same training program (or no training), and it is reasonable to expect that within classes children interacted and influenced each other throughout the study. In the same vein, in the meta-analysis we found high levels of heterogeneity, demonstrating that there is a high source of variability in the effects of music training that is unclear. Other factors that are not fully understood or accounted for could be related to confounding variables such as personality, motivation, and socioeconomic status (Ilari, 2020). In the case of our longitudinal study, one important factor that could have played a role in the effects is the COVID-19 pandemic, as our results suggest that the lockdown had a negative impact on children's auditory skills. Therefore, at this stage we cannot reach decisive conclusions regarding the near transfer effects of music training on auditory processing.

Improving aspects of the designs (e.g., sample size, random allocation, unbiased reporting of findings) and a more rigorous control of confounding variables (e.g., motivational aspects) will be crucial to reach firmer conclusions regarding the near effects of music training. Our systematic review and meta-analysis highlight the importance of examining near transfer effects, and together with the longitudinal study, contributed to the lack of evidence on this topic. Examining near transfer effects and the circumstances that these occur is crucial because it allows us to tackle the underlying mechanisms of plasticity and transfer effects. For example, existing hypotheses suggest that sharper auditory processing is required to explain far transfer from music to language (e.g., Besson et al., 2011; Patel, 2014). But if the transfer from music to linguistic processing results from sharper auditory processing, first one should establish that music training can change auditory skills.

## 2.2. Far transfer

Whether music training can bring benefits to distant non-musical domains is a longstanding debate, and the main objective of this thesis was to shed light on this topic. The results reported in the present thesis are suggestive that music training could transfer to more distant domains, but the extent to which this transfer occurs is very limited. This supposition comes from different sources, namely: (1) our meta-analysis revealed a small significant effect of music training on a wide range of linguistic skills, such as speech prosody and speech-in-noise perception; (2) the narrative synthesis was suggestive that music training changes brain responses to linguistic stimuli; (3) the longitudinal study did not reveal any significant effect of music training on executive functions, as well as on children’s socio-emotional abilities, ranging from emotion recognition to social behavior.

Why should music training benefit distant non-musical domains? The most common theoretical framework to explain far transfer is based on plasticity, that is, music training is a complex activity that can induce changes at the brain and behavioral level (Kolb, 2018). These induced changes at the brain level may underlie the capacity of transferring learned information to different domains. This hypothesis is supported by several studies showing brain and behavioral plasticity following specific training programs (e.g., Draganski et al., 2004; Maguire et al., 2000). Nonetheless, this explanation is simplistic, as it fails to explain why these training programs sometimes fail to extend their benefits to more distant domains, that is, far transfer (Gathercole et al., 2019). On the other hand, some authors describe transfer as the consequence of acquiring complex cognitive skills that can be applied to untrained tasks with some overlap. For instance, the cognitive routine framework posits that training on highly demanding tasks leads to the development of new complex cognitive skills (Gathercole et al., 2019). Transfer then occurs when one of these new skills can be applied to a novel activity (far transfer). In the same vein, Taatgen (2016) proposed that people train specific cognitive skills and as a by-product, a general cognitive skill is trained as well. These trained general cognitive skills can be helpful for other skills. Music training aligns well with the cognitive routine framework, as playing an instrument is a highly complex task involving the interaction of several modalities and higher-order cognitive functions (Herholz & Zatorre, 2012). Thus, music training requires domain-general cognitive abilities (e.g., executive functions), which can be trained through practice. Then, these enhanced cognitive abilities could transfer to other domains. This idea has been made popular by some influential studies, such as the one by Schellenberg (2004), according to which music instruction enhances general intelligence, which in turn could positively affect a wide range of other cognitive and academic abilities. Schellenberg (2011) suggested that an association between music lessons and a domain-general cognitive ability might explain all reported associations in the literature, such as executive functions (e.g., Degé et al., 2011). However, several longitudinal studies failed to replicate these findings (Haywood et al., 2015). For example, music training had no significant advantages on a broad range of cognitive measures, like non-verbal intelligence (Rickard et al., 2012). Moreover, a recent meta-analysis refuted the study by Schellenberg (2004) and did not find significant effects of music training on children´s cognitive and academic skills (Sala & Gobet, 2017). Put simply, the effects of music training on general cognitive skills are controversial, and positive findings have not always been found (Miendlarzewska & Trost, 2013). Accordingly, in our longitudinal study, we did not find evidence of significant effects of music training on executive functions, inhibitory control and cognitive interference tasks. One possible explanation may be the notion that transfer is much more likely to occur under conditions where trained and untrained activities largely overlap (Barnett & Ceci, 2002; Gathercole et al., 2019). Therefore, the transfer of learning between distant domains would rarely happen (Thorndike & Woodworth, 1901; Schellenberg, 2020).

### 2.2.1. Linguistic Processing

Along with the fact that linguistic processing is an extensively studied far transfer domain of music training, one of the most well-known theoretical frameworks on the role of transfer is the OPERA hypothesis (Patel, 2011; Patel, 2012; Patel, 2014). The results of our meta-analysis pointed to a small effect of music training on linguistic processing, which aligns with this hypothesis. According to this framework, a far transfer from music to linguistic processing may occur because music training induces higher demands on shared neural networks between auditory processing and language, thus promoting plasticity. Specifically, music training demands greater precision in certain aspects of auditory processing, driving plasticity in these networks and leading them to function with higher precision than needed for ordinary speech perception (Patel, 2012). For example, extracting pitch from complex sounds is an auditory skill that is fundamental for both music and speech processing (McDermott & Oxenham, 2008). Therefore, an overlap between domains is presumed in this framework, which is in conformity with the previously mentioned theory of the identical elements, and the notion that there should be a high overlap between the trained skills and the measured skills for transfer to happen (Pantev & Herholz, 2011; Perkins & Salomon, 1992; Thorndike & Woodworth, 1901). On the other hand, there is also evidence revealing null effects of music training on linguistic skills. For example, some meta-analyses reported a null effect of music training on reading fluency (Gordon et al., 2015; Román-Caballero et al., 2022). Furthermore, it is relevant to note that the OPERA hypothesis focuses on transfer to speech perception, while in our meta-analysis a wide range of linguistic skills were included beyond speech perception, such as reading, phonological processing, and vocabulary. Therefore, this hypothesis would only partially explain why we found a small positive effect of music training on linguistic processing. Furthermore, similarly to auditory processing, the effect found was small, and there was suggestive evidence of publication bias, as well a high level of heterogeneity. Importantly, in the longitudinal study the effects of music training on children's auditory skills were inconclusive, that is, while we found significant effects on auditory skills as compared to the sports group, we did not find significant effects as compared to the passive control group. Therefore, although our aim was not to test a possible overlap between auditory and linguistic brain networks, the present findings are not aligned with the OPERA hypothesis.

### 2.2.2. Emotion Recognition

In the present thesis, we did not find significant evidence of far transfer effects from music training to children's emotion recognition skills. Specifically, in the longitudinal study we included three emotion recognition tasks: two of them focused on vocal emotions (prosody and non-verbal vocalizations), and one including facial expressions. Moreover, we measured authenticity recognition in non-verbal vocalizations, namely laughter and crying.

The available evidence on this matter is heterogeneous and restricted to cross-sectional studies but supports the idea that music expertise is positively associated with vocal emotion perception (Martins et al., 2021; Nussbaum & Schweinberger, 2021). For example, some studies reported that music abilities are associated with enhanced emotion recognition in non-verbal vocalizations (e.g., Correia et al., 2022; Parsons et al., 2014). As for more nuanced social inferences, one study found a positive association between music abilities and the ability to recognize emotional authenticity in laughs (Lima et al., 2016). One possible mechanism can be that the neurocognitive pathways for processing music and vocal emotions overlap (Correia et al., 2022). Accordingly, there is evidence showing that music training predicts efficient auditory brainstem responses to purely non-verbal vocalizations, like crying (Strait et al., 2009). A recent critical review proposed that music training may improve fine-tune aspects of auditory processing, thus assisting vocal emotion recognition, but not facial emotion recognition (Martins et al., 2021). Indeed, we did not find music training effects on emotion recognition in facial expressions, which is also in accordance with previous cross-sectional evidence showing null results on this matter (e.g., Correia et al., 2022; Farmer et al., 2020). However, there is no evidence for associations considering vocal emotion recognition, namely non-verbal vocalizations (e.g., Weijkamp & Sadakata, 2016). Our findings agree with this evidence coming from cross-sectional studies and go further by showing that a music training program had no significant benefits on vocal emotion perception. Therefore, while several authors highlight the role of auditory sensitivity to the vocal features that express emotionality, it is not yet clear how music training interacts with vocal emotion perception through auditory pathways (Martins et al., 2021; Nussbaum & Schweinberger, 2021). One possible explanation can be that music processing and vocal emotion perception may not be linked via auditory sensitivity but rather via a supramodal emotional processor (Lima et al., 2016; Trimmer & Cuddy, 2008). Likewise, Lima & Castro (2011) proposed that music training might increase the level of "emotional granularity", resulting in a more fine-grained conceptualization and differentiation of emotions, which could aid emotional perception in other domains (Nussbaum & Schweinberger, 2021). Although this hypothesis seems plausible, it does not explain the null results that we found in the longitudinal study. As previously mentioned, other possible explanations may be associated with methodological factors, such as the amount of music training, or innate musicality (Correia et al., 2022; Lima & Castro, 2011; Martins et al., 2021).

### 2.2.3. Prosody recognition and broader aspects of socio-emotional processing

Most studies on music aptitude and vocal emotion recognition skills focus on prosody (Martins et al., 2021). There are many studies reporting that music expertise is associated with enhanced emotion recognition in prosody (e.g., Correia et al., 2022; Lima & Castro, 2011; Toh et al., 2023). On the other hand, there is also null evidence on this matter. For example, musicians and non-musicians were found to be equally adept in recognizing emotions in prosody (Trimmer & Cuddy, 2008). In this vein, we did not find a significant effect of music training on this emotion recognition skill. To our knowledge, only one longitudinal study examined the effects of music training on children's prosody recognition (Thompson et al., 2004). The authors reported that children who received music training showed improved emotional prosody recognition, as compared to a passive control group, but not as compared to a drama group (Thompson et al., 2004). Importantly, children were tested only once on the emotion recognition task, thus the design was not truly longitudinal (Martins et al., 2021; Thompson et al., 2004). Therefore, these findings provide limited evidence of an effect of music training on prosody recognition, and they do not allow to establish causality.

Trimmer & Cuddy (2008) suggested that despite the similar patterns of emotional acoustic cues between music and prosody, it is emotional intelligence that predicts performance on emotion recognition in prosody, rather than music aptitude or music training. While this hypothesis does not intend to dispute evidence showing that there are linguistic benefits associated with music training through auditory pathways (e.g., OPERA hypothesis; Patel, 2012), it points to a different framework in which both music and prosody may have less to do with an overlap of fine-tuned auditory abilities that it does with the operation of a cross-modal emotional processing system. In the present thesis, we did not measure children's emotional intelligence, but we did consider a wide range of socio-emotional categories and inspected possible associations between emotion recognition skills and overall socio-emotional adjustment. Importantly, emotion recognition in prosody was the only skill that was found to be significantly associated with children's socio-emotional adjustment, regardless of cognitive ability, age, sex and parental education. This finding highlights the importance of prosody perception as a critical skill for socio-emotional processing and helps to clarify the mixed results in the literature. That is, while some studies have reported associations between children's emotional prosody recognition abilities and aspects of socio-emotional adjustment, such as social avoidance and distress (McClure & Nowicki, 2001), peer popularity (e.g., Nowicki & Mitchell, 1998), and global social competence (e.g., Leppänen & Hietanen, 2001), other studies on this matter reported null findings (e.g., Chronaki et al., 2015). Interestingly, in an fMRI study, Park et al. (2015) found that musicians show enhanced responses to sad prosody in regions involved in general socio-emotional processing, including the medial prefrontal and anterior cingulate cortices. Thus, one could hypothesize that music training may improve sensibility to emotional cues in speech prosody and that this improvement leads to enhancements to other social-emotional aspects, such as empathy. Nonetheless, this statement remains tentative, as we did not find a significant effect of music training on emotion recognition in prosody.

Since music is fundamentally linked to socio-emotional processing, it is somewhat intriguing that we did not find significant effects of music training on any measure of socio-emotional processing (Savage et al., 2021). Importantly, there are only a few longitudinal studies inspecting music training effects on socio-emotional processing, and while recent reviews highlight the relevancy of inspecting this topic, these also confirm that it remains poorly understood (e.g., Martins et al, 2021; Schellenberg & Lima, 2023). From the few longitudinal studies available, the results found are mixed. For example, a study found positive effects of music training on children's self-report emotional self-regulation, but not considering cognitive and behavioral self-regulation (Williams & Berthelsen, 2019). On the other hand, some studies found null effects on children's prosocial skills, such as sharing and helping (Alemán et al., 2017; Ilari et al., 2021). Our findings help to clarify this topic and shed light on current claims that far transfer effects of music training are unlikely to occur (e.g., Sala & Gobet, 2017; Schellenberg & Lima, 2023). There are more skeptical frameworks claiming that the malleability of musical skills is limited even for music training programs with high overlap (e.g., Kragness et al., 2021; Mosing et al., 2014). In fact, we did not find conclusive evidence for near transfer effects of music training on auditory processing. Thus, our results do not support claims that music can improve socio-emotional skills because of low-level sensory enhancements, namely through the improvement of fine-tune aspects of auditory processing, such as pitch (e.g., Habibi et al., 2016; Moreno et al., 2009; Martins et al., 2021). Nonetheless, as mentioned previously, we cannot exclude the possibility that factors such as the lack of random assignment at the individual level, children and teachers' motivation, or the COVID-19 pandemic might have played a role on the effects of music training. Another relevant consideration are the socio-emotional measures that were included in the longitudinal study. Although we did cover a wide range of socio-emotional skills (e.g., empathy, emotion comprehension, social behavior), other relevant skills were not considered, such as synchronization. Being involved in music activities frequently engages synchronization behaviors, which in turn promotes cooperation and social bonding (Buren et al., 2021; Cirelli, 2018). Moreover, we included measures that rely to a great extent on higher-level cognitive processing, such as the Test of Emotion Comprehension (TEC), and the Index of Empathy (Albanese et al., 2010; Schellenberg & Mankarious, 2012). Accordingly, Schellenberg and Mankarious (2012) found that the association between music training and TEC scores disappeared when IQ was held constant. Nonetheless, while most socio-emotional tasks involve cognition to a significant extent, we included socio-emotional measures that rely less on higher-order cognition, namely emotion recognition skills, and the results were still not significant.

## 3. Current issues in the music training literature

Despite the increasing number of studies examining possible benefits of music training, several inconsistencies and unanswered questions prevail. These have been highlighted throughout the present thesis, and our findings spotlight some important key points on this matter. In this section, we critically examine three major key points and discuss how our findings relate to these.

### 3.1. Nature versus nurture

The extent to which musical abilities are determined by preexisting differences (nature) or by music practice (nurture) is a longstanding issue in the music training literature. At the heart of these debate lies two concepts: predisposition (nature) and plasticity (nurture). Researchers who emphasize plasticity are focused on the degree to which music training can shape brain function and structure, as well as enhance different abilities (e.g., Ericsson, 2014**).** Researchers who emphasize predisposition are focused on the extent to which individuals are born with innate musical abilities, and how genetic and environmental contribute to musicality (e.g., Mosing et al., 2014). This debate is often problematic because it promotes a dichotomic perspective: longitudinal studies frequently assume that the music training effects reflect solely experience-dependent plasticity (e.g., Habibi et al., 2020), while some studies assume opposite positions and argue that music training is not necessary nor sufficient to enhance fine-tune auditory processing (Mankel & Bidelman, 2018). While there are several studies that support both perspectives, this debate tends to oversimplify the complex interplay between genetic and environmental factors in shaping music ability. That is, plasticity and predisposition are not mutually exclusive concepts but rather interact in complex ways (Wang, 2022). While some individuals may inherit abilities that predispose them to have better musical abilities (e.g., Kragness et al., 2021; Swaminathan & Schellenberg, 2017), the extent to which this potential can be realized depends on a variety of environmental factors, such as the engagement in music training, personality, and socio-economic background (Correia et al., 2022; Schellenberg & Lima, 2023; Ullén et al., 2016). For example, twin studies show that genetic factors account for many aspects of musical behavior and achievement, including propensity for music practice (e.g., Ullén et al., 2016), and pre-existing personality and socioeconomic factors might determine who takes music lessons (e.g., Schellenberg, 2020).

In the meta-analysis, we have found that the larger the differences between groups prior to training, the smaller the benefits of music training in auditory and linguistic processing. One possibility could be that individuals with lower abilities before training could have more room for improvement (Román-Caballero et al., 2022). Accordingly, in the longitudinal study we found that children who had worse auditory and motor skills prior to training improved more than those who had better skills at pre-test (regardless of the group they belonged to). Similar results have been found for general cognitive training (e.g., Jaeggi et al., 2011). Therefore, the potential role of pre-existing factors, namely the role of individual predisposition in the magnitude of the effects of music training is an interesting and relevant avenue to follow.

## 3.2. Study design

Cross-sectional and longitudinal designs are the most frequently employed methods to study music training effects (Olszewska et al., 2021). One first important aspect is that inferences of causal effects from correlational studies of music training are frequent and violate the rules of science, creating misinterpretations in the literature (Schellenberg, 2020; Swaminathan & Schellenberg, 2021). In theory, longitudinal designs allow to disentangle nature and nurture effects, as these longitudinal studies are expected to have well-powered and well-designed designs that consider key aspects to establish causality, such as individual random assignment, the inclusion of an active control group, and the assessment of confounding variables (Ilari, 2020; Schellenberg, 2020). The systematic review and meta-analysis allowed us to confirm and thoroughly inspect these issues: we have found that almost two-thirds of the longitudinal studies inspecting music training effects on auditory and linguistic processing had a risk of bias. This risk was primarily because of the lack of randomization of participants. Indeed, if there is no random assignment of participants, one does not preclude that factors such as predisposition, self-selection, and motivation could have played a role in the effects found (Swaminathan & Schellenberg, 2021). Another important issue to be considered is the reporting of the training programs. Overall, longitudinal studies do not provide clear information on the training programs being implemented, namely in terms of total duration, frequency, and type of training. This is of utter importance: first, the length and consistency of music training have been associated with the level of proficiency achieved (e.g., Wilson et al., 2011); second, there are multiple forms of music training, ranging from individual to group lessons, or instrumental versus non-instrumental. Naturally, this variability emphasizes different domains being trained. For example, playing in group requires visual, rhythmic, and synchronization skills, as well as the discipline to sit in silence and wait for your turn (Fasano et al., 2019). On the other hand, the Suzuki method focuses on individual training, emphasizing aural learning oversight reading (Kraus & Chandrasekaran, 2010).

We conducted a longitudinal study to inspect music training effects and aimed at being as experimentally rigorous as possible. For example, the assignment considered the allocation of entire classes and ensured that there were no pre-test differences, and a passive and active control group were included. Moreover, we carefully detailed both training programs. However, we are aware that it is challenging to implement longitudinal studies, namely within educational and community settings, as these require a significant number of resources (e.g., funding, control groups) and constraints (e.g., participant retention) over a relatively long period of time (Habibi et al., 2022; Ilari, 2020; VanderWeele et al., 2020). Our study is no exception, and these difficulties lead to some methodological flaws (e.g., randomization at the class level), which will be discussed in subsection 4.

## 3.3. Transfer of learning

The ongoing debate on whether music training produces transfer effects frequently assumes a dichotomic perspective on transfer of learning. That is, music training effects are typically addressed by tasks referred to either one of two categories: near or far transfer (Noack et al., 2014). This distinction can be useful to formulate research hypotheses and to categorize the measures included in a given study, but this distinction can raise critical issues in the interpretation of the results.

First, near and far transfer represent a continuum in the transfer of learning, rather than strictly separate concepts (Willis & Schaie, 2009). By assuming near and far transfer as mutually exclusive categories, scholars are at risk of oversimplifying the complex nature of learning and overlooking that there may be an overlap between near and far transfer (Perkins & Solomon, 1992). For example, a dictation task requires several skills that are typically recognized as near and far transfer domains of music training: fine-motor skills, (near transfer) for successful handwriting, and vocabulary understanding (far transfer), for accurately reproduce the dictated material. Therefore, even if the researcher considers the dictation test as a linguistic task that falls into the far transfer domain of music training, to accurately achieve this task one needs to recruit fine-motor skills (e.g., Khoury-Metanis & Khateb, 2022).

Second, this categorization has proven to be equivocal because the positioning of the near-far transfer frequently appears to be arbitrary (Bigand & Tillmann, 2022). This unclear boundary between near and far transfer is intimately related to the training programs being implemented (discussed in the previous subsection). For example, linguistic processing is considered to be a far transfer domain of music training (e.g., Besson et al., 2011; Degé, 2021; Patel, 2012). But while a music training program focused on instrumental orchestra playing may be aligned with this idea that enhancing phonological awareness (i.e., linguistic skills) would be a far transfer, a music training program focused on choir lessons could consider a potential benefit on phonological awareness as a near transfer effect (Patscheke et al., 2016). Moreover, when active control groups are included, the equidistance of transfer in relation to the music training group is usually not considered (Bigand & Tillmann, 2022). For example, in the longitudinal study, we included a measure of gross-motor skills, which can be considered a near transfer domain of both music and sports (Bolduc et al., 2021; Burns et al., 2017). Children participating in music and basketball training improved gross-motor skills, but there was a significant advantage of music as compared to the basketball group. This result highlights that music training can be a useful tool to improve gross-motor skills. Ultimately, the distinction between near and far transfer may be less relevant than recognizing that transfer of learning occurs along a continuum (Willis & Schaie, 2009) and that there may be overlap between different types of transfer and training programs (Bigand & Tillmann, 2022; Noack et al., 2014).

## 4. Contributions and limitations

In this section, we discuss the novelty and contributions of the work outlined in the present thesis, as well as several limitations that should be acknowledged.

Given the ongoing controversies surrounding the longitudinal effects of music training, systematic reviews and meta-analyses are important, as these allow a thorough review of the literature, and enable to draw stronger conclusions (Román-Caballero et al., 2022). By showing a small positive effect of music training on both near and far transfer domains (i.e., auditory and linguistic processing), we offer additional evidence to the current debate on the extent of the effects of music training. Importantly, we shed light on the possible presence of publication bias and the high levels of heterogeneity found. We hope that highlighting these issues encourages researchers to share their data, and to report null results, considering them when discussion significant ones, for instance.

The cross-sectional study was important to shed light on a poorly explored topic, that is, how different socio-emotional processes in children relate to each other. To the best of our knowledge, this was the first study to inspect associations between emotion recognition in non-verbal vocalizations and children's socio-emotional adjustment. Combining different emotion recognition domains allowed us to determine whether associations with socio-emotional adjustment are specific to the auditory domain (prosody and non-verbal vocalizations) or an effect that extends to the visual domain (facial expressions). Moreover, combining multiple assessments can provide a more complete picture of the child's social functioning (Erdley & Jankowski, 2020). Importantly, emotion recognition in prosody was the only skill that was found to be significantly associated with children's socio-emotional adjustment, regardless of cognitive ability, age, sex and parental education. This finding highlights the importance of prosody perception as a critical skill for socio-emotional processing and helps to clarify the mixed results in the literature. An obvious limitation of this study is the correlational approach (i.e., we cannot infer causality). Nonetheless, understanding how emotion recognition associates with socio-emotional adjustment set the stage for another poorly explored topic: the effects of music training on children´s socio-emotional processing.

The longitudinal study was also important to inform the aim of this thesis, as we explore the possible benefits of music training to socio-emotional processing, a non-musical domain that is largely unexplored in the literature and has been highlighted as a strong candidate for transfer through music training (Schellenberg & Lima, 2023). Combining different socio-emotional measures allowed us to better understand possible mechanisms underlying music training benefits on children's socio-emotional processing. Some methodological limitations should be noted on this matter. First, while we ensured that there were no pre-existing differences between the groups, the design was not truly experimental (Swaminathan & Schellenberg, 2021). In other words, we conducted randomization at a class level to either the music, sports, or no training (rather than at the individual level), thus, it is possible that within the same class children interacted and influenced each other throughout the training programs, masking the true effects of the training programs. Second, the training programs had interruptions due to the COVID-19 pandemic. We tried to minimize the consequences of the school closure by measuring the impact of the lockdown through a teacher report questionnaire, but one cannot preclude that these interruptions may have played a significant role in the findings. Last but not least, it would have been ideal to collect neuroimaging data in both pre and post-test phases, in order to combine both behavioral and brain measures to inform possible effects of music training and plasticity. Unfortunately, this was not possible due to the COVID-19 pandemic, which caused time constraints and the impossibility to collect neuroimaging post-test data.

## 5. Practical implications

Although the findings of the present thesis revealed that the extent of the effects of music training are limited, several aspects that emerged are suggestive that music training could be a useful and effective tool in clinical and educational settings.

The results suggest that music training causes benefits on children's motor skills, as compared to both a sports group and a passive control group. Motor skills are fundamental for children's development (Martins et al., 2018). For instance, fine-motor skills play a pivotal role in learning how to write, and motor writing ability was found to be a strong predictor of children´s mathematics and reading achievement (e.g., Dinehart & Manfra, 2013). Therefore, music training programs could be an ideal framework to rehabilitate and improve these skills. For example, Schneider et al. (2010) found that music training was more effective than a functional motor program for the recovery of motor impairments in stroke patients.

Considering that we found suggestive evidence of a small positive effect of music training on linguistic processing, and that previous evidence shows benefits from music-based and auditory-based interventions on language impairments (Cancer & Antonietti, 2022), it would also be important to further inspect how practitioners might develop music interventions targeting linguistic abilities in normative populations. Furthermore, as the present results did not allow to reach decisive conclusions about the effects of music training on auditory processing, it could be relevant to better understand possible benefits of music interventions in non-clinical paediatric populations, as research on this topic is mainly focused on hearing rehabilitation for cochlear implant users (e.g., Cheng et al., 2018). Children’s auditory skills are linked to many crucial aspects of their development and well-being, such as oral language, writing, and reading skills (e.g., Yalçınkaya et al., 2009). Moreover, auditory skills are important for everyday communication and social interactions (e.g., Parbery-Clark et al., 2011). Therefore, establishing if music training has the potential to improve children’s auditory skills is a relevant research topic. Nonetheless, the benefits of training in auditory and linguistic processing were small, which raises questions regarding the actual practical significance.

The fact that prosody recognition was the only emotion recognition skill associated with better children’s socio-emotional adjustment has relevant implications for clinical and educational practices. Potential interventions focused on prosody perception could be delineated with the aim of improving children’s socio-emotional functioning, such as self-regulation and prosociality behaviors. On the other hand, it is also possible that promoting more and better social interactions (i.e., socio-emotional functioning), could provide opportunities for children to hone their emotion recognition skills in prosody. Even though the benefits of music training on prosody recognition were not significant, this finding of a positive association between emotion recognition in prosody and socio-emotional adjustment opens an interesting avenue for thoroughly inspecting how music training and prosody perception might be linked. For example, Jiam and Limb (2020) conducted a review focusing on cochlear-implant users and the findings are suggestive that music training improves emotion recognition in prosody, particularly for children.

Importantly, music can be a very joyful activity and is inherently linked with positive emotions and mood regulation, and these are arguably the primary motives for the ubiquity of musical behaviors (e.g., Koelsch, 2014). Indeed, we step outside the bounds of a traditional lab-based study protocol and implemented a longitudinal study with children in a community setting, which brought many practical advantages that cannot be quantified. Thus, altogether the findings from this thesis are not in agreement with the claims that policymakers should “seriously consider stop spending resources for this type of research” (Sala & Gobet, 2017). On the contrary, adding to the inherent pleasure of engaging in music activities, scholars should continue to pursue research with the aim of a better understanding of the conditions in which music training could benefit clinical and non-clinical populations.

## 6. Future directions

The music training field has undergone significant advances in the last two decades (Swaminathan & Schellenberg, 2021). While conducting this set of studies allowed us to inform ongoing debates on this matter, there are still many exciting research directions to explore. Therefore, based on the findings of the present thesis, we tackle some considerations for future research.

Future studies should focus more on transfer effects of music training to domains closely related to the training program being implemented (near transfer). Importantly, the training programs and the respective covered skills by these should be better detailed, as well as their relationship with the measures included in the study. Adopting these strategies will allow to consider the continuum of near and far transfer, and to build more consistent hypotheses on the extent of transferability, avoiding inconsistent definitions of near and far transfer (Noack, 2014). Furthermore, a higher concern with unbiased reporting of findings will be crucial to reach firmer conclusions regarding the transferability of music training. This concern could be addressed by adopting strategies like data sharing and preregistration of studies. Although we are aware of the many difficulties in conducting a longitudinal study, it is of utter important to improve the design quality of the studies, namely, to randomize participants, include active control groups, and increase the sample size. Following this should help to clarify the extent of the benefits of music training, and the mechanisms underlying plasticity and transfer effects.

Future longitudinal training studies should thoroughly examine cognitive and environmental factors that influence transfer effects, and investigate how these factors could be manipulated to promote the effectiveness of the training programs (Jaeggi et al., 2011). Specifically, the socio-economic status and parental education should be more frequently considered, as an increasing number of studies have been showing the influence of these factors on music aptitude and the likelihood of engaging in music activities, for instance (Corrigal & Schellenberg, 2015). Moreover, research on the role of genetics and predisposition in musicality is in its infancy but has already proved to be a relevant and exciting research avenue (e.g., Correia et al., 2022; Mankel & Bidelman, 2018). As musicality emerges from a combination of genetic and environmental factors (e.g., Schellenberg, 2015), and there is recent evidence suggesting that music training does not predict music abilities after accounting for prior abilities (Kragness et al., 2021), future studies should adopt more nuanced approaches that consider the multifactorial nature of musical abilities. Specifically, to consider the role of both individual predisposition and training effects. For example, by conducting a longitudinal study in which the experimental and control groups would unfold in two: one with initial “low music abilities”, and the other with “high music abilities”. Comparing within and between group differences pre and post-test would be useful to better understand how predisposition interacts with music training effects.

Even though we did not find a significant effect of music training on any measure of socio-emotional processing, future studies should still focus on this research field. Recent reviews highlight the relevancy of investigating this topic (Martins et al, 2021; Schellenberg & Lima, 2023), but longitudinal studies on this matter are scarce and the findings are mixed. Therefore, there is still much to be understood about the role of music on socio-emotional functioning. One interesting topic for future work is whether and how music training benefits synchronization behavior (e.g., Rabinowitch, 2020). Several research has identified interpersonal synchrony as a key contributor to social bonding during joint music engagement (e.g., Rabinowitch, 2022; Tarr et al., 2014). Therefore, examining if music training improves interpersonal synchrony and consequently promotes social bonding behaviors would be relevant. Considering that during social interactions we receive emotional information from multiple channels simultaneously (e.g., voices and facial expressions), it would be interesting to examine if music training benefits emotion recognition using dynamic auditory-visual stimuli. Emotion recognition was found to be more accurate for multi-modal stimuli (e.g., different combinations of facial and prosodic cues), as compared to uni-modal emotion recognition, such as static facial expressions (Paulmann & Pell, 2011). However, as far as we are concerned, there are no longitudinal studies examining effects of music training on the recognition of dynamic emotional expressions. Furthermore, if the effects of music training only reach domains closely related to the trained skills (Perkins & Salomon, 1992; Thorndike & Woodworth, 1901), then it would be relevant to inspect how music training programs that emphasize group interactions would benefit social behavior (e.g., Rabinowitch et al., 2013). Moreover, given that emotion recognition in prosody was the only emotion recognition skill that was associated with children's socio-emotional adjustment, future longitudinal research should examine the causal role of this association, and how music could play a role. That is, if emotion recognition in prosody is the cause or the result of better socio-emotional adjustment. For instance, by testing whether an emotion recognition training program leads to improved social interactions, and whether music abilities might moderate this effect.

## 7. Concluding

To conclude, the aim of this thesis was to examine whether music training provides non-musical benefits. In a series of three studies, we found (1) a small neurobehavioral effect of music training on auditory and linguistic processing, as well as high levels of heterogeneity and suggestive evidence of publication bias; (2) a positive association between emotion recognition in prosody and children's socio-emotional adjustment, but no significant associations considering emotion recognition in non-verbal vocalizations and facial expressions; and (3) a positive effect of music training on children's near transfer measures (auditory and motor skills). However, the advantage of music training on auditory skills was not significant in comparison with the passive control group. We did not find far transfer effects of music training, namely considering socio-emotional processing.

Based on these findings, we conclude that music training effects may transfer to domains closely related to the trained skills, namely motor processing, but the evidence for effects of music training on auditory skills is not conclusive. As the domains get more distant from the trained skills, the evidence for significant effects of music training weakens. That is, we found a small positive neurobehavioral effect on linguistic processing, but there were no significant far transfer effects of music training on children's socio-emotional processing.

We discussed these findings thoroughly and outlined current issues in the music training literature, giving particular emphasis to current concerns related to the nature versus nurture debate, longitudinal studies design, and definitions of transfer of learning. Furthermore, we discussed the original insights offered into the music training literature, as well as the main limitations of our work. Finally, we discussed the practical implications of this research and provided insights into future research in this field.

We hope that this thesis contribution paves the way for further basic and applied research on the extent to which music training can provide benefits for all, ranging from clinical, to community and educational contexts. Reaching the end of this thesis, this sentence written by the children that participated in the longitudinal study serves as a motto of the developed work over the last years:

> *This project was challenging, it pushed us a lot, and made us better and more capable of overcoming obstacles!*

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# APPENDICES

# APPENDIX A | CHAPTER II

| Section/topic | # | Checklist item | Reported on page # |
|---|---|---|---|
| **TITLE** | | | |
| Title | 1 | Identify the report as a systematic review, meta-analysis, or both. | 1 |
| **ABSTRACT** | | | |
| Structured summary | 2 | Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number. | 3 |
| **INTRODUCTION** | | | |
| Rationale | 3 | Describe the rationale for the review in the context of what is already known. | 4 - 8 |
| Objectives | 4 | Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS). | 8-9 |
| **METHODS** | | | |
| Protocol and registration | 5 | Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number. | 9 |
| Eligibility criteria | 6 | Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale. | 10-11 |
| Information sources | 7 | Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched. | 9-11 |
| Search | 8 | Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated | SI 4 |
| Study selection | 9 | State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis). | 10-11 |
| Data collection process | 10 | Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators. | 9-11 |
| Data items | 11 | List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made. | 9-11 |
| Risk of bias in individual studies | 12 | Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis. | 11 |
| Summary measures | 13 | State the principal summary measures (e.g., risk ratio, difference in means). | 12-13 |
| Synthesis of results | 14 | Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., $I^2$) for each meta-analysis. | 12-13 |
| Risk of bias across studies | 15 | Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies). | 15-16 |
| Additional analyses | 16 | Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified. | 13-17 |

| | | | |
|---|---|---|---|
| **RESULTS** | | | |
| Study selection | 17 | Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram. | 17-18 |
| Study characteristics | 18 | For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations. | 17-18 |
| Risk of bias within studies | 19 | Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12). | ST22-24 |
| Results of individual studies | 20 | For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot. | ST25-30 |
| Synthesis of results | 21 | Present results of each meta-analysis done, including confidence intervals and measures of consistency. | 18-20 |
| Risk of bias across studies | 22 | Present results of any assessment of risk of bias across studies (see Item 15). | ST22-24 |
| Additional analysis | 23 | Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]). | 20-21 |
| **DISCUSSION** | | | |
| Summary of evidence | 24 | Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers). | 25 & 31 |
| Limitations | 25 | Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias). | 32 |
| Conclusions | 26 | Provide a general interpretation of the results in the context of other evidence, and implications for future research. | 26-33 |
| **FUNDING** | | | |
| Funding | 27 | Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review. | 34 |

***Table S1.*** PRISMA checklist.

| Database | Query |
|---|---|
| **Web of Science Core Collection (WoS)** | TS=("music* training" OR "music* practice" OR "music* intervention" OR "music* lesson*" OR "music* classes" or "music* instruction" OR "music* program" OR “music* group”) |
| **EBSCOhost**<br>Academic Search Complete<br>Psychology and Behavioral Sciences Collection<br>PsycINFO<br>Medline | AB ("music* training" OR "music* practice" OR "music* intervention" OR "music* lesson*" OR "music* classes" or "music* instruction" OR "music* program" OR “music* group”) |
| **Scopus** | TITLE-ABS-KEY ("music* training" OR "music* practice" OR "music* intervention" OR "music* lesson*" OR "music* classes" or "music* instruction" OR "music* program" OR “music* group”) |
| **PubMed** | ("music training"[Title/Abstract] OR "music practice"[Title/Abstract] OR "music intervention"[Title/Abstract]) OR “music lesson” [Title/Abstract] OR “music instruction” [Title/Abstract] OR “music program” [Title/Abstract] OR “music group” [Title/Abstract]) |

Abbreviations: TS - topic; AB/ABS – abstract; KEY – keywords. * - Truncation command.

***Table S2***. Search queries used for each database.

| **Database** | **Hits** | | |
|---|---|---|---|
| | Initial search (up to 02.07.2019) | Search update (from 02.07.2019 to 12.06.2020) | Search update (from 12.06.2020 to 01.06.2021) |
| Web of Science (WoS) | 2380 | 382 | 428 |
| EBSCOhost | 3343 | 281 | 229 |
| Scopus | 3349 | 582 | 603 |
| PubMed | 818 | 174 | 198 |
| | | | |
| Duplicates removed | 4892 | 658 | 750 |
| **Number after duplicate removal** | **4998** | **761** | **708** |

***Table S3**.* Number of studies identified in each database for each searching period. We also present the number of duplicates removed from the total number of hits.

| | 1st Full-text Screening | | |
|---|---|---|---|
| | **Article** | **Decision** | **Reason** |
| 1 | Abril (2006) | Exclude | No baseline/post-test data |
| 2 | Addison and Moseley (1984) | Exclude | Access issues/lack of information |
| 3 | Alain et al. (2019) | **Include** | |
| 4 | Alemán et al. (2017) | Exclude | No auditory/linguistic processing outcomes |
| 5 | Allen (1967) | Exclude | Design not longitudinal |
| 6 | Anshel and Kipper (1988) | Exclude | No baseline/post-test data |
| 7 | Anastasiow and Shambaugh (1965) | Exclude | No baseline/post-test data |
| 8 | Anand et al. (2017) | Exclude | Design not longitudinal |
| 9 | Atterbury and Silcox (1993) | Exclude | No targeted music training intervention |
| 10 | Azaryahu et al. (2019) | Exclude | No targeted music training intervention |
| 11 | Bailey and Davidson (2005) | Exclude | Clinical population/condition that could impact on the outcomes |
| 12 | Bain (1978) | Exclude | Design not longitudinal |
| 13 | Balodis (2006) | Exclude | Access issues/lack of information |
| 14 | Bangert and Altenmüller (2003) | Exclude | No control group |
| 15 | Barbaroux et al. (2019) | Exclude | No control group |
| 16 | Barrett and Bond (2015) | Exclude | Design not experimental/quasi-experimental |
| 17 | Bartolomei et al. (2015) | Exclude | No targeted music training intervention |
| 18 | Besson et al. (2011) | Exclude | Review article |

| | | | |
|---|---|---|---|
| 19 | Besson et al. (2007) | Exclude | Review article |
| 20 | Belgrave (2011) | Exclude | No targeted music training intervention |
| 21 | Bergman Nutley et al. (2014) | Exclude | Access issues/lack of information |
| 22 | Bhide et al. (2013) | Exclude | Clinical population/condition that could impact on the outcomes |
| 23 | Biasutti and Mangiacotti (2018) | Exclude | Clinical population/condition that could impact on the outcomes |
| 24 | Bilhartz et al. (1999) | Exclude | Access issues/lack of information |
| 25 | Black (2005) | Exclude | Design not experimental/quasi-experimental |
| 26 | Blumenstein et al. (1995) | Exclude | No targeted music training intervention |
| 27 | Bolduc (2009) | Exclude | No control group |
| 28 | Bowers (1997) | Exclude | No targeted music training intervention |
| 29 | Bowers (1998) | Exclude | No targeted music training intervention |
| 30 | Bowmer et al. (2018) | Exclude | No auditory/linguistic processing outcomes |
| 31 | Brennan and Stevens (2002) | Exclude | Design not longitudinal |
| 32 | Brown et al. (1981) | Exclude | No targeted music training intervention |
| 33 | Buckton (1977) | Exclude | Clinical population/condition that could impact on the outcomes |
| 34 | Bugos (2018) | Exclude | Design not experimental/quasi-experimental |
| 35 | Bugos and DeMarie (2017) | Exclude | No auditory/linguistic processing outcomes |
| 36 | Bugos et al. (2016) | Exclude | No control group |
| 37 | Bugos and Kochar (2017) | Exclude | No control group |
| 38 | Bugos and Mostafa (2011) | Exclude | Design not longitudinal |

|  |  |  |  |
|---|---|---|---|
| 39 | Butler and Trainor (2015) | Exclude | No targeted music training intervention |
| 40 | Bygrave (1994) | Exclude | Clinical population/condition that could impact on the outcomes |
| 41 | Caramiaux et al (2018) | Exclude | No control group |
| 42 | Carmon et al. (2008) | Exclude | No targeted music training intervention |
| 43 | Carpentier et al. (2016) | **Include** |  |
| 44 | Chansirinukor and Khemthong (2014) | Exclude | No control group |
| 45 | Chan et al. (2009) | Exclude | No targeted music training intervention |
| 46 | Cheek and Smith (1999) | Exclude | Design not longitudinal |
| 47 | Chobert et al. (2014) | **Include** |  |
| 48 | Choi et al. (2010) | Exclude | Clinical population/condition that could impact on the outcomes |
| 49 | Cirelli et al. (2014) | Exclude | No targeted music training intervention |
| 50 | Costa-Giomi (2004) | Exclude | No auditory/linguistic processing outcomes |
| 51 | Costa-Giomi (2005) | Exclude | No auditory/linguistic processing outcomes |
| 52 | Cogo-Moreira et al. (2013) | Exclude | Clinical population/condition that could impact on the outcomes |
| 53 | Cohrdes et al. (2019) | **Include** |  |
| 54 | Corrigall and Trainor (2009) | Exclude | No targeted music training intervention |
| 55 | Corrigall and Trainor (2011) | Exclude | Design not longitudinal |
| 56 | Courey et al. (2012) | Exclude | No targeted music training intervention |
| 57 | Cuadrado (2019) | Exclude | Access issues/lack of information |
| 58 | Cuddy (1968) | Exclude | No control group |

|  |  |  |  |
|---|---|---|---|
| 59 | Cuervo (2018) | Exclude | No control group |
| 60 | Cumberledge (2016) | Exclude | Access issues/lack of information |
| 61 | Da Silva et al. (2017) | Exclude | No targeted music training intervention |
| 62 | Davidson and Lupton (2016) | Exclude | Design not experimental/quasi-experimental |
| 63 | Degé and Schwarzer (2011) | Exclude | Access issues/lack of information |
| 64 | Degé et al. (2011a) | Exclude | Access issues/lack of information |
| 65 | Degé et al. (2011b) | Exclude | Design not longitudinal |
| 66 | Degé and Kerkovius (2018) | Exclude | No auditory/linguistic processing outcomes |
| 67 | Degé and Schwarzer (2018) | **Include** |  |
| 68 | Delzell (1989) | Exclude | No control group |
| 69 | Demorest et al. (2018) | Exclude | No auditory/linguistic processing outcomes |
| 70 | Devroop (2012) | Exclude | No baseline/post-test data |
| 71 | Dittinger et al. (2016) | Exclude | No targeted music training intervention |
| 72 | Dos Santos-Luiz et al. (2016) | Exclude | No auditory/linguistic processing outcomes |
| 73 | Douglas and Willatts (1994) | Exclude | Clinical population/condition that could impact on the outcomes |
| 74 | Doxey and Wright (1990) | Exclude | Design not longitudinal |
| 75 | D'Souza and Wiseheart (2018) | **Include** |  |
| 76 | Edmonston (1969) | Exclude | No targeted music training intervention |
| 77 | Edward et al. (2018) | Exclude | Design not longitudinal |
| 78 | Ellis et al. (2013) | Exclude | No control group |

| | | | |
|---|---|---|---|
| 79 | Fasano et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 80 | Fehr (2008) | Exclude | Design not experimental/quasi-experimental |
| 81 | Feierabend et al. (2002) | Exclude | No targeted music training intervention |
| 82 | Fitzpatrick (2006) | Exclude | Design not longitudinal |
| 83 | Flohr (1981) | **Include** | |
| 84 | Flohr et al. (2000) | Exclude | Review article |
| 85 | Foley (1975) | Exclude | No control group |
| 86 | Fonseca-Mora et al. (2015) | Exclude | No targeted music training intervention |
| 87 | Forgeard et al. (2018) | Exclude | No control group |
| 88 | Frankenberg et al. (2016) | Exclude | No auditory/linguistic processing outcomes |
| 89 | Franklin et al. (2008) | Exclude | Design not longitudinal |
| 90 | François et al. (2013) | **Include** | |
| 91 | Frey et al. (2019) | Exclude | Clinical population/condition that could impact on the outcomes |
| 92 | Friendly et al. (2013) | Exclude | No targeted music training intervention |
| 93 | Froseth (1971) | Exclude | Design not longitudinal |
| 94 | Fujioka et al. (2006) | **Include** | |
| 95 | Fujioka and Ross (2017) | **Include** | |
| 96 | Fujioka et al. (2004) | Exclude | Design not longitudinal |
| 97 | Gan and Chong (1998) | Exclude | Design not experimental/quasi-experimental |
| 98 | Gérard and Auxiette (1992) | Exclude | Design not longitudinal |

|  |  |  |  |
|---|---|---|---|
| 99 | Gerry et al. (2012) | Exclude | No auditory/linguistic processing outcomes |
| 100 | Gerry et al. (2010) | Exclude | Design not longitudinal |
| 101 | Ghasemtabar et al. (2001) | Exclude | Access issues/lack of information |
| 102 | Gómez-Gama et al. (2004) | Exclude | Design not longitudinal |
| 103 | Gooding et al. (2014) | Exclude | Design not longitudinal |
| 104 | Gordon (1979) | Exclude | Clinical population/condition that could impact on the outcomes |
| 105 | Gordon et al. (2015) | Exclude | Design not experimental/quasi-experimental |
| 106 | Gouzouasis et al. (2007) | Exclude | No control group |
| 107 | Grandin et al. (1998) | Exclude | Design not experimental/quasi-experimental |
| 108 | Graziano et al. (1999) | Exclude | No targeted music training intervention |
| 109 | Grégoire et al. (2015) | Exclude | Design not longitudinal |
| 110 | Gromko (2005) | **Include** |  |
| 111 | Gromko and Poorman (1998) | Exclude | No auditory/linguistic processing outcomes |
| 112 | Gruhn et al. (2003) | Exclude | Design not longitudinal |
| 113 | Gujing et al. (2019) | Exclude | Design not longitudinal |
| 114 | Guo and Koelsch (2015) | Exclude | Design not longitudinal |
| 115 | Guo et al. (2018) | **Include** |  |
| 116 | Hassler (1992) | Exclude | No targeted music training intervention |
| 117 | Habibi et al. (2016) | **Include** |  |
| 118 | Habibi et al. (2018a) | Exclude | Not published in peer-reviewed journal |

| | | | |
|---|---|---|---|
| 119 | Habibi et al. (2018b) | **Include** | |
| 120 | Habibi et al. (2014) | Exclude | Design not longitudinal |
| 121 | Habib et al. (2016) | Exclude | Clinical population/condition that could impact on the outcomes |
| 122 | Hallberg et al. (2017) | Exclude | No auditory/linguistic processing outcomes |
| 123 | Hallett and Lamont (2019) | Exclude | No targeted music training intervention |
| 124 | Hamburg and Clair (2003) | Exclude | Design not experimental/quasi-experimental |
| 125 | Hantz et al. (1992) | Exclude | Design not longitudinal |
| 126 | Hart (2016) | Exclude | Access issues/lack of information |
| 127 | Hedayati et al. (2016) | Exclude | Design not longitudinal |
| 128 | Herdener et al. (2010) | **Include** | |
| 129 | Herholz et al. (2011) | Exclude | Design not longitudinal |
| 130 | Herlekar and Siddangoudra (2019) | Exclude | No targeted music training intervention |
| 131 | Hernández-Bravo et al. (2016) | Exclude | No control group |
| 132 | Herrera et al. (2011) | Exclude | No targeted music training intervention |
| 133 | Herrera et al. (2014) | Exclude | No auditory/linguistic processing outcomes |
| 134 | Heyworth (2013) | Exclude | Design not experimental/quasi-experimental |
| 135 | Hietolahti and Kalliopuska (1990) | Exclude | Design not longitudinal |
| 136 | Hogan et al. (2018) | Exclude | No baseline/post-test data |
| 137 | Holmes and Hallam (2017) | **Include** | |
| 138 | Holochwost et al. (2017) | Exclude | No baseline/post-test data |

|  |  |  |  |
|---|---|---|---|
| 139 | Ho et al. (2003) | Exclude | No auditory/linguistic processing outcomes |
| 140 | Hudak et al. (2019) | Exclude | Design not longitudinal |
| 141 | Hudziak et al. (2014) | Exclude | No targeted music training intervention |
| 142 | Humpal (1991) | Exclude | Clinical population/condition that could impact on the outcomes |
| 143 | Hurwitz et al. (1975) | Exclude | No baseline/post-test data |
| 144 | Hutchins (2018) | Exclude | No control group |
| 145 | Hyde et al. (2009a) | **Include** |  |
| 146 | Hyde et al. (2009b) | Exclude | Not published in peer-reviewed journal |
| 147 | Ihrke (1971) | Exclude | No baseline/post-test data |
| 148 | Ilari et al. (2016) | **Include** |  |
| 149 | Ilari et al. (2018) | Exclude | No auditory/linguistic processing outcomes |
| 150 | Jaschke et al. (2018) | **Include** |  |
| 151 | Jacobi (2019) | Exclude | Design not experimental/quasi-experimental |
| 152 | Jain et al. (2015) | Exclude | No targeted music training intervention |
| 153 | Jain (2017) | Exclude | Design not longitudinal |
| 154 | Jamshidzad et al. (2020) | Exclude | No targeted music training intervention |
| 155 | Jamali et al. (2014) | Exclude | No targeted music training intervention |
| 156 | Janus et al. (2016) | **Include** |  |
| 157 | Jentschke and Koelsch (2009) | Exclude | Design not longitudinal |
| 158 | Jeremić et al. (2015) | Exclude | No control group |

| | | | |
|---|---|---|---|
| 159 | Johnson and Memmott (2006) | Exclude | Design not longitudinal |
| 160 | Johnson (2010) | Exclude | Review article |
| 161 | Joret et al. (2017) | Exclude | Design not longitudinal |
| 162 | Kanable (1969) | Exclude | No control group |
| 163 | Kaplan (1955) | Exclude | Clinical population/condition that could impact on the outcomes |
| 164 | Kaviani et al. (2014) | **Include** | |
| 165 | Kawase et al. (2018) | Exclude | Design not longitudinal |
| 166 | Kazkayasi et al. (2006) | Exclude | Design not longitudinal |
| 167 | Keebler et al. (2014) | Exclude | No control group |
| 168 | Kempert et al. (2016) | Exclude | Clinical population/condition that could impact on the outcomes |
| 169 | Khemthong et al. (2012) | Exclude | Clinical population/condition that could impact on the outcomes |
| 170 | Kim et al. (2004) | Exclude | No control group |
| 171 | Kim and Kim (2018) | Exclude | No auditory/linguistic processing outcomes |
| 172 | Kim et al. (2006) | Exclude | Clinical population/condition that could impact on the outcomes |
| 173 | Konieczna-Nowak (2015) | Exclude | Design not longitudinal |
| 174 | Koutsoupidou and Hargreaves (2009) | Exclude | No control group |
| 175 | Kraus et al. (2014a) | Exclude | No control group |
| 176 | Kraus and Strait (2015) | Exclude | Review article |
| 177 | Kraus et al. (2014b) | Exclude | No control group |
| 178 | Kraus et al. (2014c) | **Include** | |

|  |  |  |  |
|---|---|---|---|
| 179 | Kraus et al. (2012) | Exclude | Review article |
| 180 | Kristo and Margus (2015) | Exclude | No control group |
| 181 | Kuehne et al.  (2013) | Exclude | No control group |
| 182 | Kuo et al. (2014) | Exclude | No targeted music training intervention |
| 183 | Kyme (1971) | Exclude | No targeted music training intervention |
| 184 | Lane et al. (2011) | Exclude | No control group |
| 185 | Laohawattanakun et al. (2011) | Exclude | Design not longitudinal |
| 186 | Lappe et al. (2008) | Exclude | No control group |
| 187 | Lappe et al. (2011) | Exclude | No control group |
| 188 | Largo-Wight et al. (2016) | Exclude | No targeted music training intervention |
| 189 | Lau et al. (2017) | Exclude | No targeted music training intervention |
| 190 | Lawrence et al. (1967) | Exclude | Design not longitudinal |
| 191 | Lee et al. (2007) | Exclude | Design not longitudinal |
| 192 | Lee et al. (2010) | Exclude | No targeted music training intervention |
| 193 | Leithwood and Fowler (1971) | Exclude | Access issues/lack of information |
| 194 | Lejeune et al. (2019) | Exclude | Clinical population/condition that could impact on the outcomes |
| 195 | Lindblad et al. (2007) | Exclude | No auditory/linguistic processing outcomes |
| 196 | Linnavalli et al. (2018) | Exclude | No baseline/post-test data |
| 197 | Li et al. (2019) | **Include** |  |
| 198 | Li et al. (2018) | **Include** |  |

|  |  |  |  |
|---|---|---|---|
| 199 | Loewy et al. (2013) | Exclude | Clinical population/condition that could impact on the outcomes |
| 200 | Long (2014) | Exclude | No control group |
| 201 | Lordier et al. (2019) | Exclude | Clinical population/condition that could impact on the outcomes |
| 202 | Lou et al. (2011) | Exclude | No control group |
| 203 | MacAulay et al. (2019) | Exclude | No control group |
| 204 | MacDonald et al. (1999) | Exclude | Clinical population/condition that could impact on the outcomes |
| 205 | Maclean et al. (2014) | Exclude | No targeted music training intervention |
| 206 | Madsen (1981) | Exclude | No targeted music training intervention |
| 207 | Madsen and Geringer (1976) | Exclude | No targeted music training intervention |
| 208 | Manzo (1984) | Exclude | No targeted music training intervention |
| 209 | Marin (2009) | Exclude | Design not longitudinal |
| 210 | Maróti et al. (2019) | Exclude | Design not longitudinal |
| 211 | Martins et al. (2018) | Exclude | No auditory/linguistic processing outcomes |
| 212 | Martin (1964) | Exclude | Access issues/lack of information |
| 213 | McCarthy (1980) | Exclude | Design not experimental/quasi-experimental |
| 214 | McLachlan et al. (2013) | Exclude | No control group |
| 215 | McPherson (2005) | Exclude | No control group |
| 216 | Mehr et al. (2013) | **Include** |  |
| 217 | Micheyl et al. (2006) | Exclude | No control group |
| 218 | Miksza and Gault (2014) | Exclude | No targeted music training intervention |

|  |  |  |  |
|---|---|---|---|
| 219 | Miyazaki (2004) | Exclude | Design not experimental/quasi-experimental |
| 220 | Mohammadi (2004) | Exclude | Access issues/lack of information |
| 221 | Moore et al. (2017) | Exclude | No targeted music training intervention |
| 222 | Moreno and Besson (2005) | Exclude | Not published in peer-reviewed journal |
| 223 | Moreno and Besson (2006) | **Include** |  |
| 224 | Moreno et al. (2011a) | **Include** |  |
| 225 | Moreno and Bidelman (2014) | Exclude | Review article |
| 226 | Moreno et al. (2011b) | **Include** |  |
| 227 | Moreno et al. (2015) | **Include** |  |
| 228 | Moreno et al. (2009) | **Include** |  |
| 229 | Moritz et al. (2013) | Exclude | Access issues/lack of information |
| 230 | Morris et al. (2018) | Exclude | No auditory/linguistic processing outcomes |
| 231 | Morrongiello and Roes (1990) | Exclude | Design not longitudinal |
| 232 | Morrongiello et al. (1989) | Exclude | Design not longitudinal |
| 233 | Mualem and Lavidor (2015) | Exclude | No targeted music training intervention |
| 234 | Myant et al. (2008) | Exclude | Access issues/lack of information |
| 235 | Nair et al. (2019) | Exclude | Design not longitudinal |
| 236 | Nan et al. (2018) | **Include** |  |
| 237 | Neto et al. (2016) | Exclude | No auditory/linguistic processing outcomes |
| 238 | Neufeld (1986) | Exclude | Access issues/lack of information |

|  |  |  |  |
|---|---|---|---|
| 239 | Nichols and Honig (1995) | Exclude | No targeted music training intervention |
| 240 | Norton et al. (2005) | Exclude | Design not longitudinal |
| 241 | Osborne et al. (2016) | Exclude | No control group |
| 242 | Çoban and Selçuk (2017) | Exclude | No targeted music training intervention |
| 243 | Ong et al. (2017) | Exclude | No control group |
| 244 | Ong et al. (2016) | Exclude | No targeted music training intervention |
| 245 | Orsmond and Miller (1999) | **Include** |  |
| 246 | Overy (2000) | Exclude | Clinical population/condition that could impact on the outcomes |
| 247 | Overy (2003) | Exclude | Clinical population/condition that could impact on the outcomes |
| 248 | Overy et al. (2005) | Exclude | No control group |
| 249 | Ozola (2015) | Exclude | Access issues/lack of information |
| 250 | Pantev et al. (2001) | Exclude | Design not experimental/quasi-experimental |
| 251 | Pantev et al. (2009) | Exclude | No control group |
| 252 | Pantev et al. (2015) | Exclude | No control group |
| 253 | Paraskevopoulos et al. (2014) | Exclude | No control group |
| 254 | Patscheke et al. (2016) | Exclude | Access issues/lack of information |
| 255 | Patscheke et al. (2019) | **Include** |  |
| 256 | Patel and Iversen (2007) | Exclude | Review article |
| 257 | Pechstedt et al. (1989) | Exclude | Design not longitudinal |
| 258 | Pellico et al. (2012) | Exclude | No targeted music training intervention |

|  |  |  |  |
|---|---|---|---|
| 259 | Pellico et al. (2014) | Exclude | No targeted music training intervention |
| 260 | Perna et al. (2018) | Exclude | Design not longitudinal |
| 261 | Persellin. (1994) | Exclude | No control group |
| 262 | Pfordresher (2012) | Exclude | Review article |
| 263 | Picciotti et al. (2018) | Exclude | Design not longitudinal |
| 264 | Piper and Shoemaker (1973) | Exclude | No baseline/post-test data |
| 265 | Piro and Ortiz (2009) | **Include** |  |
| 266 | Ploukou and Panagopoulou (2018) | Exclude | No auditory/linguistic processing outcomes |
| 267 | Politimou et al. (2019) | Exclude | Design not longitudinal |
| 268 | Portowitz et al. (2015) | Exclude | No control group |
| 269 | Portowitz et al. (2009) | Exclude | No auditory/linguistic processing outcomes |
| 270 | Portowitz et al. (2014) | Exclude | No auditory/linguistic processing outcomes |
| 271 | Poulos et al. (2019) | Exclude | Clinical population/condition that could impact on the outcomes |
| 272 | Putkinen et al. (2014a) | Exclude | Access issues/lack of information |
| 273 | Putkinen et al. (2014b) | Exclude | Access issues/lack of information |
| 274 | Rabinowitch et al. (2013) | **Include** |  |
| 275 | Rauscher. et al. (1997) | Exclude | No auditory/linguistic processing outcomes |
| 276 | Rauscher and Zupan (2000) | Exclude | No auditory/linguistic processing outcomes |
| 277 | Rauscher and Hinton (2011) | Exclude | Review article |
| 278 | Rautenberg (2015) | **Include** |  |

|  |  |  |  |
|---|---|---|---|
| 279 | Register (2004) | Exclude | No targeted music training intervention |
| 280 | Reifinger (2018) | Exclude | Design not longitudinal |
| 281 | Reifinger (2009) | Exclude | No control group |
| 282 | Ribeiro and Santos (2017) | Exclude | Clinical population/condition that could impact on the outcomes |
| 283 | Richmond et al. (2016) | Exclude | Clinical population/condition that could impact on the outcomes |
| 284 | Rickard et al. (2013) | Exclude | No auditory/linguistic processing outcomes |
| 285 | Rickard et al. (2012) | **Include** |  |
| 286 | Ritblatt et al. (2013) | Exclude | No targeted music training intervention |
| 287 | Črnčec et al. (2006) | Exclude | Review article |
| 288 | Rose et al. (2015) | Exclude | Access issues/lack of information |
| 289 | Rose et al. (2019) | **Include** |  |
| 290 | Rossi et al. (2018) | Exclude | No targeted music training intervention |
| 291 | Roach (1974) | Exclude | No targeted music training intervention |
| 292 | Robinson (1988) | Exclude | Design not longitudinal |
| 293 | Roden et al. (2014a) | Exclude | No auditory/linguistic processing outcomes |
| 294 | Roden et al. (2014b) | **Include** |  |
| 295 | Roden et al. (2012) | Exclude | No auditory/linguistic processing outcomes |
| 296 | Roden et al. (2016) | Exclude | No auditory/linguistic processing outcomes |
| 297 | Rowe and Ivinskis (1972) | Exclude | Clinical population/condition that could impact on the outcomes |
| 298 | Roy et al. (2015) | Exclude | Access issues/lack of information |

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|---|---|---|---|
| 299 | Runfola et al. (2012) | Exclude | No auditory/linguistic processing outcomes |
| 300 | Rutkowski and Miller (2003) | Exclude | No targeted music training intervention |
| 301 | Sachs et al. (2017) | Exclude | No baseline/post-test data |
| 302 | Sakai et al. (2017) | Exclude | No targeted music training intervention |
| 303 | Scalas et al.  (2017) | Exclude | Design not longitudinal |
| 304 | Schellenberg (2004) | **Include** | |
| 305 | Schellenberg (2005) | Exclude | Review article |
| 306 | Schellenberg (2006) | Exclude | Design not longitudinal |
| 307 | Schellenberg (2011a) | Exclude | Design not longitudinal |
| 308 | Schellenberg (2011b) | Exclude | Design not longitudinal |
| 309 | Schellenberg et al. (2015) | **Include** | |
| 310 | Schellenberg and Mankarious (2012) | Exclude | Design not longitudinal |
| 311 | Schellenberg and Moreno (2010) | Exclude | Design not longitudinal |
| 312 | Schlaug. et al. (2009) | Exclude | No auditory/linguistic processing outcomes |
| 313 | Schlaug et al. (2005) | Exclude | Access issues/lack of information |
| 314 | Schleuter and Schleuter (1989) | Exclude | Design not longitudinal |
| 315 | Schön and Tillmann (2015) | Exclude | Review article |
| 316 | See and Ibbotson (2018) | **Include** | |
| 317 | Seinfeld et al. (2013) | Exclude | No auditory/linguistic processing outcomes |
| 318 | Sena and Hanson-Abromeit (2018) | Exclude | No control group |

| | | | |
|---|---|---|---|
| 319 | Shahin et al. (2008) | **Include** | |
| 320 | Shahin et al. (2004) | Exclude | Design not longitudinal |
| 321 | Sharma (2007) | Exclude | No targeted music training intervention |
| 322 | Sharma (2012) | Exclude | Clinical population/condition that could impact on the outcomes |
| 323 | Slater et al. (2017) | Exclude | Design not longitudinal |
| 324 | Slater et al. (2015) | **Include** | |
| 325 | Slater et al. (2014) | **Include** | |
| 326 | Slater et al. (2013) | Exclude | No baseline/post-test data |
| 327 | So (2005) | Exclude | Access issues/lack of information |
| 328 | Solé et al. (2010) | Exclude | No control group |
| 329 | Sousa et al. (2005) | Exclude | No auditory/linguistic processing outcomes |
| 330 | Standley and Hughes (1997) | Exclude | Clinical population/condition that could impact on the outcomes |
| 331 | Standley et al. (2009) | Exclude | Clinical population/condition that could impact on the outcomes |
| 332 | Stefano et al. (2004) | Exclude | No targeted music training intervention |
| 333 | Strait et al. (2013) | Exclude | No control group |
| 334 | Strait et al. (2012) | Exclude | Design not longitudinal |
| 335 | Sutherland et al. (2013). | Exclude | No targeted music training intervention |
| 336 | Swaminathan and Gopinath (2013) | Exclude | Design not longitudinal |
| 337 | Taebel and Coker (1980) | Exclude | Design not experimental/quasi-experimental |
| 338 | Tai et al. (2015) | Exclude | Clinical population/condition that could impact on the outcomes |

|  |  |  |  |
|---|---|---|---|
| 339 | Teicher (1997) | Exclude | No targeted music training intervention |
| 340 | Tejada and Spain (2009) | Exclude | No targeted music training intervention |
| 341 | Theorell et al. (2014) | Exclude | Design not longitudinal |
| 342 | Thompson et al. (2015) | Exclude | Design not longitudinal |
| 343 | Thompson et al. (2003) | Exclude | Design not longitudinal |
| 344 | Thompson et al. (2004) | Exclude | No baseline/post-test data |
| 345 | Tierney et al. (2013) | **Include** |  |
| 346 | Tierney et al. (2015) | **Include** |  |
| 347 | Todhunter-Reid (2019) | Exclude | Design not longitudinal |
| 348 | Trainor et al. (2009) | Exclude | Not published in peer-reviewed journal |
| 349 | Trainor et al. (2012) | Exclude | No control group |
| 350 | Trainor et al. (2003) | Exclude | Review article |
| 351 | Tsang and Conrad (2011) | Exclude | Design not longitudinal |
| 352 | Ullén et al. (2015) | Exclude | Design not longitudinal |
| 353 | Upitis (1987) | Exclude | Design not longitudinal |
| 354 | Verschaffel (2009) | Exclude | Design not longitudinal |
| 355 | Virtala et al. (2012) | Exclude | Design not longitudinal |
| 356 | Vlismas and Bowes (1999) | Exclude | No targeted music training intervention |
| 357 | Wagner and Menzel (1977) | Exclude | No targeted music training intervention |
| 358 | Walworth (2009) | Exclude | Clinical population/condition that could impact on the outcomes |

| | | | |
|---|---|---|---|
| 359 | Watanabe et al. (2007) | Exclude | No targeted music training intervention |
| 360 | Wehrum et al. (2011) | Exclude | Design not longitudinal |
| 361 | Wenzhou (2015) | Exclude | Design not experimental/quasi-experimental |
| 362 | Wetter et al. (2009) | Exclude | Design not longitudinal |
| 363 | Williams (2005) | Exclude | Design not longitudinal |
| 364 | Winsler et al. (2011) | Exclude | Design not longitudinal |
| 365 | Yang et al. (2014) | Exclude | No targeted music training intervention |
| 366 | Yeşil and Ünal (2017) | Exclude | Design not longitudinal |
| 367 | Yong and McBride-Chang (2007) | Exclude | Access issues/lack of information |
| 368 | Yousefi et al. (2014) | Exclude | No targeted music training intervention |
| 369 | Young (1971) | Exclude | No baseline/post-test data |
| 370 | Young (1974) | **Include** | |
| 371 | Young (1975) | Exclude | No auditory/linguistic processing outcomes |
| 372 | Yu (2018) | Exclude | Access issues/lack of information |
| 373 | Yu et al. (2010) | Exclude | No control group |
| 374 | Zafranas (2004) | Exclude | No control group |
| 375 | Zapata and Hargreaves (2018) | Exclude | No auditory/linguistic processing outcomes |
| 376 | Zhao and Kuhl (2016) | Exclude | No targeted music training intervention |

**2nd Full-text Screening**

| | ***Article*** | ***Decision*** | ***Reason*** |
|---|---|---|---|

|  |  |  |  |
|---|---|---|---|
| 1 | Barbeau and Cossette (2019) | Exclude | No auditory/linguistic processing outcomes |
| 2 | Barrett et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 3 | Belden et al. (2020) | Exclude | Design not longitudinal |
| 4 | Biasutti and Mangiacotti (2019) | Exclude | Clinical population/condition that could impact on the outcomes |
| 5 | Bugos (2019) | **Include** |  |
| 6 | Caló et al. (2020) | Exclude | No control group |
| 7 | Carioti et al. (2019) | **Include** |  |
| 8 | Cheung et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 9 | Cook et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 10 | Demos et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 11 | Diaz Abrahan et al. (2019) | Exclude | Design not longitudinal |
| 12 | Dubinsky et al. (2019) | **Include** |  |
| 13 | Fancourt and Perkins (2019) | Exclude | Clinical population/condition that could impact on the outcomes |
| 14 | Fleming et al. (2019) | **Include** |  |
| 15 | Frischen et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 16 | Giacosa et al. (2019) | Exclude | Design not longitudinal |
| 17 | Gómez-Zapata et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 18 | Guo et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 19 | Hennessy et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 20 | Ilari et al. (2020) | Exclude | No auditory/linguistic processing outcomes |

|  |  |  |  |
|---|---|---|---|
| 21 | Kim and Yoo (2019) | Exclude | No auditory/linguistic processing outcomes |
| 22 | Laffere et al. (2020) | Exclude | No targeted music training intervention |
| 23 | Li et al. (2020) | **Include** |  |
| 24 | Lordie et al. (2019) | Exclude | No targeted music training intervention |
| 25 | Loui et al. (2019) | Exclude | Design not longitudinal |
| 26 | MacCutcheon et al. (2019) | **Include** |  |
| 27 | Muthivhi and Kriger (2019) | Exclude | Design not experimental/quasi-experimental |
| 28 | Norgaard et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 29 | Putkinen et al. (2019a) | Exclude | Design not longitudinal |
| 30 | Putkinen et al. (2019b) | Exclude | No baseline/post-test data |
| 31 | Rabinowitch and Cross (2019) | Exclude | Design not longitudinal |
| 32 | Saarikivi et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 33 | Shen et al. (2019) | Exclude | No auditory/linguistic processing outcomes |
| 34 | Vidal et al. (2020) | **Include** |  |
| 35 | Whitson et al. (2020) | Exclude | No control group |
| 36 | Wong et al. (2019a) | Exclude | No targeted music training intervention |
| 37 | Wong et al. (2019b) | Exclude | No targeted music training intervention |
| 38 | Zendel et al. (2019) | **Include** |  |
|  | **3rd Full-text Screening** |  |  |
|  | ***Article*** | ***Decision*** | ***Reason*** |

| | | | |
|---|---|---|---|
| 1 | Abeles et al. (2021) | Exclude | Design not longitudinal |
| 2 | Agboeze et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 3 | Azaryahu and Adi-Japha (2020) | Exclude | No auditory/linguistic processing outcomes |
| 4 | Barbaroux et al. (2021) | Exclude | No control group |
| 5 | Berthold-Losleben et al. (2021) | Exclude | No auditory/linguistic processing outcomes |
| 6 | Boucher et al. (2020) | Exclude | No control group |
| 7 | Castillejos and Godoy-Izquierdo (2021) | Exclude | No auditory/linguistic processing outcomes |
| 8 | Caulfied et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 9 | Chen et al. (2021) | Exclude | Design not longitudinal |
| 10 | Coimbra et al. (2021) | Exclude | Design not longitudinal |
| 11 | Dansereau (2020) | Exclude | Access issues/lack of information |
| 12 | Degé et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 13 | Dittinger et al. (2021) | Exclude | Design not longitudinal |
| 14 | Eccles et al. (2020) | Exclude | No control group |
| 15 | Forbes (2020) | Exclude | No control group |
| 16 | Frischen et al. (2021) | Exclude | No auditory/linguistic processing outcomes |
| 17 | Gaboury et al. (2020) | Exclude | No targeted music training intervention |
| 18 | Galal et al. (2021) | Exclude | No auditory/linguistic processing outcomes |
| 19 | Good et al. (2021) | Exclude | No auditory/linguistic processing outcomes |
| 20 | Hadjikou (2021) | Exclude | No auditory/linguistic processing outcomes |

|  |  |  |  |
|---|---|---|---|
| 21 | Hennessy et al. (2021) | **Include** |  |
| 22 | Ismail et al. (2021) | Exclude | No control group |
| 23 | Iorio et al. (2021) | Exclude | No auditory/linguistic processing outcomes |
| 24 | James et al. (2020) | Exclude | Design not experimental/quasi-experimental |
| 25 | Jekiel and Malarski (2021) | Exclude | No targeted music training intervention |
| 26 | Kasuya-Ueba et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 27 | Kim and Kang (2021) | Exclude | No auditory/linguistic processing outcomes |
| 28 | Kragness et al. (2021) | Exclude | No targeted music training intervention |
| 29 | Kyprianides and Easterbrook (2020) | Exclude | No control group |
| 30 | Lo et al. (2020) | Exclude | Clinical population/condition that could impact on the outcomes |
| 31 | Mete and Dündar (2020) | Exclude | No control group |
| 32 | Mogro-Wilson and Tredinnick (2020) | Exclude | No targeted music training intervention |
| 33 | Nijmeier et al. (2021) | Exclude | Design not experimental/quasi-experimental |
| 34 | Öztürk and Can (2020) | Exclude | No auditory/linguistic processing outcomes |
| 35 | Paolantonio et al. (2020) | Exclude | No control group |
| 36 | Paraskevopoulos et al. (2021) | Exclude | No control group |
| 37 | Pieper et al. (2020) | Exclude | No auditory/linguistic processing outcomes |
| 38 | Prichard (2021) | Exclude | No auditory/linguistic processing outcomes |
| 39 | Provenzano et al. (2020) | Exclude | No control group |
| 40 | Putkinen et al. (2021) | Exclude | Design not longitudinal |

|  |  |  |  |
|---|---|---|---|
| 41 | Raja and Bhalla (2020) | Exclude | No auditory/linguistic processing outcomes |
| 42 | Ramón and Chacón-López (2021) | Exclude | No auditory/linguistic processing outcomes |
| 43 | Seheda and Tereshchenko (2020) | Exclude | Design not experimental/quasi-experimental |
| 44 | Vibell et al. (2021) | Exclude | Design not longitudinal |
| 45 | Wang (2021) | Exclude | No control group |
| 46 | Wiener and Bradley (2020) | **Include** |  |
| 47 | Williams et al. (2020) | Exclude | Design not experimental/quasi-experimental |
| 48 | Winsler et al. (2020) | Exclude | No targeted music training intervention |
| 49 | Zioga et al. (2020) | Exclude | No control group |

**Manual Search**

|  | ***Article*** | ***Decision*** | ***Reason*** |
|---|---|---|---|
| 1 | Bolduc et al. (2020) | Exclude | Access issues/lack of information |
| 2 | Bolduc and Lefebvre (2012) | Exclude | Access issues/lack of information |
| 3 | Braun Janzen et al. (2014) | Exclude | Design not longitudinal |
| 4 | Bugos and Jacobs (2012) | **Include** |  |
| 5 | Bugos et al. (2007) | Exclude | No baseline/post-test data |
| 6 | Geoghegan and Mitchelmore (1996) | Exclude | No baseline/post-test data |
| 7 | Habibi et al. (2020) | **Include** |  |
| 8 | Haywood et al. (2015) | Exclude | Not published in peer-reviewed journal |
| 9 | James et al. (2020) | **Include** |  |

|  |  |  |  |
|---|---|---|---|
| 10 | Kirschner and Tomasello (2010) | Exclude | Design not longitudinal |
| 11 | Lukács and Honbolygó (2019) | Exclude | No baseline/post-test data |
| 12 | Yazejian and Peisner-Feinberg (2009) | Exclude | No targeted music training intervention |
| 13 | Tervaniemi et al. (2022) | **Include** |  |

***Table S4.*** List of included and excluded studies. The list includes all studies assessed for eligibility in the 1st, 2nd and 3rd full-text screening phases, as well as the reasons for exclusion. We evaluated 476 articles (1st full-text screening = 376; 2nd = 38; 3rd = 49; manual search = 13).

| Screening | Articles (*n*) |
|---|---|
| **1st Initial Screening** | |
| Both reviewers agree to include | 205 |
| Both reviewers agree to exclude | 4541 |
| Only the first reviewer wants to include | 141 |
| Only the second reviewer wants to include | 111 |
| | |
| Agreement (%) | 94.96 |
| Cohen's Kappa (κ) | 0.59 |
| **1st Full-text Screening** | |
| Both reviewers agree to include | 80 |
| Both reviewers agree to exclude | 276 |
| Only the first reviewer wants to include | 10 |
| Only the second reviewer wants to include | 10 |
| | |
| Agreement (%) | 94.68 |
| Cohen's Kappa (κ) | 0.85 |
| **2nd Initial Screening** | |
| Both reviewers agree to include | 39 |
| Both reviewers agree to exclude | 696 |
| Only the first reviewer wants to include | 12 |
| Only the second reviewer wants to include | 14 |
| | |
| Agreement (%) | 96.58 |
| Cohen's Kappa (κ) | 0.73 |
| **2nd Full-text Screening** | |
| Both reviewers agree to include | 7 |
| Both reviewers agree to exclude | 29 |
| Only the first reviewer wants to include | 0 |
| Only the second reviewer wants to include | 2 |

| | |
|---|---|
| Agreement (%) | 94.74 |
| Cohen’s Kappa (κ) | 0.84 |
| **3rd Initial Screening** | |
| Both reviewers agree to include | 25 |
| Both reviewers agree to exclude | 659 |
| Only the first reviewer wants to include | 14 |
| Only the second reviewer wants to include | 10 |
| | |
| Agreement (%) | 96.61 |
| Cohen’s Kappa (κ) | 0.66 |
| **3rd Full-text Screening** | |
| Both reviewers agree to include | 3 |
| Both reviewers agree to exclude | 46 |
| Only the first reviewer wants to include | 0 |
| Only the second reviewer wants to include | 1 |
| | |
| Agreement (%) | 98 |
| Cohen’s Kappa (κ) | 0.85 |

***Table S5***. Inter-rater reliability for the initial and full-text screening in each searching period. We calculated the Cohen´s Kappa (κ), which measures the agreement between two raters who both classify items into mutually exclusive categories (a value of 1 implies perfect agreement).

| | | | **Risk of Bias Domain** | | | |
|---|---|---|---|---|---|---|
| **(A) Individual Studies** | Randomization Process | Deviations from intended intervention | Missing outcome data | Measurement of the outcome | Selection of the reported result | **Overall Risk of Bias** |
| Tervaniemi et al. (2022) | Low | Low | Low | Low | Low | **Low** |
| Hennessy et al. (2021) | Low | Low | Low | Low | Low | **Low** |
| Wiener & Bradley (2020) | Some Concerns | Low | Low | Some Concerns | Low | **Some Concerns** |
| James et al. (2020) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| Habibi et al. (2020) | High | Low | Low | Low | Low | **High** |
| Li et al. (2020) | Low | Low | Low | Low | Low | **Low** |
| Vidal et al. (2020) | Low | Some Concerns | Low | Low | Low | **Low** |
| Dubinsky et al. (2019) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| Bugos (2019) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| Fleming et al. (2019) | Low | Low | Low | Low | Low | **Low** |
| Zendel et al. (2019) | Low | Low | Low | Low | Low | **Low** |
| Carioti et al. (2019) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| McCutcheon et al. (2019) | High | Low | Low | Low | Low | **High** |
| Cohrdes et al. (2019) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| Li et al. (2019) | Low | Low | Low | Low | Low | **Low** |
| Alain et al. (2019) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| Rose et al. (2019) | High | Low | Low | Low | Low | **High** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Patscheke et al. (2019) | Low | Low | Low | Low | Low | **Low** |
| Jaschke et al. (2018) | Some Concerns | Some Concerns | Low | Low | Low | **Some Concerns** |
| See & Ibboston (2018) | Some Concerns | Low | Low | Some Concerns | Some Concerns | **Some Concerns** |
| D'Souza & Wiseheart (2018) | Some Concerns | Low | Low | Low | Low | **Low** |
| Li et al. (2018) | Low | Low | Low | Low | Low | **Low** |
| Nan et al. (2018) | Some Concerns | Low | Low | Low | Low | **Low** |
| Habibi et al. (2018) | High | Low | Some Concerns | Low | Low | **High** |
| Degé & Schwarzer (2018) | High | Low | Low | Low | Some Concerns | **High** |
| Guo et al. (2018) | Some Concerns | Low | Low | Low | Low | **Low** |
| Fujioka & Ross (2017) | Some Concerns | Low | Low | Some Concerns | Low | **High** |
| Holmes & Hallam (2017) | Some Concerns | Low | Low | Some Concerns | Some Concerns | **Some Concerns** |
| Habibi et al. (2016) | High | Low | Some Concerns | Low | Low | **High** |
| Carpentier et al. (2016) | Some Concerns | Low | Low | Low | Low | **Low** |
| Janus et al. (2016) | Some Concerns | Low | Low | Low | Low | **Low** |
| Ilari et al (2016) | High | Low | Low | Low | Low | **High** |
| Schellenberg et al. (2015) | Some Concerns | Low | Low | Low | Some Concerns | **Some Concerns** |
| Tierney et al. (2015) | High | Low | High | Low | Low | **High** |
| Moreno et al. (2015) | Some Concerns | Low | Low | Low | Low | **Low** |
| Rautenberg (2015) | Some Concerns | Low | Low | Low | Some Concerns | **Some Concerns** |
| Slater et al. (2015) | Low | Low | Low | Low | Low | **Low** |

| | | | | | |
|---|---|---|---|---|---|
| Slater et al. (2014) | Some Concerns | Low | Low | Low | Low | **Low** |
| Chobert et al. (2014) | Some Concerns | Low | Low | Some Concerns | Low | **Some Concerns** |
| Kraus et al. (2014) | Low | Low | Low | Low | Low | **Low** |
| Roden et al. (2014) | High | Some Concerns | Low | Some Concerns | Low | **High** |
| Kaviani et al. (2014) | Some Concerns | Low | Low | Low | Low | **Low** |
| Mehr et al. (2013) | Low | Some Concerns | Low | Low | Low | **Low** |
| François et al. (2013) | Some Concerns | Low | Low | Low | Low | **Low** |
| Rabinowitch et al. (2013) | Low | Low | Some Concerns | Some Concerns | High | **High** |
| Tierney et al. (2013) | High | Low | Low | Low | Low | **High** |
| Rickard et al. (2012) | High | Low | Low | Low | Some Concerns | **High** |
| Bugos & Jacobs (2012) | Some Concerns | Low | Some Concerns | Low | Some Concerns | **Some Concerns** |
| Moreno et al. (2011a) | Some Concerns | Low | Low | Low | Low | **Low** |
| Moreno et al. (2011b) | Some Concerns | Low | Low | Low | Low | **Low** |
| Herdener et al. (2010) | High | High | Low | Low | Low | **High** |
| Moreno et al. (2009) | Some Concerns | Low | Low | Low | Low | **Low** |
| Piro & Ortiz (2009) | High | Some Concerns | Low | Low | Low | **High** |
| Hyde et al. (2009) | Some Concerns | Low | Low | Low | Low | **Some Concerns** |
| Shahin et al. (2008) | High | Low | Low | Low | Low | **High** |
| Fujioka et al. (2006) | High | High | Low | Some Concerns | Low | **High** |
| Moreno & Besson (2006) | Some Concerns | Low | Some Concerns | Low | Low | **Some Concerns** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Gromko (2005) | High | Low | Low | Low | Some Concerns | **High** |
| Schellenberg (2004) | Low | Low | Low | Low | Some Concerns | **Some Concerns** |
| Orsmond & Miller (1999) | High | Some Concerns | Some Concerns | Low | Some Concerns | **High** |
| Flohr (1981) | Low | Low | Low | Some Concerns | Some Concerns | **Some Concerns** |
| Young (1974) | High | Low | Some Concerns | Some Concerns | Low | **High** |

| **(B) All Studies**<br>***N* = 62** | Randomization Process | Deviations from intended intervention | Missing outcome data | Measurement of the outcome | Selection of the reported result | **Overall Risk of Bias** |
|---|---|---|---|---|---|---|
| **Low** | 15 (24.19%) | 54 (87.10%) | 54 (87.10%) | 52 (83.87%) | 50 (80.65%) | **24 (38.71%)** |
| **Some Concerns** | 29 (46.77%) | 6 (9.68%) | 7 (11.29%) | 10 (16.13%) | 11 (17.74%) | **18 (29.03%)** |
| **High** | 18 (29.03%) | 2 (3.23%) | 1 (1.61%) | 0 (0%) | 1 (1.61%) | **20 (32.26%)** |

***Table S6.*** Risk of bias assessment of all included studies according to Rob2. In this table is depicted (A) the individual risk of bias assessment for each Rob2 domain, and (B) overall risk of bias for each Rob2 domain (*N* = 62).

| Category | Measure | Study | $\bar{g}_{\Delta}$ | CI (95%) | Weight (%) |
|---|---|---|---|---|---|
| **Rhythm Discrimination** | AMMA[a] | James et al. (2020) | 0.98 | [0.31; 1.64] | 0.54 |
| | Hill Primary Music Ability Test | Young (1974)[GC1] | 0.75 | [0.10; 1.40] | 0.45 |
| | | Young (1974)[GC2] | 0.93 | [0.25; 1.61] | 0.44 |
| | IMMA[b] | Roden et al. (2014) | 0.30 | [0.05; 0.55] | 0.23 |
| | MINT (accuracy) | Hennessy et al. (2021) | 0.46 | [-0.32; 1.23] | 0.55 |
| | MINT (reaction time) | Hennessy et al. (2021) | 0.01 | [-0.78; 0.75] | 0.56 |
| | PMMA[c] | Ilari et al. (2016) | -2.78 | [-4.04; -1.51] | 0.13 |
| | | Rose et al. (2019) | -0.21 | [-1.06; 0.64] | 0.39 |
| **Pitch Discrimination** | AMMA[a] | James et al. (2020) | 1.02 | [0.36; 1.69] | 0.54 |
| | Auditory Oddball (accuracy) | Hennessy et al. (2021) | -0.42 | [-1.20; 0.35] | 0.55 |
| | Auditory Oddball (reaction time) | Hennessy et al. (2021) | 0.29 | [-1.06; 0.47] | 0.55 |
| | Harmony Discrimination | Cohrdes et al. (2019)[GC1] | 0.07 | [-0.34; 0.47] | 1.80 |
| | | Cohrdes et al. (2019)[GC2] | 0.06 | [-0.34; 0.47] | 1.79 |
| | MINT (accuracy) | Hennessy et al. (2021) | -0.07 | [-0.83; 0.70] | 0.56 |
| | MINT (reaction time) | Hennessy et al. (2021) | 0.67 | [-1.45; 0.11] | 0.54 |
| | Pitch Discrimination - Frequency difference limens | Dubinsky et al. (2019) | -0.31 | [-0.28; 0.90] | 0.55 |
| | Pitch Discrimination Test, Melodies (congruous endings) | Moreno et al. (2009) | -0.08 | [-0.79; 0.96] | 0.42 |
| | Pitch Discrimination Test, Melodies (strong incongruities) | Moreno et al. (2009) | -0.09 | [-0.79; 0.97] | 0.42 |

| | | | | | |
|---|---|---|---|---|---|
| | Pitch Discrimination Test, Melodies (weak incongruities) | Moreno et al. (2009) | -0.42 | [-0.45; 1.29] | 0.43 |
| | PMMA[c] | Cohrdes et al. (2019)[GC1] | -0.04 | [-0.46; 0.38] | 1.70 |
| | | Cohrdes et al. (2019)[GC2] | 0.22 | [-0.19; 0.64] | 1.73 |
| | | Ilari et al. (2016) | 2.34 | [0.56; 4.11] | 0.09 |
| | | Rose et al. (2019) | -0.30 | [-1.13; 0.52] | 0.41 |
| | Pitch Discrimination | Yun Nan et al. (2018)[GC1] | -0.00 | [-0.72; 0.72] | 0.59 |
| | | Yun Nan et al. (2018)[GC2] | 0.59 | [-0.24; 1.42] | 0.46 |
| | Tonometric Adaptive Pitch Test | Wiener & Bradley (2020) | -0.28 | [-0.84; 1.41] | 0.18 |
| **Timbre Discrimination** | Timbre Discrimination | Cohrdes et al. (2019)[GC1] | -0.12 | [-0.54; 0.30] | 1.70 |
| | | Cohrdes et al. (2019)[GC2] | 0.28 | [-0.12; 0.69] | 1.80 |
| **General Auditory Music Discrimination** | AMMA [a] (Tonal & Rhythm) | Degé & Schwarzer (2018) | 0.18 | [-0.76; 1.12] | 0.15 |
| | | James et al. (2020) | 1.27 | [0.55; 2.00] | 0.49 |
| | Harmony, rhythm & melody discrimination | Fujioka et al. (2006) | 1.25 | [0.65; 2.69] | 0.14 |
| | MINT (accuracy) | Hennessy et al. (2021) | 0.10 | [-0.67; 0.86] | 0.56 |
| | MINT (reaction time) | Hennessy et al. (2021) | -0.10 | [-0.69; 0.89] | 0.52 |
| | PMMA[c] (Tonal & Rhythm) | Flohr (1981) | 1.06 | [-0.01; 2.13] | 0.13 |

GC - Group Comparison.
Note: [a] Advanced Measures of Music Audiation; [b] Intermediate Measures of Music Audiation; [c] Primary Measures of Music Audiation.

***Table S7***. Individual effect sizes ($\overline{g}_{\Delta}$) and 95% confidence intervals (CI) from all the studies investigating the effects of music training on auditory processing included in the meta-analysis. Category refers to the general construct assessed by the tasks. Measure refers to the dependent variable used to quantify the effects of music training on auditory processing. Weight quantifies the contribution of each effect size to the pooled effect as estimated in the multilevel model summarizing the effects of music training on auditory and linguistic processing.

| Category | Measure | Study | $\bar{g}_{\Delta}$ | CI (95%) | Weight (%) |
|---|---|---|---|---|---|
| **Phonological Awareness** | Test CMF – spoonerisms (seconds) [a] | Carioti et al. (2019) | -0.49 | [-0.07; 1.06] | 1.02 |
| | Test CMF - spoonerisms (errors) [a] | Carioti et al. (2019) | -0.07 | [-0.48; 0.62] | 1.05 |
| | Conf-IRA[b] | Vidal et al. (2020) | 1.34 | [0.39; 2.28] | 0.15 |
| | CTOPP [c] | Slater et al. (2014) | -0.23 | [-0.96; 0.50] | 0.53 |
| | | Tierney et al. (2015) | 0.49 | [-0.32; 1.29] | 0.34 |
| | DIBELS – letter naming fluency [d] | Gromko (2005) | 0.08 | [-0.40; 0.56] | 0.96 |
| | DIBELS – non-sense word fluency [d] | Gromko (2005) | -0.25 | [-0.74; 0.24] | 0.95 |
| | DIBELS – phonemic segmentation [d] | Gromko (2005) | 0.67 | [0.06; 1.28] | 0.73 |
| | TPB [e] | Patscheke et al. (2019)[GC1] | 0.47 | [-0.53; 1.46] | 0.22 |
| | | Patscheke et al. (2019)[GC2] | 0.32 | [-0.67; 1.31] | 0.22 |
| | WJ III COG [f] | Moreno et al. (2011) | 0.11 | [-0.51; 0.74] | 0.19 |
| **Speech Discrimination** | AX-discrimination test | Wiener & Bradley (2020) | -0.13 | [-1.26; 1] | 0.18 |
| | BKB-SIN | Hennessy et al. (2021) | 0.30 | [-0.45; 1.04] | 0.59 |
| | QuickSIN Test [g] | Dubinsky et al. (2019) | -0.55 | [-0.05; 1.14] | 0.55 |
| | SIN – 0db (accuracy) | Hennessy et al. (2021) | 1.56 | [0.13; 3] | 0.17 |
| | SIN – 5db (accuracy) | Hennessy et al. (2021) | 1.35 | [0.49; 2.20] | 0.45 |
| | SIN – 10db (accuracy) | Hennessy et al. (2021) | 0.93 | [0.11; 1.76] | 0.49 |
| | SIN – 0db (reaction time) | Hennessy et al. (2021) | 0.35 | [-1.14; 0.45] | 0.52 |

| | | | | | |
|---|---|---|---|---|---|
| | SIN – 5db (reaction time) | Hennessy et al. (2021) | 0.13 | [-0.91; 0.65] | 0.54 |
| | SIN – 10db (reaction time) | Hennessy et al. (2021) | 0.13 | [-0.91; 0.65] | 0.54 |
| | Sentences Discrimination - congruous endings | Moreno et al. (2009) | 0.41 | [-1.29; 0.48] | 0.41 |
| | Sentences Discrimination - strong incongruities | Moreno et al. (2009) | 0.00 | [-0.88; 0.88] | 0.42 |
| | Sentences Discrimination - weak incongruities | Moreno et al. (2009) | -0.47 | [-0.44; 1.38] | 0.39 |
| | Speech in Noise Test | MacCutcheon et al. (2019) | -0.23 | [-0.68; 1.13] | 0.15 |
| | | Zendel et al. (2019) $^{GC1}$ | 0.29 | [-1.44; 0.87] | 0.18 |
| | | Zendel et al. (2019) $^{GC2}$ | 0.76 | [-1.73; 0.21] | 0.21 |
| | Speech Segmentation | François et al. (2013) | 2.30 | [0.72; 3.87] | 0.09 |
| | The Hearing in Noise Test | Slater et al. (2015) | -0.46 | [-0.31; 1.24] | 0.17 |
| | Word Discrimination | Yun Nan et al. (2018)$^{GC1}$ | 0.31 | [-0.50; 1.12] | 0.48 |
| | | Yun Nan et al. (2018)$^{GC2}$ | 0.91 | [0.05; 1.78] | 0.43 |
| **Reading** | Reading – Early Learning Goals | Holmes & Hallam (2017) $^{GC1}$ | -0.16 | [-1.05; 0.73] | 0.20 |
| | | Holmes & Hallam (2017) $^{GC2}$ | 1.66 | [0.03; 3.30] | 0.11 |
| | | See & Ibboston (2018) | -0.12 | [-0.81; 0.57] | 0.18 |
| | DDE-2 Battery - reading pseudo-words (seconds) [h] | Carioti et al. (2019) | 0.10 | [-0.71; 0.51] | 0.87 |
| | DDE-2 Battery - reading pseudo-words (errors) [h] | Carioti et al. (2019) | 0.09 | [-0.64; 0.46] | 1.06 |
| | MT Advanced Reading Battery – text (seconds) | Carioti et al. (2019) | 0.10 | [-0.72; 0.52] | 0.86 |
| | MT Advanced Reading Battery – text (errors) | Carioti et al. (2019) | -0.33 | [-0.90; 0.24] | 1 |
| | DDE-2 Battery - reading words (seconds) [h] | Carioti et al. (2019) | 0.18 | [-0.78; 0.43] | 0.89 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | Reading words (seconds) | Rautenberg (2015) $^{GC1}$ | -0.20 | [-0.42; 0.81] | 0.78 |
|  |  | Rautenberg (2015) $^{GC2}$ | 0.00 | [-0.55; 0.55] | 0.94 |
|  | Reading words (accuracy) | Rautenberg (2015) $^{GC1}$ | 1.10 | [0.34; 1.87] | 0.54 |
|  |  | Rautenberg (2015) $^{GC2}$ | 0.71 | [0.00; 1.42] | 0.62 |
|  | DDE-2 Battery - reading words (errors) [h] | Carioti et al. (2019) | -0.07 | [-0.48; 0.63] | 1.04 |
|  | Reading words (prosody) | Rautenberg (2015) $^{GC1}$ | -0.29 | [-0.28; 0.86] | 0.89 |
|  |  | Rautenberg (2015) $^{GC2}$ | -0.32 | [-0.19; 0.83] | 1.06 |
|  | ALEPE – print simple complexity [i] | Moreno et al. (2009) | -0.61 | [-0.39; 1.61] | 0.33 |
|  | ALEPE – consistent complexity [i] | Moreno et al. (2009) | 0.13 | [-1.06; 0.80] | 0.38 |
|  | ALEPE – inconsistent complexity [i] | Moreno et al. (2009) | -1.07 | [-0.03; 2.18] | 0.27 |
|  | TOSWRF [j] | Slater et al. (2014) | 0.53 | [-0.21; 1.27] | 0.52 |
|  | TOWRE [k] | Slater et al. (2014) | 0.09 | [-0.64; 0.82] | 0.53 |
| **Verbal Fluency** | CTOPP – Rapid Naming [c] | Slater et al. (2014) | 0.41 | [-0.32; 1.14] | 0.53 |
|  |  | Tierney et al. (2015) | 0.10 | [-0.65; 0.85] | 0.35 |
|  | D-KEFS - letter fluency [l] | Bugos (2019) $^{GC1}$ | -0.07 | [-0.54; 0.39] | 1.33 |
|  |  | Bugos (2019) $^{GC2}$ | 0.48 | [-0.03; 0.99] | 1.14 |
|  | D-KEFS - category fluency [l] | Bugos (2019) $^{GC1}$ | 0.28 | [-0.19; 0.76] | 1.29 |
|  |  | Bugos (2019) $^{GC2}$ | 0.48 | [-0.04; 1.00] | 1.11 |
|  | D-KEFS – category switching [l] | Bugos (2019) $^{GC1}$ | 0.16 | [-0.31; 0.63] | 1.31 |
|  |  | Bugos (2019) $^{GC2}$ | 0.30 | [-0.22; 0.82] | 1.12 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | D-KEFS – verbal fluency [l] | Bugos & Jacobs (2012) | 0.34 | [-0.61; 1.28] | 0.25 |
|  | KTEA-3 – Decoding [m] | Schellenberg (2004) [GC1] | 0.29 | [-0.34; 0.91] | 0.87 |
|  |  | Schellenberg (2004) [GC2] | 0.10 | [-0.52; 0.72] | 0.88 |
|  |  | Schellenberg (2004) [GC3] | 0.13 | [-0.47; 0.74] | 0.93 |
|  |  | Schellenberg (2004) [GC4] | -0.05 | [-0.65; 0.55] | 0.93 |
|  | Rapid Automatized Naming | Guo et al. (2018) | 0.23 | [-0.57; 1.02] | 0.34 |
|  | Verbal Fluency Test – Phonemic Fluency | Carioti et al. (2019) | -0.39 | [-0.95; 0.18] | 1.02 |
|  | Verbal Fluency Test – Semantic Fluency | Carioti et al. (2019) | 0.04 | [-0.51; 0.59] | 1.06 |
|  | Verbal Fluency | Janus et al. (2016) | -0.29 | [-0.91; 0.34] | 0.69 |
| **General Linguistic Skills** | Co.Si.Mo – neologisms manipulation [n] | Carioti et al. (2019) | -0.01 | [-0.58; 0.55] | 1.01 |
|  | Co.Si.Mo – active to passive transformations [n] | Carioti et al. (2019) | 0.43 | [-0.16; 1.01] | 0.94 |
|  | KBIT-2 – Verbal IQ | Rickard et al. (2012) [GC1] | 0.17 | [-0.34; 0.68] | 0.67 |
|  |  | Rickard et al. (2012) [GC2] | 0.03 | [-0.54; 0.59] | 0.64 |
|  | KTEA-3 – Comprehension [m] | Schellenberg (2004) [GC1] | 0.14 | [-0.53; 0.81] | 0.75 |
|  |  | Schellenberg (2004) [GC2] | 0.23 | [-0.43; 0.88] | 0.79 |
|  |  | Schellenberg (2004) [GC3] | 0.17 | [-0.48; 0.82] | 0.81 |
|  |  | Schellenberg (2004) [GC4] | 0.25 | [-0.38; 0.88] | 0.85 |
|  | Meeker Structure of Intellect - Vocabulary | Piro & Ortiz (2009) | 2.02 | [1.37; 2.67] | 0.46 |
|  | Meeker Structure of Intellect – Verbal Sequencing | Piro & Ortiz (2009) | 2.82 | [2.16; 3.48] | 0.46 |
|  | PPVT | Alain et al. (2019) [GC1] | -0.06 | [-0.85; 0.73] | 0.32 |

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|---|---|---|---|---|
|  | Alain et al. (2019) $^{GC2}$ | -0.44 | [-1.27; 0.39] | 0.31 |
|  | D´Souza & Wiseheart (2018) $^{GC1}$ | 0.33 | [-0.34; 1.00] | 0.43 |
|  | D´Souza & Wiseheart (2018) $^{GC2}$ | 0.34 | [-0.34; 1.02] | 0.43 |
|  | Janus et al. (2016) | 0.24 | [-0.38; 0.86] | 0.70 |
|  | Mehr et al. (2013) $^{GC1}$ | -0.21 | [-1.10; 0.69] | 0.30 |
|  | Mehr et al. (2013) $^{GC2}$ | -0.30 | [-1.00; 0.40] | 0.35 |
|  | Orsmond & Miller (1999) | -0.02 | [-0.76; 0.71] | 0.17 |
|  | Schellenberg et al. (2015) | 0.18 | [-0.33; 0.69] | 0.20 |
| Sentence Judgement - Anomalous | Janus et al. (2016) | -0.17 | [-0.83; 0.49] | 0.63 |
| Sentence Judgement - Ungrammatical | Janus et al. (2016) | -0.15 | [-0.76; 0.47] | 0.70 |
| Stanford-Binet Intelligence Scale – Verbal Reasoning | Kaviani et al. (2014) | 0.83 | [0.20; 1.46] | 0.19 |
| WASI – Similarities [q] | Rose et al. (2019) | 0.05 | [-0.71; 0.81] | 0.45 |
| WASI – Vocabulary [q] | Rose et al. (2019) | 0.32 | [-0.48; 1.12] | 0.42 |
|  | Slater et al. (2014) | 0.12 | [-0.71; 0.95] | 0.43 |
| WISC – Comprehension [r] | Moreno et al. (2009) | -0.17 | [-1.03; 0.68] | 0.48 |
|  | Schellenberg (2004) $^{GC1}$ | 0.06 | [-0.52; 0.64] | 1 |
|  | Schellenberg (2004) $^{GC2}$ | 0.50 | [-0.08;1.09] | 0.99 |
|  | Schellenberg (2004) $^{GC3}$ | 0.15 | [-0.42;0.72] | 1.03 |
|  | Schellenberg (2004) $^{GC4}$ | 0.60 | [0.02;1.17] | 1.02 |

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|---|---|---|---|---|---|
| | WISC – Information $^{r}$ | Moreno et al. (2009) | 0.07 | [-0.77; 0.91] | 0.44 |
| | | Schellenberg (2004) $^{GC1}$ | -0.01 | [-0.63; 0.62] | 0.86 |
| | | Schellenberg (2004) $^{GC2}$ | 0.10 | [-0.52; 0.71] | 0.89 |
| | | Schellenberg (2004) $^{GC3}$ | -0.42 | [-1.00; 0.17] | 0.98 |
| | | Schellenberg (2004) $^{GC4}$ | -0.36 | [-0.93; 0.22] | 1.01 |
| | WISC – Similarities $^{r}$ | Moreno et al. (2009) | 0.13 | [-0.71; 0.97] | 0.46 |
| | | Rabinowitch et al. (2013) $^{GC1}$ | 0.39 | [-0.68; 1.45] | 0.26 |
| | | Rabinowitch et al. (2013) $^{GC2}$ | 0.22 | [-0.52; 0.97] | 0.45 |
| | | Schellenberg (2004) $^{GC1}$ | -0.10 | [-0.68; 0.49] | 0.99 |
| | | Schellenberg (2004) $^{GC2}$ | -0.26 | [-0.84; 0.33] | 0.99 |
| | | Schellenberg (2004) $^{GC3}$ | 0.49 | [-0.12; 1.09] | 0.92 |
| | | Schellenberg (2004) $^{GC4}$ | 0.45 | [-0.15; 1.06] | 0.92 |
| | WISC – Vocabulary $^{r}$ | Bugos & Jacobs (2012) | -0.13 | [-1.05; 0.79] | 0.25 |
| | | Guo et al. (2018) | -0.33 | [-1.08; 0.43] | 0.35 |
| | | Moreno et al. (2009) | 0.31 | [-0.54; 1.15] | 0.45 |
| | | Rabinowitch et al. (2013) $^{GC1}$ | 0.33 | [-0.73; 1.38] | 0.27 |
| | | Rabinowitch et al. (2013) $^{GC2}$ | 0.08 | [-0.66; 0.82] | 0.45 |
| | | Schellenberg (2004) $^{GC1}$ | 0.45 | [-0.14; 1.04] | 0.98 |

| | | | | | |
|---|---|---|---|---|---|
| | | Schellenberg (2004) $^{GC2}$ | 0.21 | [-0.36; 0.79] | 1.02 |
| | | Schellenberg (2004) $^{GC3}$ | 0.57 | [-0.00; 1.15] | 1 |
| | | Schellenberg (2004) $^{GC4}$ | 0.36 | [-0.21; 0.92] | 1.05 |
| | WISC – Verbal IQ [r] | Jaschke et al. (2018) $^{GC1}$ | 0.95 | [-0.20; 2.09] | 0.22 |
| | | Jaschke et al. (2018) $^{GC2}$ | 3.00 | [2.10; 3.89] | 0.30 |
| | | Jaschke et al. (2018) $^{GC3}$ | 1.71 | [0.38; 3.04] | 0.17 |
| | | Jaschke et al. (2018) $^{GC4}$ | 3.98 | [2.85; 5.20] | 0.22 |
| | WPPSI – Similarities [s] | Nan et al. (2018) $^{GC1}$ | -0.41 | [-1.07; 0.25] | 0.69 |
| | | Nan et al. (2018) $^{GC2}$ | -0.13 | [-0.92; 0.66] | 0.51 |
| | WPSSI – Vocabulary [s] | Moreno et al. (2011) | 4.61 | [2.63; 6.60] | 0.06 |
| | | Nan et al. (2018) $^{GC1}$ | 0.04 | [-0.59; 0.68] | 0.73 |
| | | Nan et al. (2018) $^{GC2}$ | 0.08 | [-0.68; 0.83] | 0.54 |

GC - Group Comparison.

Note: [a] Battery for the evaluation of meta-phonological abilities; [b] Phonological awareness screening and assessment instrument; [c] Comprehensive test of phonological processing; [d] Dynamic indications of basic early literacy skills; [e] Testfürphonologische Bewusstheitsfähigkeiten; [f] Woodcock-Johnson III Tests of Cognitive Abilities; [g] Quick Speech in Noise Test; [h] Battery for the assessment of Developmental Dyslexia and Dysorthographia-2; [i] Portuguese European Reading Battery; [j] Test of silent word reading fluency; [k] Test of word reading efficiency; [l] Delis Kaplan Executive Function Measure; [m] Kaufmann Test of Educational Achievement; [n] Battery for morphological and morphosyntactic skills; [o] Kaufman Brief Intelligence Test; [p] Peabody Picture Vocabulary Test;[q] Wechsler Abbreviated Scale of Intelligence; [r] Wechsler Intelligence Scale for Children; [s] Wechsler Preschool & Primary Scale of Intelligence.

***Table S8**.* Individual effect sizes ($\bar{g}_{\Delta}$) and 95% confidence intervals (CI) from all the studies investigating the effects of music training on linguistic processing included in the meta-analysis. Category refers to the general construct assessed by the tasks. Measure refers to the dependent variable used to quantify the effects of music training on linguistic processing. Weight quantifies the contribution of each effect size to the pooled effect as estimated in the multilevel model summarizing the effects of music training on auditory and linguistic processing.

| Moderator | Studies (*n*) | Effect Sizes (*n*) | *F(df)* | *p* |
|---|---|---|---|---|
| **Domain of outcomes measure** | **42** | **155** | *F*(1,40) = 0.29 | .592 |
| Auditory Processing | 14 | 34 | | |
| Linguistic Processing | 34 | 121 | | |
| **Publication year** | **42** | **155** | *F*(2,39) = 1.39 | .260 |
| Published before 2000 | 3 | 4 | | |
| Published between 2000 and 2009 | 4 | 41 | | |
| Published between 2010 and 2022 | 35 | 110 | | |
| **Age** | **42** | **154** | *F*(3,38) = 0.53 | .662 |
| 10 years-old or less (children) | 31 | 99 | | |
| Between 11 and 17 (adolescents) | 5 | 26 | | |
| Between 18 and 59 (adults) | 2 | 17 | | |
| 60 years-old and over (older adults) | 4 | 12 | | |
| **Randomization** | **42** | **155** | *F*(1,40) = 1.53 | .224 |
| Random assignment | 11 | 57 | | |
| Non-random assignment | 31 | 98 | | |
| **Type of control group** | **42** | **155** | *F*(1,40) = 1.52 | .226 |
| Active control group | 16 | 61 | | |
| Passive control group | 26 | 94 | | |
| **Risk of Bias** | **42** | **155** | *F*(2,39) = 0.17 | .848 |
| Low Risk | 16 | 61 | | |
| Some Concerns | 14 | 70 | | |
| High Risk | 12 | 24 | | |
| **Type of training** | **42** | **155** | *F*(1,40) = 2.21 | .145 |
| Instrumental | 15 | 71 | | |
| Non-Instrumental | 27 | 84 | | |
| **Duration of training (months)** | **42** | **155** | *F*(1,40) = 1.22 | .275 |
| **Hours of training per week** | **38** | **145** | *F*(1,36) = 1.25 | .271 |
| **Baseline diferences** | **42** | **55** | *F*(1,40) = 15.61 | **<.001** |

***Table S9***. Meta-regression models for each moderator. We present the results of ten meta-regressions conducted to identify putative moderators of the effects of music training on auditory and linguistic processing. Studies (*n*) and effect sizes (*n*) refer to either the total number of studies or effect sizes referring to the specific moderator and its respective levels (where applicable – categorical variables). We report the degrees of freedom (*df*), *F* value and *p* value of the omnibus test of moderation (uncorrected for multiple comparisons). Significant *p* values are in bold (*p* < .05).

## References of the full-text screening phase

(Studies included in the systematic review and meta-analysis are in bold)

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# APPENDIX B | CHAPTER III

| Emotion Recognition (average Hu scores) | Mean ± SD (min – max) | Skewness | Kurtosis |
|---|---|---|---|
| Emotional Prosody | | | |
| Neutral | .28 ± .19 (.00 – .83) | 0.44 | -0.13 |
| Happy | .52 ± .21 (.01 – 1.00) | -0.18 | -0.35 |
| Sad | .29 ± .23 (.00 – .81) | 0.13 | -1.36 |
| Fear | .48 ± .29 (.00 – 1.00) | -0.16 | -1.17 |
| Angry | .56 ± .28 (.00 – 1.00) | -0.42 | -0.81 |
| Disgust | .31 ± .27 (.00 – 1.00) | 0.75 | -0.35 |
| Total | .41 ± .18 (.04 – .85) | 0.00 | -0.73 |
| Nonverbal Vocalisations | | | |
| Neutral | .74 ± .23 (.00 – 1.00) | -1.01 | 0.54 |
| Happy | .71 ± .17 (.17 – 1.00) | -0.48 | 0.39 |
| Sad | .75 ± .14 (.30 – 1.00) | -0.41 | 0.26 |
| Fear | .64 ± .22 (.00 – 1.00) | -0.85 | 0.36 |
| Angry | .75 ± .16 (.25 – 1.00) | -0.69 | 0.08 |
| Disgust | .72 ± .17 (.23 – 1.00) | -0.40 | -0.07 |
| Total | .72 ± .11 (.35 – .94) | -0.39 | -0.10 |
| Facial Expressions | | | |
| Neutral | .72 ± .14 (.23 – 1.00) | -0.39 | 0.22 |
| Happy | .89 ± .12 (.36 – 1.00) | -1.38 | 2.64 |
| Sad | .63 ± .21 (.10 – 1.00) | -0.46 | -0.38 |
| Fear | .65 ± .22 (.00 – 1.00) | -1.07 | 1.13 |
| Angry | .56 ± .20 (.08 – 1.00) | -0.10 | -0.44 |
| Disgust | .55 ± .23 (.00 – 1.00) | -0.37 | -0.46 |
| Total | .67 ± .13 (.35 – .94) | -0.30 | -0.27 |

***Supplementary Table S1***. Summary statistics for emotion recognition in emotional prosody, nonverbal vocalisations and facial expressions.

Emotional Prosody

| Intended emotion | Response Categories<br>Angry | Neutral | Happy | Fear | Sad | Disgust |
|---|---|---|---|---|---|---|
| Angry | 71.12 | 7.04 | 12.38 | 4.34 | 1.85 | 3.27 |
| Neutral | 5.25 | 56.21 | 3.41 | 4.90 | 25.91 | 4.33 |
| Happy | 4.68 | 5.46 | 79.71 | 5.46 | 1.70 | 2.98 |
| Fear | 3.98 | 10.94 | 10.22 | 61.70 | 10.52 | 2.64 |
| Sad | 6.61 | 31.04 | 1.78 | 7.53 | 49.35 | 3.69 |
| Disgust | 10.02 | 15.36 | 25.33 | 7.61 | 3.13 | 38.53 |

Nonverbal Vocalisations

| Intended emotion | Response Categories<br>Angry | Neutral | Happy | Fear | Sad | Disgust |
|---|---|---|---|---|---|---|
| Angry | 89.19 | 1.57 | 0.14 | 4.55 | 0.43 | 4.12 |
| Neutral | 3.48 | 86.67 | 3.83 | 4.11 | 0.43 | 1.49 |
| Happy | 0.57 | 2.13 | 80.80 | 0.43 | 15.51 | 0.57 |
| Fear | 7.29 | 9.85 | 2.57 | 74.23 | 3.06 | 3.00 |
| Sad | 0.14 | 0.85 | 4.20 | 2.65 | 92.02 | 0.14 |
| Disgust | 7.37 | 4.87 | 2.57 | 2.15 | 3.24 | 79.81 |

Facial Expressions

| Intended emotion | Response Categories<br>Angry | Neutral | Happy | Fear | Sad | Disgust |
|---|---|---|---|---|---|---|
| Angry | 74.85 | 10.57 | 0.28 | 5.74 | 1.71 | 6.84 |
| Neutral | 1.28 | 95.53 | 1.49 | 0.92 | 0.43 | 0.21 |
| Happy | 0.14 | 5.60 | 93.19 | 0.07 | 0.64 | 0.35 |
| Fear | 4.75 | 1.28 | 1.21 | 75.96 | 3.62 | 13.19 |
| Sad | 1.49 | 17.91 | 1.70 | 5.89 | 68.89 | 4.11 |
| Disgust | 22.83 | 0.29 | 0.64 | 3.49 | 1.72 | 71.03 |

***Supplementary Table S2***. Distribution of responses for each emotion in emotional prosody, nonverbal vocalizations, and facial expressions. Values represent percentages, and diagonal cells indicate correct categorizations (raw hit rates, before Hu correction).

| | Mean ± SD (min – max) | Skewness | Kurtosis |
|---|---|---|---|
| CSBQ subscales | | | |
| Sociability | 3.64 ± 0.70 (1.86 – 5.00) | -0.01 | -0.45 |
| Externalising Problems | 1.84 ± 0.71 (1.00 – 3.80) | 0.86 | 0.05 |
| Internalising Problems | 1.65 ± 0.64 (1.00 – 3.20) | 0.72 | -0.58 |
| Prosocial Behaviour | 3.61 ± 0.70 (1.40 – 5.00) | -0.13 | -0.02 |
| Behavioural Self-regulation | 3.54 ± 0.81 (1.17 – 5.00) | -0.27 | -0.26 |
| Cognitive Self-regulation | 3.11 ± 0.99 (1.00 – 5.00) | 0.10 | -0.84 |
| Emotional Self-regulation | 3.86 ± 0.72 (2.00 – 5.00) | -0.62 | -0.17 |
| General Socio-emotional Index | 3.75 ± 0.55 (2.27 – 4.85) | -0.06 | -0.36 |

*Note*. Scores range from 1 - 5; CSBQ - Child Self-Regulation and Behaviour Questionnaire; SD - Standard deviation.

***Supplementary Table S3.*** Summary statistics and reliability for the CSBQ subscales (sociability, externalising problems, internalising problems, prosocial behaviour, behavioural self-regulation, cognitive self-regulation, and emotional self-regulation) and general socio-emotional index.

|  | 1. | 2. | 3. | 4. | 5. | 6. | 7. |
|---|---|---|---|---|---|---|---|
| 1. Sociability | - |  |  |  |  |  |  |
| 2. Externalising Problems | -.16 | - |  |  |  |  |  |
|  | *0.63* |  |  |  |  |  |  |
| 3. Internalising Problems | -.64*** | .38*** | - |  |  |  |  |
|  | *> 100* | *> 100* |  |  |  |  |  |
| 4. Prosocial Behaviour | .67*** | -.40*** | -.43*** | - |  |  |  |
|  | *> 100* | *> 100* | *> 100* |  |  |  |  |
| 5. Behavioural SR | .26* | -.70*** | -.37*** | .63*** | - |  |  |
|  | *10.48* | *> 100* | *> 100* | *> 100* |  |  |  |
| 6. Cognitive SR | .55*** | -.14 | -.50*** | .58*** | .46*** | - |  |
|  | *> 100* | *0.38* | *> 100* | *> 100* | *> 100* |  |  |
| 7. Emotional SR | .25* | -.76*** | -.40*** | .52*** | .70*** | .16 | - |
|  | *7.69* | *> 100* | *> 100* | *> 100* | *> 100* | 0.61 |  |

*Note*. $BF_{10}$ values are indicated in italics. CSBQ - Child Self-Regulation and Behaviour Questionnaire; SR - Self-Regulation.

* *p* < .05; ** *p* < .01; *** *p* < .001 (Holm Bonferroni-corrected).

***Supplementary Table S4.*** Correlations between the CSBQ subscales.

| CSBQ subscales | *r* | $BF_{10}$ |
|---|---|---|
| Sociability | .68*** | > 100 |
| Externalising Problems | -.67*** | > 100 |
| Internalising Problems | -.71*** | > 100 |
| Prosocial Behaviour | .83*** | > 100 |
| Behavioural Self-regulation | .81*** | > 100 |
| Cognitive Self-regulation | .70*** | > 100 |
| Emotional Self-regulation | .72*** | > 100 |

Note. CSBQ - Child Self-Regulation and Behaviour Questionnaire.

*** $p < .001$ (Holm Bonferroni-corrected).

***Supplementary Table S5***. Pairwise correlations between the general socio-emotional index and each of the CSBQ subscales.

|  | Adj. $R^2$ | $F$ (5, 133) | $BF_{10}$ | $b^a$ | $SE$ | $B^b$ | $t$ | CI 95% | Partial $r$ | $BF_{10}$ partial $r$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Model 1: Neutrality | .28 | 11.85*** | > 100 |  |  |  |  |  |  |  |
| Constant |  |  |  | 4.70 | .64 |  | 7.39*** | [3.44, 5.96] |  |  |
| Age |  |  |  | -.30 | .08 | -.28 | -3.72*** | [-.46, -.14] | -.31 | 85.22 |
| Sex |  |  |  | .20 | .08 | .18 | 2.52* | [.04, .36] | .21 | 2.46 |
| Parental Education |  |  |  | .05 | .01 | .32 | 3.99*** | [.03, .08] | .33 | > 100 |
| Cognitive Ability |  |  |  | .01 | .01 | .08 | 1.00 | [-.01, .03] | .09 | 0.18 |
| Emotion Recognition |  |  |  | .48 | .22 | .17 | 2.22* | [.05, .90] | .19 | 1.24 |
| Model 2: Happiness | .29 | 12.49*** | > 100 |  |  |  |  |  |  |  |
| Constant |  |  |  | 4.37 | .63 |  | 6.93*** | [3.12, 5.62] |  |  |
| Age |  |  |  | -.27 | .08 | -.25 | -3.40** | [-.43, -.11] | -.28 | 29.16 |
| Sex |  |  |  | .20 | .08 | .18 | 2.50* | [.04, .36] | .21 | 2.34 |
| Parental Education |  |  |  | .04 | .01 | .28 | 3.46** | [.02, .07] | .29 | 35.66 |
| Cognitive Ability |  |  |  | .01 | .01 | .10 | 1.27 | [-.01, .03] | .11 | 0.24 |
| Emotion Recognition |  |  |  | .52 | .19 | .20 | 2.69** | [.14, .90] | .23 | 3.81 |
| Model 3: Sadness | .27 | 11.04*** | > 100 |  |  |  |  |  |  |  |
| Constant |  |  |  | 4.47 | .64 |  | 6.97*** | [3.20, 5.74] |  |  |
| Age |  |  |  | -.27 | .08 | -.24 | -3.27** | [-.43, -.11] | -.27 | 19.57 |
| Sex |  |  |  | .20 | .08 | .18 | 2.42* | [.04, .36] | .21 | 1.96 |
| Parental Education |  |  |  | .05 | .01 | .29 | 3.53** | [.02, .07] | .29 | 45.53 |
| Cognitive Ability |  |  |  | .01 | .01 | .11 | 1.43 | [-.01, .03] | .12 | 0.30 |
| Emotion Recognition |  |  |  | .26 | .18 | .11 | 1.43 | [-.10, .62] | .12 | 0.30 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Model 4: Fear | .29 | 12.19*** | > 100 | | | | | | | |
| Constant | | | | 4.60 | .63 | | 7.30*** | [3.35, 5.84] | | |
| Age | | | | -.29 | .08 | -.26 | -3.59*** | [-.44, -.12] | -.30 | 54.22 |
| Sex | | | | .19 | .08 | .18 | 2.42* | [.04, .35] | .21 | 1.97 |
| Parental Education | | | | .05 | .01 | .29 | 3.65*** | [.02, .07] | .30 | 66.46 |
| Cognitive Ability | | | | .01 | .01 | .09 | 1.15 | [-.01, .03] | .10 | 0.21 |
| Emotion Recognition | | | | .35 | .14 | .18 | 2.48* | [.07, .63] | .21 | 2.26 |
| Model 5: Anger | .29 | 12.39*** | > 100 | | | | | | | |
| Constant | | | | 4.53 | .63 | | 7.22*** | [3.29, 5.77] | | |
| Age | | | | -.29 | .08 | -.26 | -3.58*** | [-.44, -.13] | -.30 | 52.83 |
| Sex | | | | .19 | .08 | .17 | 2.39* | [.03, .35] | .20 | 1.83 |
| Parental Education | | | | .05 | .01 | .29 | 3.63*** | [.02, .07] | .30 | 61.85 |
| Cognitive Ability | | | | .01 | .01 | .10 | 1.24 | [-.01, .03] | .11 | 0.23 |
| Emotion Recognition | | | | .38 | .15 | .19 | 2.62* | [.09, .67] | .22 | 3.20 |
| Model 6: Disgust | .27 | 11.15*** | > 100 | | | | | | | |
| Constant | | | | 4.46 | .64 | | 6.96 | [3.19, 5.73] | | |
| Age | | | | -.27 | .08 | -.25 | -3.28 | [-.43, -.11] | -.27 | 20.30 |
| Sex | | | | .20 | .08 | .19 | 2.51 | [.04, .37] | .21 | 2.40 |
| Parental Education | | | | .05 | .01 | .29 | 3.65 | [.02, .07] | .30 | 67.21 |
| Cognitive Ability | | | | .01 | .01 | .11 | 1.40 | [-.01, .03] | .12 | 0.29 |
| Emotion Recognition | | | | .24 | .15 | .12 | 1.55 | [-.07, .54] | .13 | 0.36 |
| Model 7: All Emotions | .29 | 6.53*** | > 100 | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Constant | 4.51 | .65 | | 6.95*** | [3.23, 5.80] | | |
| Age | -.29 | .08 | -.27 | -3.52** | [-.45, -.13] | -.30 | 54.94 |
| Sex | .20 | .08 | .18 | 2.49* | [.04, .36] | .22 | 2.57 |
| Parental Education | .04 | .01 | .27 | 3.31** | [.02, .07] | .28 | 27.36 |
| Cognitive Ability | .01 | .01 | .07 | 0.86 | [-.01, .03] | .08 | 0.16 |
| Neutrality | .21 | .26 | .07 | 0.80 | [-.30, .71] | .07 | 0.15 |
| Happiness | .24 | .27 | .09 | 0.90 | [-.29, .77] | .08 | 0.16 |
| Sadness | .12 | .20 | .05 | 0.61 | [-.27, .46] | 05 | 0.13 |
| Fear | .08 | .19 | .04 | 0.42 | [-.30, .46] | .04 | 0.12 |
| Anger | .17 | .18 | .09 | 0.95 | [-.19, .54] | .08 | 0.17 |
| Disgust | -.03 | .18 | -.01 | -0.16 | [-.39, .33] | -.01 | 0.11 |

*Note*. * $p < .05$; ** $p < .01$; *** $p < .001$ (uncorrected *p*-values). [a] Unstandardized regression coefficient. [b] Standardized regression coefficient.

***Supplementary Table S6.*** Multiple regression analyses, modelling general socio-emotional adjustment as a function of specific prosodic emotions. Additional predictors were age, sex, parental education, and cognitive ability.

**Supplementary Analyses**

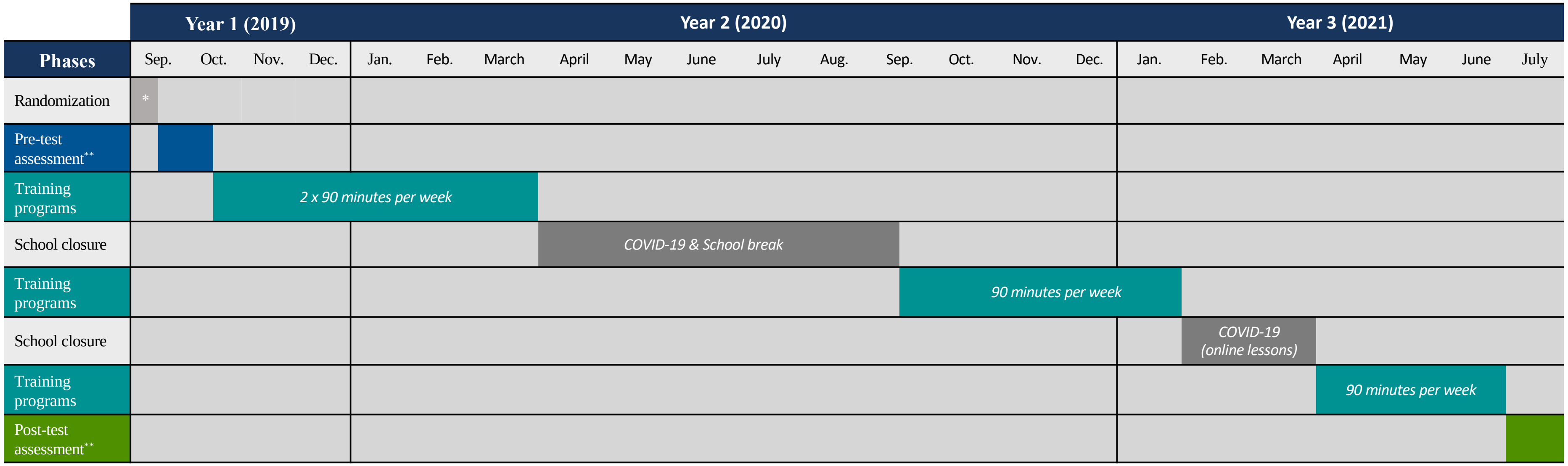
Statistical analyses based on arcsine transformed Hu values:

- Correlation between emotion recognition in speech prosody and general socio-emotional adjustment, *r* = .33, *p* < .001, $BF_{10}$ > 100
- Correlation between emotion recognition in nonverbal vocalizations and general socio-emotional adjustment, *r* = .11, *p* = .43, $BF_{10}$ = 0.22
- Correlation between emotion recognition in facial expressions and general socio-emotional adjustment, *r* = .10, *p* = .24, $BF_{10}$ = 0.21
- Multiple regression modelling socio-emotional adjustment scores as a function of age, sex, parental education, cognitive ability, and average accuracy on the emotional prosody recognition task. This model explained 31.07% of the variance, *R* = .58, *F*(5,133) = 13.44, *p* < .001, $BF_{10}$ > 100. Independent contributions were evident for age, partial *r* = -.30, *p* < .001, $BF_{10}$ = 54.94, sex, partial *r* = .22, *p* = .01, $BF_{10}$ = 2.57, and parental education, partial *r* = .28, *p* = .001, $BF_{10}$ = 27.36, but not for cognitive ability, *p* = .38, $BF_{10}$ = 0.16. Emotional prosody recognition made an independent contribution to the model, partial *r* = .27, *p* = .001, and the Bayesian analysis provided strong evidence for this contribution, $BF_{10}$ = 19.26.
- Multiple regressions modelling scores on each CSBQ subscale as a function of age, sex, parental education, cognitive ability, and average accuracy on emotional prosody recognition. Model on sociability, *R* = .47, *F*(5,133) = 7.57, *p* < .001, $BF_{10}$ > 100, independent contribution of emotional prosody recognition, partial *r* = .21, *p* = .02, $BF_{10}$ = 2.03; model on externalising problems, *R* = .34, *F*(5,133) = 3.52, *p* = .005, $BF_{10}$ = 2.84, independent contribution of emotional prosody recognition, partial *r* = -.08, *p* = .37, $BF_{10}$ = 0.16; model on internalising problems, *R* = .47, *F*(5,133) = 7.58, *p* < .001, $BF_{10}$ > 100, independent contribution of emotional prosody recognition, partial *r* = -.09, *p* = .28, $BF_{10}$ = 0.19; model on prosocial behaviour, *R* = .47, *F*(5,133) = 7.34, *p* < .001, $BF_{10}$ > 100, independent contribution of emotional prosody recognition, partial *r* = .23, *p* = .007, $BF_{10}$ = 3.72; model on behavioural self-regulation, *R* = .47, *F*(5,133) = 7.61, *p* < .001, $BF_{10}$ > 100, independent contribution of emotional prosody recognition, partial *r* = .23, *p* = .007, $BF_{10}$ = 3.72; model on cognitive self-regulation, *R* = .67, *F*(5,133) = 21.44, *p* < .001, $BF_{10}$ > 100, independent contribution of emotional prosody recognition, partial *r* = .25, *p* = .003, $BF_{10}$ = 7.42; model on emotional self-regulation, *R* = .36, *F*(5,133) = 3.94, *p* = .002, $BF_{10}$ = 6.37, independent contribution of emotional prosody recognition, partial *r* = .23, *p* = .008, $BF_{10}$ = 3.58.

# APPENDIX C | CHAPTER IV

## How Does Music Training Affect Socio-Emotional Abilities in Children?

### Timeline & Measures



*N = 110, 6 classes – 2 classes allocated to each group ⟶ Music group = 37, Sports group = 40, Passive control group = 33 children

| Measures | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Near transfer | | | | | | Far transfer | | | |
| **General cognition** | **Auditory memory** | **Auditory discrimination** | **Auditory rhythm copying** | **Finger dexterity** | **Arm-hand dexterity** | **Motor coordination** | **Executive Functions** | **Emotion recognition** | **Emotional authenticity recognition** | **Socio-emotional skills** |
| Non-verbal cognitive reasoning | short-term memory<br>working memory | Discrimination of melodies<br>Discrimination of rhythm<br>Recognition of unfamiliar melodies | Rhyhtm copy | Inserting pegs in a board<br>*preferred hand*<br>*non-preferred hand*<br>*both hands* | Placing disks in a board<br>*preferred hand*<br>*non-preferred hand* | Plate tapping<br>*preferred hand*<br>*non-preferred hand* | Inhibitory control<br>Interference control | Prosody<br>Vocalizations<br>Faces | Laughter<br>Crying | Social behavior<br>Empathy<br>Emotion comprehension |

**Auditory skills** **Fine-motor skills** **Gross-motor skills**

***Supplementary Figure 1***. Timeline of the Longitudinal Study, Group Allocation and Collected Measures.

# Training Programs

| Domains | Music training |
|---|---|
| **Music awareness** | Auditory and visual recognition of Orff and orchestra music instruments |
| | Recognition of different music genres and expression of personal interests related to them |
| | Identification of basic music structures, and of emotions expressed in music |
| **Elementary music concepts** | Rhythm, melody and harmony |
| | Rhythm figures, notes (whole, half, quarter, eighth and sixteenth), rests (half, quarter and eighth), and time signature (2/4, 3/4, 4/4, 6/8) |
| | Beat, measure, bar line, double bar and repeat sign |
| | Dynamics: *ff* to *pp*, *crescendo* and *diminuendo; Tempo*: lento, adagio, moderato, allegro, presto |
| | *Tutti*, solo, duet |
| | Major and pentatonic scales; treble clef; sharp and flat |
| **Rhythm and pitch** | Recognition and execution of rhythm figures including notes and rests, simple and compound rhythm patterns and ostinatos with steady and variable beat |
| | Perception of pitch variations and association with body movement |
| | Recognition and execution of melodic patterns |
| | Recognition of pitch notes on staff (treble clef) |
| **Performance** | Individual and choir vocal performance, one to two vocal layers |
| | Individual and group instrumental performance with Orff instruments (drums, xylophones and metallophones) or descant recorder (single to four-part harmony) |
| | Vocal and instrumental improvisation/imitation through echo (call and response) |
| | Body movement in response to tempo and dynamics variations |
| | Following conductor directions (tempo, dynamics and extra cues) |
| | Appropriate rehearsal behavior |

| Domains | Sports training |
|---|---|
| **Physical fitness (basketball-oriented)** | Warm-up exercises (with and without materials, namely balls) |
| | Running technique: control of body and motion, pace, and coordination (resistance, velocity running and sprinting) |
| | Strength and flexibility activities |
| | Exploring several ways of jumping (taking off from one foot or two feet, and landing on two feet) |
| | Exploring several ways of throwing (different positions of arms and differently sized materials) |
| **Coordination skills** | Coordination of upper and lower limbs, separately and with each other |
| | Eye-hand coordination |
| | Eye-foot coordination |
| | Complex movements of body parts and body actions, including weight transference |
| **Team sports: basketball** | Development of ball-handling skills and pair/group relays |
| | Learning dribble, block, pass and shooting technique |
| | Working rebounding in basketball |
| | The game: rules and team practice |
| **Team work: tactical planning** | Pre-team games to explore:<br>- occupation of space<br>- cooperation<br>- companionship |
| | Discussion and implementation of tactical plans |

***Supplementary Table 1***. Detailed Description of the Music Training (Orff-based) and Sports Training (Basketball) Programs. Adapted from Martins et al. (2018).

**Measures Description**

| Domain | Test | Sub-domains | Task | Items & Score |
|---|---|---|---|---|
| General cognition | Raven's Colored Progressive Matrices (RCPM) | - | The participant is presented with an incomplete design and is required to choose one answer from six available alternatives to best complete the design | Sum of correct items (*N* = 36 items) |
| COVID-19 lockdown effects | Teacher-report questionnaire developed in the context of the present study | Academic achievement; school participation; emotional state (during the lockdown, as compared to pre- | Educator report questionnaire – Likert scale for each sub-domain: 1 (a lot worse) to 5 (improved a lot) | Average of the 3 sub-domains |
| Auditory memory | Weschler Intelligence Scale for Children (WISC-III) | Digit span forward<br>Digit span backwards | Repeat numbers in the same order as read aloud by the examiner<br>Repeat numbers in the reverse order as read aloud by the examiner | Sum of correct sequences (*N* = 30 sequences) |
| Auditory discrimination | The Montreal Battery of Evaluation of Musical Abilities (MBEMA) | Melody discrimination<br>Rhythm discrimination<br>Memory | Same-different response<br>Same-different response<br>Identify if the melody has been presented earlier or not | d'prime values (*N* = 60 items) |
| Auditory rhythm copying | Musical Aptitude Tests (MATS) | Rhythm copy | A short rhythm is presented over headphones and the participant copies it on a marked key of a keyboard | Sum of correct items (*N* = 20 items) |
| Fine motor dexterity | Purdue Pegboard Test (PPT) | Preferred hand; non-preferred hand; both hands | Insert as many pegs and as quickly as possible in a board with holes | Number of pegs inserted in 30 seconds |
| Arm-hand dexterity | Minnesota Manual Dexterity Test (MMDT) | Preferred hand; non-preferred hand | Placing as many disks as possible and as quickly as possible in a board with several holes | Time spent to complete the task (*N* = 60 holes) |
| Motor coordination | Plate tapping (Eurofit Fitness Testing Battery) | Preferred hand; non-preferred hand | Moving one hand back and forth between two discs over the other hand in the middle, as quickly as possible | Time spent to complete the task (*N* = 25 taps) |
| Executive functions | Go/no-go | - | Press a key on go trials (red/yellow butterflies) and not press a key on no-go trials (red/yellow birds) | d'prime values (*N* = 100 items) |

| | | | | |
|---|---|---|---|---|
| | Simon task | - | Cartoon pictures containing both position and response information are presented with a rule that requires the participant to ignore the position and respond only to the relevant target feature (left/right arrow). The cartoon may appear on the same display as the correct response expected (congruent trial), or the cartoon position might conflict with the correct response (incongruent trial) | Simon Effect:<br>% of correct answers in the congruent trials - % of correct answers in the incongruent trials<br>(*N* = 80 items) |
| Emotion recognition | Prosody database: Castro & Lima (2010)<br>https://doi.org/10.3758/BRM.42.1.7.4 | Prosody | Stimuli were short sentences with emotionally neutral semantic content; six-alternative forced-choice decision for each stimulus: identify the expressed emotion from a list that included neutrality, anger, disgust, fear, happiness, and sadness | % of correct answers<br>(Hu scores)<br>(*N* = 60 items for each task) |
| | Vocalizations database: Lima et al. (2013)<br>https://doi.org/10.3758/s13428-012-0324-3 | Vocalizations | Stimuli consisted of brief vocal sounds without linguistic content; six-alternative forced-choice decision for each stimulus: identify the expressed emotion from a list that included neutrality, anger, disgust, fear, happiness, and sadness | |
| | Faces database: Karolinska Directed Emotional Faces<br>https://doi.org/10.1080/02699930701626582 | Faces | Stimuli consisted of colour photographs of actors; six-alternative forced-choice decision for each stimulus: identify the expressed emotion from a list that included neutrality, anger, disgust, fear, happiness, and sadness | |
| Emotional authenticity | Laughter and crying databases: adapted from Neves et al. (2018)<br>https://doi.org/10.1177/1747021817741800 | Laughter | Stimuli consisted of spontaneous and voluntary laughs; two-alternative forced-choice decision for each stimulus: identify if the expressed vocalization is spontaneous or voluntary | % of correct answers<br>(Hu scores)<br>(*N* = 24 items for each task) |
| | | Crying | Stimuli consisted of spontaneous and voluntary cries; two-alternative forced-choice decision for each stimulus: identify if the expressed vocalization is spontaneous or voluntary | |

| | | | | |
|---|---|---|---|---|
| Social behavior | Child Self-Regulation and Behaviour Questionnaire (CSBQ) | Subscales: sociability; prosocial; externalizing; internalizing; emotional self-regulation; behavioral self-regulation; cognitive self-regulation | Educator report questionnaire – Likert scale: 1 (not true) to 5 (certainly true) | Sum of items ($N$ = 33) |
| Empathy | Bryant Empathy Scale for Children | - | Self-report questionnaire (yes/no answer) | Sum of items ($N$ = 22) |
| Emotion comprehension | Test of Emotion Comprehension (TEC) | Domains: recognition of emotions; comprehension of external emotional causes; impact of desire on emotions; emotions based on beliefs; memory influence on emotions; possibility of emotion regulation; possibility of hiding an emotional state; having mixed emotions; contribution of morality to emotional experiences | The examiner presents nine short stories to the child, accompanied by drawings. Below the drawing for each vignette, its protagonist is portrayed with four out of five possible different emotion outcomes: “happy,” “sad,” “angry,” “scared,” or “neutral” | Sum of items ($N$ = 21) |

***Supplementary Table 2.*** Detailed Description of the Collected Measures: Control Measure of General Cognition and COVID-19 Lockdown Effects - White Rows; Near transfer Measures - Light Grey Rows; and Far transfer Measures - Dark Grey Rows.

|  |  |  | Effects |  | Model fit |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| **Domain** | **Model name** | **Nested** | **Fixed** | **Random over participants** | **AIC** | **BIC** | **LL** | **df** | **χ2** (df in parenthesis) | ***p*** |
| **Auditory** | A0 (null) | - | - | Intercept | 629.3 | 639.4 | -311.6 | 217 | - | - |
|  | A1 (1 main effect) | A0 | Time | Intercept | 438.1 | 451.7 | -215 | 216 | 193.17 (1) | < .001 |
|  | A2 (2-way interaction) | A1 | Time * Group | Intercept | 413.4 | 440.5 | -198.7 | 212 | 32.71 (4) | < .001 |
|  | A3 (3-way interaction) | A2 | Time * Group * Predisposition | Intercept | 346.7 | 394,2 | -159.4 | 206 | 78.64 (6) | < .001 |
|  | **A4 (3-way interaction + 1 main effect)** | **A3** | **Time * Group * Predisposition + COVID** | **Intercept** | **332.3** | **383.2** | **-151.1** | **205** | **16.44 (1)** | **< .001** |
| **Motor (fine)** | Mf0 (null) | - | - | Intercept | 629.3 | 639.5 | -311.7 | 217 |  |  |
|  | Mf1 (1 main effect) | Mf0 | Time | Intercept | 488.9 | 502.5 | -240.5 | 216 | 142.40 (1) | < .001 |
|  | Mf2 (2-way interaction) | Mf1 | Time * Group | Intercept | 416.3 | 443.4 | -200.1 | 212 | 80.64 (4) | < .001 |
|  | **Mf3 (3-way interaction)** | **Mf2** | **Time * Group * Predisposition** | **Intercept** | **328.4** | **375.9** | **-150.2** | **206** | **99.92 (6)** | **< .001** |
|  | Mf4 (3-way interaction + 1 main effect) | Mf3 | Time * Group * Predisposition + COVID | Intercept | 329.6 | 380.5 | -149.8 | 205 | 0.81 (1) | 0,37 |
| **Motor (gross)** | Mg0 (null)a | - | - | Intercept | 629.3 | 639.5 | -311.7 | 217 | - | - |
|  | Mg1 (1 main effect) | Mg0 | Time | Intercept | 446.0 | 459.5 | -219.0 | 216 | 185.37 (1) | < .001 |
|  | Mg2 (2-way interaction) | Mg1 | Time * Group | Intercept | 440.5 | 467.6 | -212.2 | 212 | 13.50 (4) | < .01 |
|  | **Mg3 (3-way interaction)** | **Mg2** | **Time * Group * Predisposition** | **Intercept** | **313.4** | **361.0** | **-142.7** | **206** | **139.02 (6)** | **< .001** |
|  | Mg4 (3-way interaction + 1 main effect) | Mg3 | Time * Group * Predisposition + COVID | Intercept | 314.7 | 365.6 | -142.3 | 205 | 0.79 (1) | 0,38 |
| **Inhibitory control** | IC0 (null) | - | - | Intercept | 524.1 | 534.3 | -259.1 | 217 | - | - |
|  | **IC1 (1 main effect)** | **IC0** | **Time** | **Intercept** | **398.4** | **412** | **-195.2** | **216** | **127.68 (1)** | **< .001** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | IC2 (2-way interaction) | IC1 | Time * Group | Intercept | 402.5 | 429.7 | -193.3 | 212 | 3.88 (4) | 0.42 |
| | IC3 (2 main effects) | IC1 | Time + COVID | Intercept | 399.7 | 416,7 | -194.9 | 215 | 0.71 (1) | 0.4 |
| **Interference** | I0 (null) | - | - | Intercept | 1764.2 | 1774,4 | -879.1 | 216 | - | - |
| | **I1 (1 main effect)** | **I0** | **Time** | **Intercept** | **1755.5** | **1769** | **-873.7** | **215** | **10.75 (1)** | **0.001** |
| | I2 (2-way interaction) | I1 | Time * Group | Intercept | 1761.6 | 1788.7 | -872.8 | 211 | 1.85 (4) | 0.76 |
| | I3 (2 main effects) | I1 | Time + COVID | Intercept | 1753,8 | 1770.7 | -871.9 | 214 | 3.67 (1) | 0.06 |
| **Emotion recognition in prosody** | ERp0 (null) | - | - | Intercept | -113.3 | -103.1 | 59,6 | 217 | - | - |
| | ERp1 (1 main effect) | ERp0 | Time | Intercept | -221.5 | -208 | 114.8 | 216 | 110.28 (1) | < .001 |
| | ERp2 (2-way interaction) | ERp1 | Time * Group | Intercept | -227.2 | -200 | 121.6 | 212 | 13.61 (4) | 0,008 |
| | **ERp3 (3-way interaction)** | **ERp2** | **Time * Group * Predisposition** | **Intercept** | **-343.9** | **-296.4** | **186** | **206** | **128.78 (6)** | **< .001** |
| | ERp4 (3-way interaction + 1 main effect) | ERp3 | Time * Group * Predisposition + COVID | Intercept | -345.6 | -294.7 | 187.8 | 205 | 3.65 (1) | 0,06 |
| **Emotion recognition in vocalizations** | ERv0 (null) | - | - | Intercept | -318.2 | -308.1 | 162.1 | 217 | - | - |
| | **ERv1 (1 main effect)** | **ERv0** | **Time** | **Intercept** | **-356.0** | **-342.4** | **182.0** | **216** | **39.77 (1)** | **< .001** |
| | ERv2 (2-way interaction) | ERv1 | Time * Group | Intercept | -351.7 | -324.5 | 183.8 | 212 | 3.68 (4) | 0,45 |
| | ERv3 (2 main effects) | ERV1 | Time + COVID | Intercept | -354.1 | -337.1 | 182.0 | 215 | 0.06 (1) | 0,81 |
| **Emotion recognition in faces** | ERf0 (null) | - | - | Intercept | -291.0 | -280.9 | 148.5 | 216 | - | - |
| | ERf1 (1 main effect) | ERf0 | Time | Intercept | -351.3 | -337.8 | 179.7 | 215 | 62.26 (1) | < .001 |
| | ERf2 (2-way interaction) | ERf1 | Time * Group | Intercept | -354.6 | -327.4 | 185.3 | 211 | 11.25 (4) | 0,02 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **ERf3 (2 main effects)** | **ERf2** | **Time + Group** | **Intercept** | **-356.9** | **-336.6** | **184.5** | **213** | **1.65 (2)** | **0,44** |
| | ERf4 (3 main effects) | ERf3 | Time + Group + COVID | Intercept | -356.2 | -332.5 | -185.1 | 212 | 1.30 (1) | 0,25 |
| **Emotional authenticity recognition in laughter** | EARl0 (null) | - | - | Intercept | 560.6 | 570.8 | -277.3 | 216 | - | - |
| | **EARl1 (1 main effect)** | **EARl0** | **Time** | **Intercept** | **548.0** | **561.6** | **-270.0** | **215** | **14.56 (1)** | **< .001** |
| | EARl2 (2-way interaction) | EARl1 | Time * Group | Intercept | 553.4 | 580.5 | -268.7 | 211 | 2.62 (4) | 0,62 |
| | EARl3 (2 main effects) | EARl1 | Time + COVID | Intercept | 549.7 | 566.6 | -269.8 | 214 | 0.36 (1) | 0,55 |
| **Emotional authenticity recognition in crying** | **EARc0 (null)** | **-** | **-** | **Intercept** | **475.2** | **485.4** | **-234.6** | **216** | **-** | **-** |
| | EARc1 (1 main effect) | EARc0 | Time | Intercept | 477.1 | 490.7 | -234.6 | 215 | 0.06 (1) | 0,81 |
| | EARc2 (1 main effect) | EARc0 | Group | Intercept | 478.8 | 495.7 | -234.4 | 214 | 0.43 (2) | 0,81 |
| | EARc3 (1 main effect) | EARc0 | COVID | Intercept | 475.6 | 489.2 | -233.8 | 215 | 1.54 (1) | 0,21 |
| **Social behavior** | SB0 (null) | - | - | Intercept | 239,5 | 249,7 | -116,7 | 217 | - | - |
| | SB1 (1 main effect) | SB0 | Time | Intercept | 220 | 233,5 | -106 | 216 | 21.54 (1) | < .001 |
| | SB2 (2-way interaction) | SB1 | Time * Group | Intercept | 218.9 | 246 | -101.4 | 212 | 9.08 (4) | 0,06 |
| | **SB3 (2 main effects)** | **SB1** | **Time + COVID** | **Intercept** | **200.8** | **217.7** | **-95.4** | **215** | **21.20 (1)** | **< .001** |
| **Empathy** | E0 (null) | - | - | Intercept | 1138.6 | 1148.8 | -566.3 | 217 | - | - |
| | **E1 (1 main effect)** | **E0** | **Time** | **Intercept** | **1116.4** | **1129.9** | **-554.2** | **216** | **24.22 (1)** | **< .001** |
| | E2 (2-way interaction) | E1 | Time * Group | Intercept | 1121.8 | 1149 | -552.9 | 212 | 2.51 (4) | 0,64 |
| | E3 (2 main effects) | E1 | Time + COVID | Intercept | 1116.9 | 1133.9 | -553.5 | 215 | 1.41 (1) | 0,23 |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| **Emotion comprehension** | EC (null) | - | - | Intercept | 833.38 | 843.55 | 413.69 | 216 | - | - |
|  | **EC1 (1 main effect)** | **EC0** | **Time** | **Intercept** | **758.01** | **771.57** | **-375** | **215** | **77.37 (1)** | **< .001** |
|  | EC2 (2-way interaction) | EC1 | Time * Group | Intercept | 760.76 | 787.87 | 372.38 | 211 | 5.25 (4) | 0,26 |
|  | EC3 (2 main effects) | EC2 | Time + COVID | Intercept | 759.69 | 776.64 | 374.85 | 214 | 0,3 | 0,57 |

Note. *N* total observations = 220; *N* subjects = 110; the selected model for each domain is shown in bold.

ⴕ *p* < .1; * *p* < .05; ** *p* < .01; *** *p* < .001 (Bonferroni-adjusted p-values); Significant *p*-values indicated in bold.
AIC – Aikake Information Criterion; BIC – Bayesian Information Criterion; LL – Loglikelihood; df – degrees of freedom; LR – Likelihood Ratio; X2 – Chi-square; Sig - Significance.

***Supplementary Table 3.*** Overview and model comparisons of the estimated models for near and far transfer domains.

| **Domain** | **Linear Mixed Model** | | | | | |
|---|---|---|---|---|---|---|
| | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
| **Auditory**<br>A4: Auditory skills ~ Time * Group * Predisposition + COVID + (1\|Participant)<br>Marginal / Conditional R2 = .71 / .88<br>Number of observations: 220; Participants: 110 | Intercept | 0.34 | 0.07 | [0.20; 0.48] | 4.69 (110) | **< .001** |
| | Time [ Post-test ] | 0.60 | 0.04 | [0.53; 0.67] | 16.47 (110) | **< .001** |
| | Group [ Control ] | 0.15 | 0.12 | [-0.09; 0.39] | 1.21 (110) | 0.45 |
| | Group [ Sports ] | -0.30 | 0.09 | [-0.47; -0.13] | -3.43 (110) | **0.002** |
| | Predisposition [ High ] | 0.64 | 0.07 | [0.50; 0.78] | 8.96 (110) | **< .001** |
| | COVID [ Without ] | 0.21 | 0.05 | [0.11; 0.31] | 4.21 (110) | **< .001** |
| | Time [ Post-test ] * Group [ Control ] | -0.02 | 0.06 | [-0.14; 0.11] | -0.25 (110) | 1.00 |
| | Time [ Post-test ] * Group [ Sports] | -0.15 | 0.04 | [-0.24; -0.06] | -3.35 (110) | **0.002** |
| | Time [ Post-test ] * Predisposition [ High ] | -0.08 | 0.04 | [-0.15; -0.01] | -2.12 (110) | **0.03** |
| | Group [ Control ] * Predisposition [ High ] | 0,19 | 0.12 | [-0.05; 0.43] | 1.53 (110) | 0.26 |
| | Group [ Sports ] * Predisposition [ High ] | -0.08 | 0.09 | [-0.26; 0.09] | -0.98 (110) | 0.66 |
| | Time [ Post-test ] * Group [ Control ] * Predisposition [High] | -0.08 | 0.06 | [-0.04; 0.21] | 1.32 (110) | 0.38 |
| | Time [ Post-test ] * Group [ Sports ] * Predisposition [ High ] | -0.05 | 0.04 | [-0.14; 0.03] | -1.17 (110) | 0.48 |
| | **Random effects** | **Variance** | **SD** | | | |
| | Participant (Intercept) | 0.17 | 0.41 | | | |
| | Residual | 0.12 | 0.34 | | | |

|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Motor (fine)**<br>Mf3: Fine-motor skills ~ Time * Group * Predisposition + (1\|Participant)<br>Marginal / Conditional R2 = .75 / .85<br>Number of observations: 220; Participants: 110 | Intercept | -0.00 | 0.04 | [-0.08; 0.07] | -0.12 (110) | 0,91 |
|  | Time [ Post-test ] | 0.62 | 0.03 | [0.57; 0.67] | 23.8 (110) | **< .001** |
|  | Group [ Control ] | -0.25 | 0.06 | [-0.37; -0.14] | -4.31 (110) | **< .001** |
|  | Group [ Sports ] | -0.19 | 0.06 | [-0.30; -0.08] | -3.44 (110) | **0,001** |
|  | Predisposition [ High ] | 0.40 | 0.04 | [0.32; 0.48] | 9.96 (110) | **< .001** |
|  | Time [ Post-test ] * Group [ Control ] | -0.23 | 0.04 | [-0.30; -0.15] | -5.95 (110) | **< .001** |
|  | Time [ Post-test ] * Group [ Sports] | -0.11 | 0.04 | [-0.18; -0.04] | -3.16 (110) | **0,004** |
|  | Time [ Post-test ] * Predisposition [ High ] | -0.13 | 0.03 | [-0.18; -0.08] | -5.06 (110) | **< .001** |
|  | Group [ Control ] * Predisposition [ High ] | -0.05 | 0.06 | [-0.17; 0.06] | -0.91 (110) | 0,72 |
|  | Group [ Sports ] * Predisposition [ High ] | 0.08 | 0.06 | [-0.03; 0.18] | 1.35 (110) | 0.36 |
|  | Time [ Post-test ] * Group [ Control ] * Predisposition [High] | 0.02 | 0.04 | [-0.05; 0.10] | 0.63 (110) | 1,00 |
|  | Time [ Post-test ] * Group [ Sports ] * Predisposition [ High ] | 0.05 | 0.04 | [-0.02; 0.13] | 1.51 (110) | 0.26 |
|  | **Random effects** | **Variance** | **SD** |  |  |  |
|  | Participant (Intercept) | 0.10 | 0.32 |  |  |  |
|  | Residual | 0.15 | 0.39 |  |  |  |

**Motor (gross)**

Mg3: Gross motor skills ~ Time * Group * Predisposition + (1|Participant)

Marginal / Conditional R2 = .76 / .87

Number of observations: 220; Participants: 110

| **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|
| Intercept | 0.00 | 0.04 | [-0.08; 0.08] | 0.05 (110.00) | 0,96 |
| Time [ Post-test ] | -0.68 | 0.02 | [-0.73; -0.63] | -28.03 (109.99) | **< .001** |
| Group [ Control ] | 0.11 | 0.06 | [-0.01; 0.22] | 1.86 (110.00) | 0.14 |
| Group [ Sports ] | 0.05 | 0.06 | [-0.06; 0.16] | 0.84 (110.00) | 0.80 |
| Predisposition [ High ] | -0.46 | 0.04 | [-0.54; -0.38] | -11.34 (110.00) | **< .001** |
| Time [ Post-test ] * Group [ Control ] | 0.14 | 0.04 | [0.07; 0.21] | 4.05 (109.99) | **< .001** |
| Time [ Post-test ] * Group [ Sports] | -0.07 | 0.03 | [-0.14; -0.01] | -2.11 (109.99) | 0.08 |
| Time [ Post-test ] * Predisposition [ High ] | 0.19 | 0.02 | [0.14; 0.24] | 7.87 (109.99) | **< .001** |
| Group [ Control ] * Predisposition [ High ] | 0.08 | 0.06 | [-0.04; 0.19] | 1.35 (110.00) | 0,36 |
| Group [ Sports ] * Predisposition [ High ] | -0.09 | 0.06 | [-0.20; 0.02] | -1.64 (110.00) | 0.20 |
| Time [ Post-test ] * Group [ Control ] * Predisposition [High] | -0.04 | 0.04 | [-0.10; 0.03] | -1.00 (109.99) | 0.62 |
| Time [ Post-test ] * Group [ Sports ] * Predisposition [ High ] | 0.00 | 0.03 | [-0.06; 0.07] | 0.05 (109.99) | 1.00 |
| **Random effects** | **Variance** | **SD** | | | |
| Participant (Intercept) | 0.11 | 0.34 | | | |
| Residual | 0.13 | 0.36 | | | |

|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Inhibitory control**<br>IC1: Inhibitory control ~ Time + (1\|Participant)<br>Marginal / Conditional R2 = .43 / .54<br>Number of observations: 220; Participants: 110 | Intercept | 2.30 | 0.04 | [2.22; 2.39] | 52.86 (110) | **< .001** |
|  | Time [ Post-test ] | 0.52 | 0.04 | [0.44; 0.59] | 14.31 (110) | **< .001** |
|  | **Random effects** | **Variance** | **SD** |  |  |  |
|  | Participant (Intercept) | 0.07 | 0.26 |  |  |  |
|  | Residual | 0.29 | 0.53 |  |  |  |

|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Interference**<br>I1: Interference ~ Time + (1\|Participant)<br>Marginal / Conditional R2 = .04 / .24<br>Number of observations: 219; Participants: 110 | Intercept | 12.06 | 0.98 | [10.13; 13.98] | 12.29 (109.68) | **< .001** |
|  | Time [ Post-test ] | -2.67 | 0.80 | [-4.23; -1.11] | -3.36 (109.47) | **0,001** |
|  | **Random effects** | **Variance** | **SD** |  |  |  |
|  | Participant (Intercept) | 36.38 | 6.03 |  |  |  |
|  | Residual | 138.39 | 11.76 |  |  |  |

|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Emotion recognition in prosody**<br>ERp3: Emotion recognition in prosody ~ Time * Group * Predispositions + (1\|Participant)<br>Marginal / Conditional R2 = .65 / .84<br>Number of observations: 220; Participants: 110 | Intercept | 0.49 | 0.01 | [0.47; 0.51] | 49.49 (110) | **< .001** |
|  | Time [ Post-test ] | 0,09 | 0.01 | [0.08; 0.10] | 15.92 (110) | **< .001** |
|  | Group [ Control ] | 0.00 | 0.01 | [-0.02; 0.03] | 0.33 (110) | 1.00 |
|  | Group [ Sports ] | -0.02 | 0,01 | [-0.05; 0.00] | -1.74 (110) | 0.16 |
|  | Predisposition [ High ] | 0.12 | 0.01 | [0.10; 0.14] | 11.85 (110) | **< .001** |
|  | Time [ Post-test ] * Group [ Control ] | 0.01 | 0.01 | [-0.01; 0.02] | 0.90 (110) | 0.74 |
|  | Time [ Post-test ] * Group [ Sports] | -0.02 | 0.01 | [-0.03; -0.00] | -2.20 (110) | 0.060 |
|  | Time [ Post-test ] * Predisposition [ High ] | -0.03 | 0.01 | [-0.04; -0.02] | -6.20 (110) | **< .001** |
|  | Group [ Control ] * Predisposition [ High ] | 0.01 | 0.01 | [-0.02; 0.04] | 0.63 (110) | 1.00 |
|  | Group [ Sports ] * Predisposition [ High ] | 0.02 | 0.01 | [-0.01; 0.04] | 1.24 (110) | 0.44 |
|  | Time [ Post-test ] * Group [ Control ] * Predisposition [High] | 0.01 | 0.01 | [-0.01; 0.02] | 0.72 (110) | 0.96 |
|  | Time [ Post-test ] * Group [ Sports ] * Predisposition [ High ] | -0.01 | 0.01 | [-0.02; 0.01] | -0.81 (110) | 0.84 |
|  | **Random effects** | **Variance** | **SD** |  |  |  |
|  | Participant (Intercept) | 0.01 | 0.08 |  |  |  |
|  | Residual | 0.01 | 0.08 |  |  |  |

|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Emotion recognition in vocalizations**<br>ERv1: Emotion recognition in vocalizations ~ Time + (1\|Participant)<br>Marginal / Conditional R2 = .12 / .44<br>Number of observations: 220; Participants: 110 | Intercept | 0.76 | 0.01 | [0.74; 0.77] | 87.58 (110) | **< .001** |
|  | Time [ Post-test ] | 0.04 | 0.01 | [0.03; 0.05] | 6.92 (110) | **< .001** |
|  | **Random effects** | **Variance** | **SD** |  |  |  |
|  | Participant (Intercept) | 0.00 | 0.07 |  |  |  |
|  | Residual | 0.01 | 0.09 |  |  |  |

|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Emotion recognition in faces**<br>ERf3: Emotion recognition in faces ~ Time + Group + (1\|Participant)<br>Marginal / Conditional R2 = .20 / .64<br>Number of observations: 219; Participants: 110 | Intercept | 0.71 | 0.01 | [0.70; 0.73] | 74.18 (110.22) | **< .001** |
|  | Time [ Post-test ] | 0.05 | 0.01 | [0.04; 0.06] | 9.13 (109.72) | **< .001** |
|  | Group [ Control ] | 0.01 | 0.01 | [-0.02; 0.03] | 0.40 (110.07) | 1.000 |
|  | Group [ Sports ] | -0.04 | 0.01 | [-0.06; -0.01] | -2.91 (110.54) | **0.008** |
|  | **Random effects** | **Variance** | **SD** |  |  |  |
|  | Participant (Intercept) | 0.01 | 0.08 |  |  |  |
|  | Residual | 0.01 | 0.08 |  |  |  |

| | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Emotional authenticity recognition in laughter**<br>EARl1: Emotional authenticity recognition in laughter ~ Time + (1\|Participant)<br>Marginal / Conditional R2 = .04 / .44<br>Number of observations: 219; Participants: 110 | Intercept | 1.54 | 0.07 | [1.40; 1.67] | 21.96 (110.31) | **< .001** |
| | Time [ Post-test ] | 0.18 | 0.05 | [0.09; 0.27] | 3.95 (109.89) | **< .001** |
| | **Random effects** | **Variance** | **SD** | | | |
| | Participant (Intercept) | 0.31 | 0.56 | | | |
| | Residual | 0.44 | 0.67 | | | |

| | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Emotional authenticity recognition in crying**<br>EARc0: Emotional authenticity recognition in crying ~ (1\|Participant)<br>Marginal / Conditional R2 = .00 / .14<br>Number of observations: 219; Participants: 110 | Intercept | 0.22 | 0.05 | [0.11; 0.32] | 4.20 (109.11) | **< .001** |
| | **Random effects** | **Variance** | **SD** | | | |
| | Participant (Intercept) | 0.07 | 0.27 | | | |
| | Residual | 0.43 | 0.66 | | | |

| | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
|---|---|---|---|---|---|---|
| **Social behavior**<br>SB3: Social behavior ~ Time + COVID + (1\|Participant)<br>Marginal / Conditional R2 = .18 / .87<br>Number of observations: 220; Participants: 110 | Intercept | 3.79 | 0.05 | [3.69; 3.88] | 76.34 (109.99) | **< .001** |
| | Time [ Post-test ] | 0.07 | 0.01 | [0.04; 0.09] | 4.88 (110.00) | **< .001** |
| | COVID [ Without ] | 0.24 | 0.05 | [0.14; 0.34] | 4.84 (109.99) | **< .001** |
| | **Random effects** | **Variance** | **SD** | | | |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  | Participant (Intercept) | 0.22 | 0.47 |  |  |  |
|  | Residual | 0.04 | 0.2 |  |  |  |
|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
| **Empathy** | Intercept | 12.82 | 0.23 | [12.37; 13.27] | 56.20 (110) | **< .001** |
| E1: Empathy ~ Time + (1\|Participant) | Time [ Post-test ] | 0.94 | 0.18 | [0.58; 1.29] | 5.21 (110) | **< .001** |
| Marginal / Conditional R2 = .09 / .30 | **Random effects** | **Variance** | **SD** |  |  |  |
| Number of observations: 220; Participants: 110 | Participant (Intercept) | 2.16 | 1.47 |  |  |  |
|  | Residual | 7.12 | 2.67 |  |  |  |
|  | **Fixed Effects** | **B** | **SE** | **95% CI** | ***t* (df)** | ***p*** |
| **Emotion comprehension** | Intercept | 18.52 | 0.11 | [18.31; 18.73] | 172.41 (109.64) | **< .001** |
| EC1: Emotion comprehension ~ Time + (1\|Participant) | Time [ Post-test ] | 0.81 | 0.08 | [0.66; 0.96] | 10.57 (109.31) | **< .001** |
| Marginal / Conditional R2 = .26 / .50 | **Random effects** | **Variance** | **SD** |  |  |  |
| Number of observations: 219; Participants: 110 | Participant (Intercept) | 0.63 | 0.79 |  |  |  |
|  | Residual | 1.28 | 1.13 |  |  |  |

*Note*. For each cue comparison, the reference condition is indicated in squared brackets; p-values for fixed effects calculated using Satterthwaite approximations.
∔ p < .1; * p < .05; ** p < .01; *** p < .001 (Bonferroni-adjusted p-values); Significant p-values indicated in bold.

***Supplementary Table 4.*** Parameters estimates of the final models.