Sound Cognition and Performance: From Mind to Meaning

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PREFACE

For the first time in Latvia, a dedicated scholarly volume has been published focusing specifically on research in systematic musicology. The XXIII issue of the academic journal *Mūzikas akadēmijas raksti (scriptamusica.lv)* brings together a collection of articles that reflect both the thematic diversity of the field and the cumulative research experience developed over time. This body of work is grounded in sustained scholarly collaboration, international networking, and the deliberate advancement of interdisciplinary approaches.

Research in systematic musicology is increasingly situated at the intersection of multiple domains, integrating the study of music perception and performance with insights from neurolinguistics, neuroscience, cognitive psychology, mathematics, biology, and related disciplines. Such an approach enables the investigation of complex research questions through the combined perspectives of several fields.

Accordingly, the participation of multiple authors within a single publication, as well as the recurrence of authors across different contributions, reflects an internationally recognized model of scientific collaboration. The studies included in this issue – authored by researchers from Latvia, Lithuania, Germany, Austria, and Switzerland – highlight both individual scholarly endeavors and interinstitutional research conducted within diverse academic networks.

The issue offers an evidence-based and thematically multilayered perspective on the processes of music perception, cognition, and cognitive processing, constituting a significant contribution to the advancement of contemporary systematic musicology. Its structure is conceptualized as a multi-level research framework – ranging from mechanisms of music perception and cognition to approaches in ear training, individual differences in neural processing of music, dimensions of musical development and well-being, as well as the interaction between music and neurotechnology.

The volume opens with two articles by **Markus Christiner** and **Christine Groß**, which examine the interrelationship between music and language perception and processing. Both contributions highlight the role of musical abilities in the discrimination of acoustic information and in the perception of unfamiliar speech. The first study, ***Examining the Relationship Between Musical Aptitude and Auditory Phonological Pattern Recognition in Single- and Multi-Speaker Language Contexts***, investigates listening conditions by comparing individuals operating in monolingual and multilingual contexts. The authors demonstrate that musical aptitude particularly enhances the precision of speech perception in situations requiring fine-grained acoustic discrimination. The second article, ***Turning into the Unknown: Exploring Individual Differences in Unfamiliar Speech Perception Across Groups***, adopts a multifactorial approach to examine how musical training, foreign language proficiency, socio-economic status, and neurodevelopmental conditions relate to the perception of unfamiliar speech across different age groups. Together, these contributions complement one another, offering a multi-perspective on the role of musical abilities in speech perception – both across varying listening conditions and within a broader framework of cognitive and social factors.

A novel conceptual perspective is introduced in the article ***From Ear Training to Cognitive Ear Training: Establishing the CETra Framework*** by **Valdis Bernhofs**, **Markus Christiner**, and **Christine Groß**, which examines the approach of Cognitive Ear Training (CETra). Within this framework, ear training is conceptualized as a multidimensional model integrating the development of perception, attention, memory, emotional regulation, decision-making, and creativity. The article establishes a theoretical bridge between research on perception and music processing, on the one hand, and questions of music education and musical development, on the other.

The perspective of individual differences is further advanced in the article ***The Impact of Multilingualism on Music Abilities*** by **Maria Schneider**, **Christine Groß**, and **Markus Christiner**, which explores the influence of multilingualism on musical abilities. The findings highlight the cognitive interplay between language and music, demonstrating that proficiency in multiple languages is positively correlated with music perception, singing quality, and foreign language pronunciation, regardless of educational background.

The perspective of neurodiversity is articulated in the volume in the article ***Neurodivergent Soundscapes: Profiling Musical Strengths in ADHD, ADD and Dyslexia*** by **Christine Groß**, **Bettina L. Serrallach**, **Valdis Bernhofs**, and **Markus Christiner**. This study conceptualizes the auditory neural profile as an integrated and complex system characterizing auditory and musical processing in individuals with neurodivergent development. Drawing on long-term research, the authors analyze structural and functional features of the auditory cortex, psychoacoustic and musical performance measures, as well as metacognitive self-assessment. Their findings demonstrate that musical abilities emerge from the interaction of perceptual precision, temporal processing, creative music-making, and self-reflection. The article positions auditory neural profiling as a significant tool for both future research and the development of inclusive music education.

The interaction between musical development and educational systems is examined in the article ***Harmonizing Growth: Exploring Musical Development Through Psychological Skill in Adolescent Education*** by **Tatjana Voitova**. The study highlights the importance of psychosocial skills in adolescent musical development, emphasizing their connection to mental health and well-being. The author analyzes the role of educational environments – particularly music education – in fostering psychosocial growth, describing the music education system in Latvia as a unique and sustainable context that significantly supports both musical and psychosocial development in youth.

With a focus on musical development and well-being, the volume continues with the article ***Linking Singing Skill Development to Life Satisfaction: Evidence from Boys' Choirs*** by **Reinis Maurītis** and **Valdis Bernhofs**. The findings indicate that structured choral singing promotes not only the development of musical skills but also subjective well-being, underscoring the socio-psychological significance of collective music-making.

The concluding section of the journal addresses the interaction between music, the brain, and technology. In ***Impact of Audiovisual Stimulation on Music Improvisation and EEG Hyperscanning: A Case Study***, **Jachin Edward Pousson** and **Mahrad Ghodousi** analyze the effects of audiovisual stimulation on creative improvisation and inter-brain synchronization using EEG hyperscanning. The issue concludes with ***Making Music with Brainwaves: Bridging Systematic Musicology and Neuroscience with Brain–Computer Music Interface Research*** by **Jachin E. Pousson** and **Valdis Bernhofs**, which explores the potential of brain–computer music interfaces as an emerging direction in both research and artistic practice. This work highlights the convergence of neuroscience and systematic musicology and proposes new perspectives for investigating musical performance and expression.

Taken together, the studies presented in this collection form a coherent narrative that positions sound as a core element of perception, cognition, mental development, and creative activity, demonstrating the multifaceted nature of music both as a field of scientific inquiry and as a fundamental dimension of human experience.

Valdis Bernhofs
Scientific Editor

PRIEKŠVĀRDS

Pirmo reizi Latvijā sistemātiskās mūzikas zinātnes pētījumiem tapis atsevišķs zinātnisks izdevums. Žurnāla *Mūzikas akadēmijas raksti* XXIII numurā apkopotie raksti atspoguļo gan jomas tematisko daudzpusību, gan ilgtermiņā uzkrāto pētniecības pieredzi, kuras pamatā ir pētnieku sadarbība, starptautiskie tīklojumi un mērķtiecīga starpdisciplināru pieeju attīstīšana. Sistemātiskās muzikoloģijas pētījumi arvien biežāk top dažādu kompetenču krustpunktā – savienojot mūzikas uztveres un muzicēšanas izpēti ar neirolingvistiku, neirozinātni, kognitīvo psiholoģiju, matemātiku, bioloģiju u.c. Šāda pieeja ļauj izvirzīto problēmjautājumu analizēt vairāku disciplīnu apvienojumā. Līdz ar to vairāku autoru līdzdalība vienā publikācijā un autoru atkārtošanās dažādos rakstos atbilst starptautiski atzītam zinātniskās sadarbības modelim. Krājumā ietvertie Latvijas, Lietuvas, Vācijas, Austrijas un Šveices autoru pētījumi raksturo gan individuālu autoru pētniecisko darbību, gan starpinstitucionālu pētniecību dažādos tīklojumos.

Krājums piedāvā uz pierādījumiem balstītu un tematiski daudzslāņainu skatījumu uz mūzikas uztveres, izziņas un kognitīvās apstrādes procesiem, veidojot nozīmīgu ieguldījumu mūsdienu sistemātiskās muzikoloģijas attīstībā. Tā struktūra konceptualizēta kā daudzpakāpju pētnieciska sistēma – no mūzikas uztveres un izziņas mehānismiem līdz dzirdes treniņa ietvariem, individuālajām atšķirībām mūzikas apstrādē smadzenēs, muzikālās attīstības un labbūtības dimensijām, kā arī mūzikas un neirotehnoloģiju mijiedarbībai.

Krājumu ievada divi **Markusa Kristinera** (*Markus Christiner*) un **Kristīnes Grosas** (*Christine Groß*) raksti, kuros analizēta mūzikas un valodas uztveres un apstrādes savstarpējā saikne. Abi raksti uzsver muzikālo spēju nozīmi akustiskās informācijas atšķiršanā un nepazīstamas runas uztverē. Pirmajā pētījumā ***Saistība starp muzikālajām spējām un dzirdes fonoloģisko struktūru atpazīšanu vienā un vairākās valodās runājošu indivīdu kontekstā*** (*Examining the Relationship Between Musical Aptitude and Auditory Phonological Pattern Recognition in Single- and Multi-Speaker Language Contexts)* analizēts klausīšanās konteksts, salīdzinot vienā un vairākās valodās runājošus indivīdus. Autori norāda, ka muzikālās spējas īpaši veicina valodas uztveres precizitāti situācijās, kur nepieciešama niansēta akustiskā atšķiršana. Savukārt otrajā pētījumā ***Saskarsme ar nezināmo: individuālo atšķirību izpēte nepazīstamas runas uztverē dažādās grupās*** (*Turning into the Unknown: Exploring Individual Differences in Unfamiliar Speech Perception Across Groups*) daudzfaktoru pieejā analizēta muzikālās izglītības, svešvalodu prasmju, sociālekonomiskā statusa un neiroattīstības traucējumu saistība ar nepazīstamas runas uztveri dažādās vecuma grupās. Abi raksti papildina viens otru, piedāvājot daudzdimensionālu skatījumu uz muzikālajām spējām valodas uztverē gan dažādos klausīšanās apstākļos, gan plašākā kognitīvo un sociālo faktoru kontekstā.

Jaunu konceptuālu perspektīvu piedāvā **Valda Bernhofa**, **Markusa Kristinera** un **Kristīnes Grosas** raksts ***No dzirdes treniņa uz kognitīvu orientētu dzirdes trenēšanu: CETra ietvara pamatojums*** (*From Ear Training to Cognitive Ear Training: Establishing *the CETra Framework*) kurā analizēta kognitīvā dzirdes treniņa (CETra) pieeja. Šajā pieejā dzirdes treniņš analizēts kā multidimensionāls modelis, kas integrē uztveres, uzmanības, atmiņas, emocionālās regulācijas, lēmumpieņemšanas un radošuma attīstību. Raksts veido teorētisku tiltu starp uztveres un mūzikas apstrādes pētījumiem un mūzikas izglītības un muzikālās attīstības jautājumiem.

Individuālo atšķirību perspektīvu turpina **Marijas Šnaideres** (*Maria Schneider*), **Kristīnes Grosas** un **Markusa Kristinera** raksts ***Daudzvalodības ietekme uz muzikālajām spējām*** (*The Impact of Multilingualism on Music Abilities*) par daudzvalodības ietekmi uz muzikālajām spējām. Pētījuma rezultāti uzsver valodas un mūzikas kognitīvo mijiedarbību, parādot, ka vairāku valodu pārvaldīšana pozitīvi korelē ar mūzikas uztveri, dziedāšanas kvalitāti un svešvalodu izrunu neatkarīgi no izglītības līmeņa.

Neirodaudzveidības perspektīvu krājumā iezīmē **Kristīnes Grosas**, **Betinas Seralahas** (*Bettina L. Serrallach*), **Valda Bernhofa** un **Markusa Kristinera** raksts ***Neirodiverģentas skaņainavas: muzikālā profila īpatnības personām ar UDHS, UDS un disleksiju*** (*Neurodivergent Soundscapes: Profiling Musical Strengths in ADHD, ADD and Dyslexia*), kurā dzirdes neirālais profils tiek aplūkots kā integrēta, kompleksa sistēma, kas raksturo dzirdes un mūzikas apstrādes īpatnības personām ar neiroatšķirīgu attīstību. Integrējot ilgtermiņa pētījumus, autori analizē dzirdes garozas strukturālās un funkcionālās īpatnības, psihoakustiskos un muzikālās izpildes rādītājus, kā arī metakognitīvo pašnovērtējumu, parādot, ka muzikālās spējas veidojas no uztveres precizitātes, temporālās apstrādes, radošas muzicēšanas un pašrefleksijas mijiedarbības. Raksts iezīmē dzirdes neirālo profilēšanu kā nozīmīgu instrumentu gan turpmākajos pētījumos, gan iekļaujošas mūzikas izglītības attīstībā.

Muzikālās attīstības un izglītības sistēmas mijiedarbes dimensiju analizē **Tatjanas Voitovas** raksts ***Harmoniska izaugsme: muzikālās attīstības izpēte caur psihosociālajām prasmēm pusaudžu izglītībā*** (*Harmonizing Growth: Exploring Musical Development Through Psychological Skill in Adolescent Education*), kurā izcelta psihosociālo prasmju nozīme pusaudžu muzikālajā attīstībā. Autore uzsver šo prasmju saistību ar jauniešu mentālo veselību un labbūtību, analizējot izglītības vides – īpaši mūzikas izglītības – nozīmi psihosociālās izaugsmes veicināšanā. Latvijas mūzikas izglītības sistēma šajā kontekstā tiek raksturota kā unikāla un ilgtspējīga vide, kas būtiski ietekmē jauniešu muzikālo un psihosociālo attīstību.

Ar fokusu uz muzikalitātes attīstību un labbūtību seko **Reiņa Maurīša** un **Valda Bernhofa** raksts ***Dziedāšanas prasmju attīstības saikne ar dzīves apmierinātību: pētījums zēnu koros*** (*Linking Singing Skill Development to Life Satisfaction: Evidence from Boys' Choirs*) par dziedāšanas prasmju attīstības saistību ar dzīves apmierinātību zēnu koru kontekstā. Pētījuma rezultāti liecina, ka strukturēta kora dziedāšana veicina gan muzikālo prasmju attīstību, gan subjektīvo labbūtību, izgaismojot muzicēšanas sociāli psiholoģisko nozīmi.

Žurnāla noslēguma sadaļa pievēršas mūzikas, smadzeņu un tehnoloģiju mijiedarbībai. **Džeikina Pūsona** un **Mahrāda Godūsi** (*Jachin Edwards Pousson*, *Mahrad Ghodousi*) rakstā ***Audiovizuālās stimulācijas ietekme uz muzikālo improvizāciju: EEG hiperskenēšanas gadījuma izpēte*** (*Impact of Audiovisual Stimulation on Music Improvisation and EEG Hyperscanning: A Case Study*) analizēta audiovizuālās stimulācijas ietekme uz radošu improvizāciju un starpsmadzeņu sinhronizāciju, izmantojot EEG hiperskenēšanas metodi. Krājumu noslēdz **Džeikina Pūsona** un **Valda Bernhofa** raksts ***Mūzikas radīšana ar smadzeņu viļņiem: tilts starp sistemātisko muzikoloģiju un neirozinātni smadzeņu–datora mūzikas saskarnes pētījumos*** (*Making Music with Brainwaves: Bridging Systematic Musicology and Neuroscience with Brain–Computer Music Interface Research*), kurā analizēts smadzeņu-datora mūzikas saskarņu potenciāls kā jauns pētniecības un mākslinieciskās prakses virziens, iezīmējot neirozinātnes un sistemātiskās muzikoloģijas jomu saplūšanu un piedāvājot jaunas perspektīvas muzikālā izpildījuma un muzikālās izteiksmes izpētē.

Kopumā krājumā apkopotie pētījumi veido vienotu naratīvu par skaņu kā uztveres, kognīcijas, mentālās attīstības un radošas darbības kodolu, apliecinot mūzikas jomas daudzpusību gan zinātniskajā izpētē, gan tās nozīmi cilvēka attīstības un pieredzes izpratnē.

Valdis Bernhofs,
sastādītājs un zinātniskais redaktors

EXAMINING THE RELATIONSHIP BETWEEN MUSICAL APTITUDE AND AUDITORY PHONOLOGICAL PATTERN RECOGNITION IN SINGLE- AND MULTI-SPEAKER LANGUAGE CONTEXTS

Markus Christiner, Christine Groß

Research has demonstrated that musical aptitude is closely associated with a range of linguistic abilities, highlighting the interrelation between these two faculties. Musicians are often characterized by fine-grained auditory skills that emerge through both innate aptitude and systematic training. Consequently, an increasing body of research has shown that individuals with advanced musical skills tend to outperform those with lower musical proficiency across several cognitive domains, most notably in the acquisition of foreign languages. This advantage is particularly evident in early stages of language learning, when learners must rely primarily on acoustic parameters before fully establishing connections to semantic context.

We sought to determine whether fine-grained auditory abilities underlie the relationship between musical aptitude and language performance in initial learning contexts, particularly when learners are exposed to unfamiliar linguistic material. We examined whether musical aptitude is differentially related to language performance by contrasting a *Single-Speaker* task, which places high demands on fine-grained auditory discrimination, with a *Multi-Speaker* task, which introduces greater variability in auditory input and relies less on precise auditory acuity.

Musical aptitude measures were strongly interrelated and showed the expected gradient of association with speech tasks (stronger in Single-Speaker vs. weaker in Multi-Speaker conditions). The findings suggest that musical aptitude plays a pivotal role in contexts where refined auditory discrimination is required. The findings suggest that musical aptitude plays a pivotal role in contexts where refined auditory discrimination is required. By contrast, in settings involving multiple speakers and languages, its influence weakens substantially and appears to play a minor role.

Keywords: musical aptitude, language aptitude, fine-grained auditory skills, musicality

1. INTRODUCTION

Musical aptitude has garnered increasing interest over the past decade, not only within music research but also across various other scientific domains. This growing attention can be attributed to multiple factors, including the suggestion that understanding the underlying components of musical aptitude may also illuminate processes in other cognitive areas (Christiner 2020, 12-13). Therefore, understanding the underlying dimensions of musical aptitude could provide valuable insights for developing new approaches to facilitate learning processes, not only within the musical domain but also in related cognitive areas.

Generally speaking, aptitude is defined as a complex ability that predicts high achievement and represents an individual's inherent potential within a specific domain (Jørgensen 2008). It distinguishes individuals who are predisposed to perform above their peers in that area (Gagné 2004; Gagné 2008). According to aptitude research, this potential transforms into talent when an individual actively engages in relevant activities. Aptitude manifests and stabilizes more readily at younger ages but can still be observed and assessed in adults by measuring the speed of new skill acquisition (Gagné 2004, 2).

Musically gifted individuals possess enhanced auditory discrimination abilities, enabling them to detect subtle differences in pitch and rhythm within musical sequences (Seither-Preisler, Parncutt and Schneider 2014, 10938). They also tend to perform superiorly in other music-related domains that are crucial for high-level musical performance, such as selective attention and inhibitory control (Joyal et al. 2024, 166). Consequently, musical aptitude measures encompass a range of tasks designed to capture how quickly and accurately individuals perceive, discriminate, and remember musical elements fundamental to auditory processing. Therefore, musical aptitude assessments typically evaluate consonance/dissonance discrimination, pitch contour/harmonic perception, style recognition, melody memory, and sensitivity to loudness/pitch/intensity (Bentley 1966; Gordon 1967; Gordon 1979; Gordon 1982; Gordon 1989; Law 2012; Law and Zentner 2012; Seashore 1919; Seashore 1919; Wallentin et al. 2010). Most common measures, however, focus on melody/rhythm via same-different discrimination of unfamiliar sequences such as the *Advanced Measures of Music Audiation* (*AMMA*) developed by Edwin Gordon (Gordon 1989, 1-3).

Following the discussion on musical aptitude and its measurement, it becomes evident that language aptitude measures share numerous similarities, both in the underlying cognitive processes involved – such as auditory discrimination, memory, and pattern recognition – and in the methodologies employed to assess these aptitudes. Consequently, research indicates that the productive, perceptual and processing mechanisms engaged in musical and linguistic aptitudes overlap significantly, suggesting a potential transfer and interplay between these domains (Christiner et al. 2021; Christiner and Reiterer 2013; Christiner and Reiterer 2019; Coumel et al. 2023; Milovanov 2009; Milovanov and Tervaniemi 2011; Patel 2007). Language aptitude assessments frequently employ unfamiliar tasks designed to evaluate not only the accuracy but also the speed of language acquisition, thus providing a comprehensive measure of an individual's efficiency in acquiring new languages. The *VORD* test utilizes an artificial language structurally similar to Turkish, which typologically differs considerably from Western European languages (Parry and Child 1990, 3-5). In contrast, the *LLAMA* test employs a made-up language based on Central American languages, designed to be language-neutral and applicable to a target audience with diverse native languages (Meara 2005, 2-4). Additionally, the *High-Level Language Aptitude Battery* includes subsections assessing phonemic discrimination with Hindi stimuli, an English pseudo-contrastive test, and phonemic categorization with Russian stimuli, targeting participants from varied linguistic backgrounds (Doughty et al. 2008, 15-17). Given the fine-grained auditory skills required for these tasks, it is unsurprising that empirical evidence consistently shows strong associations between musicality and early foreign language acquisition. For instance, studies have shown that musical ability is associated with duration perception in speech (Chobert et al. 2014), speech segmentation (François et al. 2013), speech perception (Christiner 2020) , speech processing (Besson, Chobert and Marie 2011), pronunciation accuracy (Christiner et al. 2023; Christiner, Bernhofs and Groß 2022; Christiner, Rüdegger and Reiterer 2018) and the capacity to mimic foreign accents (Coumel et al. 2023).

Collectively, research demonstrates a robust correlation between musical aptitude and phonetic proficiency, particularly in contexts requiring the discrimination of highly similar or unfamiliar auditory stimuli. Such demands are characteristic of foreign language acquisition, where learners must discern subtle phonetic contrasts. The transfer of musical aptitude to linguistic ability thus appears most salient when precise auditory discrimination is essential for distinguishing linguistic units like words and phrases (Christiner and Groß 2025, 12-13). This scenario is often encountered at the onset of language learning or in controlled instructional environments where a single foreign language instructor delivers input. Conversely, in naturalistic settings, especially within European multilingual contexts where multiple speakers and languages coexist, the reliance on fine-grained auditory discrimination – and thus the influence of musical aptitude – may be attenuated.

We aimed to investigate whether musical aptitude is differentially associated with language tasks that demand fine-grained auditory processing compared to tasks where such detailed discrimination is less critical. To this end, we designed a task wherein a single speaker articulates a sequence of different words or phrases in an unfamiliar language, followed by a response prompt. Participants are required to determine whether the response was present in the sequence (*Single-Speaker condition*). This task primarily engages fine-grained auditory processing skills and has been shown in previous research to be strongly associated with musical aptitude (Christiner and Groß 2025, 11). Conversely, we developed a complementary task characterized by reduced demands on fine-grained auditory discrimination. In this task, multiple speakers produce sequences in different languages, and participants must again decide if the response was part of the sequence (*Multi-Speaker condition*). This paradigm introduces greater variability in auditory input and thus relies less on nuanced auditory acuity for successful performance.

We hypothesized that the advantage conferred by musical aptitude would be especially pronounced in situations demanding fine-grained auditory discrimination, as musical aptitude is closely linked to enhanced auditory resolution and timing skills that facilitate the detection of subtle acoustic differences crucial in such contexts. Conversely, we hypothesized that conditions involving multiple speakers would show a weaker or no association with musical aptitude.

2. METHODS

2.1 Participants

We recruited 349 participants through online platforms, schools, and universities, providing them with information about the eligibility criteria they needed to meet. First, participants should neither speak nor comprehend Tagalog, Mandarin, Farsi, Turkish, or Japanese as a second, third, or foreign language. This should simulate a foreign language learning setting in initial learning stages when individuals listen to unfamiliar utterances that they retain for a short period. This should ensure that participants had no prior knowledge about any of the languages included in the research design. The mean age of the participants was 25.22 years (SD = 12.1); 212 were female, 133 were male, and 4 indicated a non-binary gender.

2.2 Testing procedure

The entire testing procedure was conducted online. Participants were provided with individualized login credentials to access the study platform. Initially, they completed a questionnaire assessing their linguistic and musical background. This information confirmed that none of the participants spoke any of the languages included in the experiment and provided additional details regarding their musical training and experience. Subsequently, participants performed the language task, followed by the assessment of musical aptitude. Both the language and musical tasks included familiarization trials that participants could repeat at their discretion. After the familiarization phase, each experimental trial was presented only once.

2.3 Musical aptitude

The AMMA test (Advanced Measures of Music Audiation, Gordon 1989) was utilized to evaluate participants' music perception abilities. This test presented participants with pairs of musical statements, prompting them to identify whether these pairs were identical or exhibited rhythmic or tonal differences. Rhythmic variations included changes in tempo, meter, or duration, while tonal differences involved discrepancies in a few notes between the two statements. The melodies are played on the piano and based on Western harmony. Compared to many newer musicality measures, the AMMA test's complex and lengthy sequences suggest it assesses a combination of musical skills. The test comprised 33 items, with participants completing three practice trials followed by 30 experimental trials. Of these, 10 pairs were identical, 10 differed rhythmically, and 10 differed tonally. The order of presentation for the trials was randomized. For the analysis in this study, we used the composite score (AMMA total) that consists of the results of all trials.

2.4 Auditory phonological pattern recognition

The auditory phonological pattern recognition task used in this study comprises language strings that are either spoken by a single speaker (*Single-Speaker condition*), or by multiple speakers (*Multi-Speaker condition*) encompassing different speakers and languages. Each string contains eight, ten, or twelve constituents or phrases, with complexity depending on the task level. The length of these constituents varies between one and eleven syllables. After listening to a given string, participants are presented with one, two, or three comparison phrases and must decide whether these phrases appear within the original string. Each correct identification contributes one point to the participant's score, forming the core scoring mechanism. The test included five languages: Tagalog, Mandarin, Farsi, Turkish, and Japanese. In the Single-Speaker condition, five trials were presented for each language, ensuring that all participants were exposed to multiple examples from every language. Typological differences among the languages played only a minor role (Christiner et al. 2023), the inclusion of several linguistically diverse languages primarily served to enhance the reliability of the measure. In total, the test includes 12 *Multi-Speaker items* and 25 *Single-Speaker* items. In the *Single-Speaker* language condition, more fine-grained auditory processing abilities are required compared to the *Multi-Speaker* condition where such detailed auditory discrimination is less critical.

This difference arises from the varying nature of linguistic cues in each condition. In the *Multi-Speaker* condition, the diversity of languages and speakers provides many distinctive cues, enabling listeners to recognize phrases using broader, less detailed auditory information. Conversely, the *Single-Speaker* condition demands heightened sensitivity to subtle phonetic and prosodic details within a single linguistic system, requiring more precise auditory analysis to distinguish similar elements.

3. RESULTS

3.1 Statistical analysis

First, we present the descriptive statistics of the two language measures and the AMMA test. Subsequently, we conducted correlational analyses to examine the relationship between these variables. We wanted to determine whether musical aptitude is more strongly associated with the Single-Speaker condition than with the Multi-Speaker condition.

3.2 Descriptives

Table 1 below presents the means and standard deviations of the main variables under consideration.

Table 1 represents the descriptive of the variables

Variables	***Mean (M)***	***Standard Deviation (SD)***
Multi-Speaker total	*7.23*	*2.19*
Single-Speaker total	*16.39*	*3.08*
AMMA Score	*51.68*	*8.91*

3.3 Correlational analysis

The correlational analysis indicates that musical aptitude is significantly associated with both language variables. Importantly, the relationship with the fine-grained *Single-Speaker* condition, which required highly detailed auditory processing abilities, was considerably stronger than with the *Multi-Speaker* condition, in which such auditory precision played a less critical role (see Table 2 for the values).

Table 2 shows the correlational analysis for the variables under consideration

	Multi-Speaker total	*Single-Speaker total*	*AMMA Score*
Multi-Speaker total		*0.413 *****	*0.130**
Single-Speaker total			*0.349****

$p < 0.05$ (uncorrected, two-tailed). $p < 0.01$ (uncorrected, two-tailed).*

4. DISCUSSION

The results of the correlational analyses demonstrated significant associations between musical aptitude and both language perception conditions. Notably, as hypothesized, the strength of this relationship was greater in the fine-grained (*Single-Speaker*) condition, which requires highly detailed auditory discrimination abilities. This suggests that musical aptitude, likely through enhanced auditory resolution and temporal processing skills, plays a more critical role where precise perception of subtle acoustic cues is necessary. In contrast, the *Multi-Speaker* condition, characterized by greater linguistic variability and multiple speaker cues, may allow for more reliance on broader, less specific auditory information, resulting in a comparatively weaker correlation. These findings indicate that musical aptitude is differentially associated with performance depending on the auditory processing demands of the linguistic context.

The *Single*-*Speaker* condition in our study, characterized by the presence of a single language, places strong demands on fine-grained auditory processing. The phonological pattern recognition task of this study parallels musical aptitude tests by employing novel stimuli (melodies or phonological sequences) that require pure acoustic processing and engaging similar cognitive mechanisms (sound classification, pattern recognition, memory). This could indicate a relationship between music and auditory phonological processing (Christiner and Groß 2025, 12)**.** Similar relationships have been established by extensive interdisciplinary research demonstrating substantial overlap between the neural and cognitive mechanisms underlying music and speech processing (Asaridou and McQueen 2013; Ding et al. 2017; Patel 2007; Patel 2011; Peretz et al. 2015; Perrachione et al. 2013; Rogalsky et al. 2011; Wong et al. 2007). Enhanced musical perception and musical aptitude correlate with improved speech perception abilities (Besson, Chobert and Marie 2011; Chobert et al. 2014; Christiner et al. 2022; Coumel et al. 2023; François et al. 2013; Ho, Cheung and Chan 2003; Moreno 2009; Wong and Perrachione 2007), including duration perception (Chobert et al. 2014), speech segmentation (François et al. 2013), pitch discrimination relevant to tone-syllables (Christiner et al. 2022), and general speech processing (Besson, Chobert and Marie 2011). Most studies have focused on fine-grained perceptual abilities, which aligns well with the findings of our study.

The findings of this study have significant implications for understanding the intersection between musical aptitude and language perception. One important implication of our study is that the *Single-Speaker* condition closely resembles typical foreign language learning environments, where often a single teacher delivers instruction. In such settings, individuals with higher musical aptitude clearly demonstrate an advantage in discriminating novel linguistic input, presumably due to their enhanced fine-grained auditory processing skills. This demonstrates that the design of learning systems and the structure of learning environments, particularly in the context of foreign language learning, influence the cognitive demands placed on learners, thereby facilitating or hindering the learning process. Another crucial aspect is that musical aptitude plays a significant role in initial foreign language acquisition but may be less important in later stages. For instance, research has shown that unfamiliar language material perceived as more melodic tends to be retained, memorized, and retrieved more quickly (Christiner et al. 2021, 9-10). Consequently, raising participants' awareness not only of the musical features inherent in languages but also of the benefits of their own musical abilities for early learning processes may be essential to facilitate faster acquisition of the phonetic elements of new language material.

In the *Multi-Speaker* condition, the presence of multiple languages and different speakers provides a wider array of distinctive cues, allowing listeners to rely on coarse-grained or global perceptual markers for phrase segmentation and identification. This reduces the reliance on fine-grained auditory discrimination, as specific speaker- and language-specific features serve as anchoring points. Consequently, musical aptitude appears to be less predictive of speech perception performance in contexts featuring multiple speakers and languages. This scenario predominates outside structured educational environments, suggesting that musical abilities may be less critical for language perception and acquisition in naturalistic, multilingual communicative settings.

To date, there are no known studies that have investigated or compared perceptual performance related to musical aptitude across tasks involving two distinct speech conditions: *Single-Speaker* versus *Multi-Speaker* and multi-language environments, specifically with adult speakers for whom all languages were unintelligible. Although this study does not allow drawing causal conclusions based on the correlational analysis, our results shed light on critical discrepancies between laboratory testing conditions and real-world language learning settings. Specifically, they underscore the necessity of reintegrating experimental paradigms with ecological validity to better translate scientific findings into practical applications. In addition, the results of our study have important implications for both language and music research. They underscore the need for more nuanced experimental designs that incorporate contrasting conditions –

such as the *Multi-Speaker* versus *Single-Speaker* speech environments employed in our study – to more comprehensively delineate the benefits as well as the limitations of musical aptitude. Such an approach facilitates the development of a detailed taxonomy categorizing positive, neutral, and negative effects of musical ability on language perception and learning. By broadening the scope of investigation beyond homogeneous conditions, future research can better capture the complex interactions between musical skills and language processing in ecologically valid contexts.

5. CONCLUSION

Our study shows that musical aptitude is closely related to initial foreign language ability due to fine-grained auditory skills that facilitate faster memorization of unfamiliar utterances. The results of this study suggest that, in contexts characterized by greater linguistic variability and multiple speaker cues, listeners may rely on broader, less specific auditory information, thereby reducing the strength of the observed association between musicality and auditory–phonological ability. Therefore, this study not only substantiates the close interrelation between musical and language aptitude but also delineates the specific learning contexts in which musical aptitude proves most advantageous for language acquisition, as well as those in which its influence is more limited. This nuanced understanding facilitates a systematic identification of conditions under which positive transfer effects from music to language are maximized and when they are diminished. By clarifying these contextual boundaries, the findings contribute to a more precise framework for future research and practical applications aimed at leveraging musical skills to enhance language learning outcomes.

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SUMMARY

This study explores the intricate relationship between musical aptitude and foreign language learning, emphasizing the pivotal role of fine-grained auditory skills. Musical aptitude, shaped by innate ability and systematic training, equips individuals with superior auditory discrimination, which significantly benefits the early stages of language acquisition, particularly when learners are exposed to unfamiliar linguistic material. The research contrasts language performance in contexts requiring precise auditory discrimination, represented by a *Single-Speaker* task, with more variable *Multi-Speaker* settings that offer broader and less specific auditory cues. Findings reveal that musical aptitude strongly correlates with language performance in the *Single-Speaker* condition, highlighting its role in supporting fine auditory discrimination skills critical for memorization and processing of novel utterances. Conversely, this correlation weakens in *Multi-Speaker* scenarios, where linguistic variability and multiple speaker cues reduce dependence on detailed auditory acuity.

These results not only reinforce the close interrelation of musical and language aptitudes but also elucidate the contextual boundaries in which musical aptitude influences language learning. By clarifying the specific environments where positive transfer from musical skills to linguistic proficiency is maximized or diminished, this study provides a nuanced framework for understanding how musicality can be leveraged in language education. The findings underscore the necessity for future research to adopt ecologically valid experimental designs that reflect real-world multilingual communication settings, enabling the development of targeted interventions that harness musical abilities to enhance language acquisition outcomes effectively.

This comprehensive understanding contributes to advancing theoretical knowledge and practical applications, situating musical aptitude as a significant but context-dependent facilitator of language learning success.

SAISTĪBA STARP MUZIKĀLAJĀM SPĒJĀM UN DZIRDES FONOLOĢISKO STRUKTŪRU ATPAZĪŠANU VIENĀ UN VAIRĀKĀS VALODĀS RUNĀJOŠU INDIVĪDU KONTEKSTĀ

Markuss Kristiners, Kristīne Grosa

KOPSAVILKUMS

Pētījumā analizētas sarežģītā saikne starp muzikālajām spējām un svešvalodu apguvi, īpašu uzmanību pievēršot audiālajām prasmēm. Muzikālās spējas, ko veido gan iedzimti priekšnosacījumi, gan sistemātiska pilnveide, nodrošina augstāku akustiskās informācijas atšķiršanas līmeni. Tas būtiski veicina valodas apguves sākumposmu, īpaši saskaroties ar nepazīstamu lingvistisko materiālu. Pētījumā raksturotas valodas snieguma atšķirības dažādās situācijās – tad, ja nepieciešama precīza akustiskas informācijas atšķiršana (viena runātāja uzdevums), kā arī situācijas, kurās pastāv lielāka daudzveidība (t.s. daudzvalodības apstākļi) ar mazāk specifiskiem audiāliem signāliem.

Raksta autori norāda, ka muzikālās spējas cieši korelē ar valodas sniegumu viena runātāja apstākļos, uzsverot muzikālo spēju nozīmi tādas niansētas dzirdes informācijas uztveršanā un apstrādē, kas ir būtiska jaunu valodas izteikumu iegaumēšanai un apstrādei. Savukārt daudzvalodu pratēju situācijās šī korelācija samazinās, jo lingvistiskā dažādība un dažādie runātāju signāli mazina atkarību no dzirdes uztveres precizitātes.

Pētījuma rezultāti ne tikai apstiprina ciešo saikni starp muzikālajām un valodas spējām, bet arī atklāj kontekstuālās robežas, kurās muzikālās spējas ietekmē valodu apguvi. Precizējot apstākļus, kuros muzikālo prasmju pozitīvā pārnese uz lingvistisko kompetenci tiek pastiprināta vai, tieši pretēji, vājināta, pētījums analizē muzikālo spēju lomu valodu apguvē.

Rezultāti uzsver nepieciešamību turpmākajos pētījumos izmantot ekoloģiski derīgus eksperimentālos dizainus, kas atspoguļo reālās daudzvalodīgās komunikācijas situācijas. Tas ļaus izstrādāt mērķtiecīgas pieejas, kurās muzikālās spējas tiek efektīvi izmantotas valodu apguves veicināšanai.

Šī visaptverošā izpratne paplašina gan teorētiskās zināšanas, gan praktiskās lietojuma iespējas, pozicionējot muzikālās spējas kā nozīmīgu, taču kontekstatkarīgu faktoru veiksmīgā valodu apguvē.

TURNING INTO THE UNKNOWN: EXPLORING INDIVIDUAL DIFFERENCES IN UNFAMILIAR SPEECH PERCEPTION ACROSS GROUPS

Christine Groß, Markus Christiner

Research has shown that speech perception ability can vary tremendously depending on mechanisms such as musical ability, musical status second, and/or foreign language capacity. In this study, we wanted to assess individual differences in unfamiliar speech perception (auditory phonological pattern recognition) across diverse groups (children with and without musical training, adolescents and adults with varying levels of foreign language proficiency, with different degrees of musical ability and individuals with ADHD). Our sample consists of 724 participants (including N=56 individuals with ADHD) who voluntarily participated in this study. We divided the participants into different groups according to age (N=77 children; N=171 adolescents; N=476 adults), language and music background and tested them for their ability to perceive unfamiliar languages, as well, we assessed their musical background, their foreign language capacity, their educational status, the educational status of the parents and gender. Our study reveals that musical training has an impact on unfamiliar speech perception across ages. In adolescence, the impact of foreign language capacity and musical training seems to be of equal importance, while in adulthood, musical training surpasses foreign language capacity, particularly in comparison to adolescents. Individuals with ADHD showed reduced speech perception performance, suggesting potential challenges in early foreign language perception that warrant further investigation. In addition, SES based on parental education has been identified as a good predictor to outline individual differences in speech perception. However, current socioeconomic status does not significantly correlate with adult language perception; rather, childhood SES remains the primary determinant of these linguistic variations.

Keywords: foreign language perception; musicality; socio-economic status (SES); children; adolescents; adults; ADHD, musicians;

1. INTRODUCTION

Research on individual differences in learning foreign languages has focused on multiple domains, such as cognitive abilities (e.g., working memory, short-term memory) (Baddeley 2003; Baddeley 2010), personality traits (e.g., extraversion, anxiety) (Dörnyei and Ushioda 2013), social factors (motivation, peer interaction) (Dönyei and Ryan 2015; Dörnyei and Skehan 2003), and aptitude measures (Wen 2012; Wen et al. 2019; Wen and Skehan 2011). Foreign language learning is shaped by a mix of cognitive abilities (such as musicality), environmental factors (such as socio-economic status or SES), and prior linguistic experience (such as extensive foreign language capacity). Previous studies have shown that both musical training and musical aptitude, as well as extensive experience with foreign languages, can facilitate the learning of additional languages (Christiner 2020; Christiner and Groß 2025), suggesting perceptual benefits in processing novel linguistic input. These group differences were particularly pronounced when contrasting neurotypical participants with those diagnosed with ADHD, consistent with prior research on auditory processing differences (Groß et al. 2022; Groß et al. 2023). In this study, we examine the role of socioeconomic status (SES), musicality, and extensive foreign language capacity, as well as ADHD-related differences, shape learners' ability to discriminate between unfamiliar languages, drawing on research linking acoustic, cognitive, and experiential factors across music and language learning.

In the early stages of foreign language learning, acoustic signals are particularly important for successful acquisition. At this stage, utterances are often limited in linguistic content (i.e. lexicon and grammar), and therefore resemble melody learning where acoustic contours dominate. (Christiner et al. 2021). Research has shown that musical skills– particularly singing, – are associated with performance in pronunciation tasks involving unfamiliar languages that simulate learning situations for the acquisition of new vocabulary and phrases (Christiner et al. 2022; Franco et al. 2021; Christiner et al. 2018; Christiner et al. 2021; François et al. 2013). Evidence further suggests that singing ability is directly linked to generating intelligible unfamiliar utterances (Christiner et al. 2023), remembering new vocabulary (Ludke, Ferreira and Overy 2014) and pronouncing unfamiliar languages (Christiner 2020; Christiner et al. 2023; Christiner and Renner et al. 2022). In addition, measures of singing ability – such as direct singing performance tasks and self-assessed singing ability – have been associated with the capacity to imitate foreign accents convincingly (Coumel et al. 2023). Research on children further shows that participation in singing activities and vocal play promotes the development of advanced vocal abilities. (Calì 2017; Christiner and Reiterer 2018; Franco et al. 2021; Thiessen and Saffran 2009), Accordingly, individuals who sing frequently during childhood appear to retain a certain degree of vocal plasticity for producing new sounds and unfamiliar languages in adult life (Christiner, Bernhofs and Groß 2022). On the contrary, singing ability and singing performance rarely explain individual differences in unfamiliar foreign language perception tasks (Christiner, Bernhofs and Groß 2022; Coumel et al. 2023). In light of previous research, the benefits of singing appear to depend on at least two factors. First, singing may enhance sensorimotor ability and integration of vocal-motor skills that support various forms of vocalization (Christiner, Bernhofs and Groß 2022; Christiner and Renner et al. 2022). Second, melodic structure mayfunction as a mnemonic device or a memory booster that facilitates memory for linguistic material. (Christiner et al. 2021; Christiner and Renner et al. 2022).

Perceptual research on the overlaps between music and language has shown that musical training improves speech processing and speech perception (Besson, Chobert and Marie 2011; François et al. 2013; Kraus and Chandrasekaran 2010; Thompson, Schellenberg and Husain 2004). In this respect, findings have shown that musical ability influences foreign language proficiency, particularly in the subtle aspects such as the ability to perceive tonal features of languages (Christiner and Renner et al. 2022) and to segment speech (François et al. 2013). Segmentation of speech patterns is most difficult for learners of foreign languages in the initial stages. They often lack the ability to recognize where utterances begin or end (Patel 2007). As musicians have a sense for rhythmical structures, this may be another fundamental reason why musical capacity is associated with the ability to segment speech (François et al. 2013). Musicians' enhanced pitch perception skills also equip them with an advantage in perceiving non-native lexical tones (Alexander, Wong and Bradlow 2005) and unfamiliar languages more effectively (Christiner 2020).

As outlined, musicians display enhanced auditory processing of both music stimuli (melody/rhythm recognition) (Benner et al. 2017) and speech sounds (Polat and Ataş 2014), while neurodevelopmental conditions such as ADHD (Groß et al. 2023) and dyslexia (Christiner and Serrallach et al. 2022; Groß et al. 2022; Serrallach et al. 2016) are associated with challenges in similar tasks (e.g., melody discrimination, word memory).

Research on musicians and language has provided evidence that musical training and musical ability improve language-related functions across multiple domains. From a linguistic perspective, individuals who grow up speaking two or more languages – or who acquire multiple languages during their lives –may share similarities with musicians from a linguistic perspective (Christiner and Groß 2025). In particular, they appear to show advantages in learning new languages (Papagno and Vallar 1995). Researchers distinguish between early and late bilinguals. What they have in common is the generally accepted notion that both early and late bilingualism, as well as multilingualism, can enhance the ability to acquire novel phonological forms (Hell and Mahn 1997; Kaushanskaya and Marian 2009; Papagno and Vallar 1995). It is widely recognized that age plays a crucial role in language acquisition, with earlier exposure to additional languages typically leading to superior outcomes (Johnson and Newport 1989; Lenneberg 1967). Language learners typically apply L1 segmentation strategies, which create perceptual difficulties and transfer errors (Patel 2007). Similarly, they often substitute unfamiliar target sounds with similar native phonemes, or struggle to perceive and produce non-native contrasts (Werker and Tees 2005). Critically, phonetic ability has been argued to be the only linguistic capacity governed by a strict critical period (Moyer 2014), though subsequent research has challenged this view. A relatively low number of individuals can reach native-like foreign language proficiency when they are adults (Selinker 1972). Individuals who learn a second or third language after their first language – such as successive and late bi- and multilinguals, as well as polyglots –have been found to benefit from familiar phonemic inventories and seem to learn further languages faster (Hell and Mahn 1997; Kaushanskaya and Marian 2009; Papagno and Vallar 1995). Therefore, studies also found that the number of foreign languages is related to new word learning and foreign accent imitation (Christiner 2020; Christiner et al. 2021; Hell and Mahn 1997; Papagno and Vallar 1995).

Individual differences in language skills are also associated with differences in social status. As such, socioeconomic status constitutes a key dimension that reflects an individual's access to economic and social resources as well as their social standing, and it is closely associated with educational and academic attainment (Hauser and Warren 1997; Li, Xu and Xia 2019; Szabó, Polonyi and Abari 2019). The influence of SES on language ability extends across a lifespan, from childhood to adulthood, and continues to affect academic performance. (Hoff 2013). Differences in language abilities between children from high- and low-SES backgrounds reflect disparities in both the quantity and quality of language exposure (Calvo and Bialystok 2014; Cartmill et al. 2013; Huttenlocher et al. 2010; Rowe 2018).

Building on our previous research and findings, we propose that individuals with musical training and extensive foreign language capacity demonstrate superior performance compared to individuals without musical training (Q1) and without extensive foreign language capacity (Q2) in tasks related to language discrimination ability. Given evidence of challenges in auditory processing among individuals with ADHD, we hypothesize differences in language perception performance between individuals with and without ADHD (Q3). Our research design also integrates singing self-estimation criteria and the average weekly singing frequency as variables. We hypothesize that none of these singing-related variables will exhibit a significant association with the perception of unfamiliar speech (Q4). We hypothesize that parental SES influences participants' language abilities but not necessarily their educational attainment. (Q5). Although three age groups (children, adolescents, and adults) were included in the present study, the design was not intended as a longitudinal lifespan investigation. Rather, the age groups were compared cross-sectionally to explore whether the influence of musical training, foreign language capacity, socioeconomic status, and ADHD differs across developmental stages. Accordingly, the findings should be interpreted as cross-sectional comparisons rather than evidence of developmental trajectories.

2. MATERIALS AND METHODS

2.1. Participants

We recruited 724 participants who participated voluntarily in this study. All participants were native speakers of German. A small subgroup reported a bilingual upbringing (see respective group descriptions below). None of the participants reported prior exposure to or proficiency in any of the unfamiliar target languages used in the speech perception task (Tagalog, Mandarin, Farsi, Japanese). We divided the participants into different groups according to age, language, and music background. Participants who did not match any of our descriptors and did not finish the entire testing battery were excluded from the analysis. Participants reported normal hearing and no history of diagnosed hearing impairments. Individuals with known neurological or auditory disorders were excluded from participating. A formal audiometric screening was not conducted. As we have defined several variables, we have compiled a list of abbreviations to facilitate understanding (see table 1).

Table 1. List of abbreviations.

Abbreviation	Meaning
EFL	Extensive Foreign Language Capacity
NoEFL	Without Extensive Foreign Language Capacity
MT	Musical Training
NoMT	Without Musical Training
PME	Professional Musical Education

2.1.1. Children

77 participants were children between 11 and 12 years of age (M= 11.36; SD = 0.48). Within the children group 39 participants, (children NoMT), reported to have never been trained in a musical instrument for a longer period, while 38 participants (children MT) had received formal musical training for more than 2 years in a row before testing took place. In addition, the children were only trained in English as a foreign language.

2.1.2. Adolescents

The group of adolescents consisted of 171 individuals aged 13-17 years (M= 15.64; SD = 1.18). The adolescents were divided into different groups based on their musical experience and foreign language capacity. The participants were categorized as adolescents with or without musical training when they fulfilled the following criteria. The adolescents without musical training did not receive any formal musical training for any musical instrument or had not received singing lessons before testing took place. Learning the recorder in school was not considered musical training, excluding those who reported playing the recorder consistently for more than two consecutive years prior to testing. Additionally, the participants without musical training reported that they were unable to play a musical instrument and had not learned one through either formal or informal instruction. In contrast, the adolescent participants were categorized as having musical training if they had played a musical instrument regularly for more than two consecutive years prior to testing.

The participants were also distinguished according to their foreign language capacity. All adolescents received training in foreign languages. All of them received training in English. Participants were classified as adolescents with extensive spoken foreign language training and could comprehend at least 3 languages at a high level. This could mean that they were able to master two foreign languages besides their mother tongue at a B2 or C1 level, or, this included a few participants who grew up (N=4) with two mother tongues and spoke one or more foreign languages at a B2 or C1 level. The collection of language proficiency data was facilitated through an online questionnaire, capturing participants' self-reported language skills.

All participants were asked in the questionnaire whether they had previously received a clinical diagnosis of Attention Deficit Hyperactivity Disorder (ADHD). A subgroup reported a prior clinical diagnosis and was assigned to the ADHD group accordingly. No additional diagnostic assessments were conducted within the framework of the present study. ADHD has a worldwide prevalence of approximately 5% (Polanczyk et al. 2007), which explains the presence of individuals with ADHD in a large and heterogeneous sample. The prevalence citation is provided for contextualization only and does not reflect group assignment procedures. The ADHD group neither consisted of individuals who played a musical instrument for a longer period nor who had mastered more foreign languages besides English. According to the above description, the adolescents were divided into adolescents without musical training with no extensive foreign language training (NoMT+NoEFL; N=39), adolescents with musical training with no extensive foreign language training (MT+NoEFL; N= 31), adolescents with musical training and extensive foreign language capacity (MT+EFL; N=42), adolescents without musical training but with extensive foreign language capacity (NoMT+EFL; N= 30) and adolescents possessing ADHD (N= 29).

2.1.3. Adults

The categorization of adult participants followed a similar approach to that used for adolescents. The age group of adult participants included individuals (N=476) between the ages of 19 and 69 (M= 30.79; SD = 11.87). They were also grouped according to both their musical background and their foreign language proficiency. The participants were categorized as adults with or without musical training when they fulfilled the following criteria. Adult participants without musical training had not undergone any formal instruction in any musical instrument or had not received any singing lessons prior to the testing sessions. Learning the recorder in school was also not considered as musical training for the adult participants. Additionally, the participants without musical training reported t being unable to play a musical instrument and not having received in either formal or informal instruction. Musicians who no longer train or play instruments, often referred to as “sleeping musicians”, were excluded from this study, because they could not be classified in a meaningful category.

Adult participants were categorized as having musical training if they had played a musical instrument regularly for more than three years, including at least some practice within the last five years prior to testing time. In addition, a further subcategory of participants was introduced for the adults who were professional musicians. As professional musicians, we considered participants who had either a minimum of four years’ experience performing regularly in public as orchestra members, had completed at least six semesters of music studies, or, had worked as music educators. Furthermore, the participants were differentiated based on their foreign language proficiency. All adults underwent foreign language training. Participants were categorized as adults with extensive foreign language training if they had demonstrated proficiency in speaking and could comprehend at least three languages at a high level. This implies that participants were considered to have extensive foreign language proficiency if they were able to master at least two foreign languages, in addition to their mother tongue, at the B2 or C1 level. Additionally, it encompassed a subgroup of participants (N=12) who grew up with bilingual backgrounds and who had achieved a B2 or C1 level in one or more foreign languages. We did not further divide the professional participants based on their language proficiency, as this would have resulted in groups that were e too small. To assess group differences between professional musicians with and without extensive foreign language experience, we performed an independent *t*-Test which outlined no significant differences between the two groups. The results are provided in the supplementary material (see table S1). In addition, a subgroup of adults reported a prior clinical diagnosis of ADHD. As in the adolescent sample, inclusion in the ADHD group was based on self-reported prior clinical diagnosis collected via questionnaires. The ADHD group included neither participants with extended musical training nor participants who had mastered additional foreign languages beyond English at a high level.According to the above description, we had six different groups: adults without musical training with no extensive foreign language capacity (NoMT+NoEFL; N=73), adults with musical training with no extensive foreign language training (MT+NoEFL; N= 58), adults with professional musical education (PME; N=49); adults with musical training and extensive foreign language (MT+EFL; N=154); adults with extensive foreign language without musical training (NoMT+EFL; N= 115) and adults with ADHD (N= 27).

2.2. Speech perception measurement

We used an adapted and short version of a previously developed speech perception task – specifically assessing auditory pattern recognition ability for unfamiliar speech (Christiner, Bernhofs and Groß 2022; Coumel et al. 2023; Groß et al. 2023). Therefore, we selected languages (Tagalog, Mandarin, Farsi, Japanese) which are rarely spoken in Europe and neither spoken, comprehended, nor learnt by the participants of this study. The perception task simulated language learning situations in which learners receive speech input lacking semantic content. This measure parallels musical aptitude assessments, which assume that the stimuli (e.g., a specific melody) are unfamiliar to the participants.. During the test condition of the speech perception task, participants were instructed to listen to a sequence of speech strings, each consisting of eight different words or short phrases, then provide a response. This response was either present or absent from the preceding string that the participants had heard. Each utterance of the string is separated by a short pause of 50 milliseconds, while the response is separated from the string by a longer pause of two seconds and is further signaled by a change in screen color. After listening to a stimulus, participants were asked to indicate whether or not the response was present in the stimulus they had just heard. If the response was part of the string, participants should click the correct button. Conversely, if the response was not part of the string, participants must click the wrong button. The response may vary, encompassing either a single utterance or up to three utterances.

In cases where a response contained more than one utterance, it was scored as correct only if all the utterances from the presented string were included. The tasks consisted of 20 items, with 0.05 points awarded for each correct response, yielding a maximum possible score of 1.

The experiment was conducted online. Participants were instructed to complete the task in a quiet environment using headphones. Auditory stimuli were presented via a standardized online platform. Although listening conditions could not be fully controlled detailed instructions were provided to ensure comparable testing conditions across participants.

2.3. Questionnaire

To gather background information, we administered an online questionnaire that inquired about the music, singing, language, and educational backgrounds of the participants. The questionnaire encompassed the music and language parameters as delineated in accordance with our group divisions. Furthermore, we included questions about their self-estimated singing abilities and the average number of hours they spent singing each week. The participants had to decide which of the descriptors described their singing ability best. These were "very poor", "poor", "average", "good" and "very good". We used these singing variables as previous research outlined that all variables were associated with and reflect the participants singing ability (Christiner 2020; Coumel et al. 2023).

We also collected the educational status of the participants and of their parents. We utilized parental educational backgrounds as a measure to evaluate the socioeconomic status (SES) of the participants. Therefore, we followed the classification of UNESCO. The demarcation between low and high SES is established at the ISCED-97 level 3a, which corresponds to A-levels and/or their equivalents. This implies that participants with parents whose educational status fell below level 3a were categorized as belonging to the low SES group, whereas those at level 3a and above were categorized as high SES (OECD 1999). We followed previous research and decided on the following. If at least one of the parents possessed an educational level exceeding 3a, the participants were classified as high SES. Conversely, if both parents had completed their highest level of education below 3a, the participants were categorized as low SES. For completeness, in the adult group 16 parents did not provide their educational status. According to these descriptions, in the children's group, 47 belonged to high SES and 30 to low SES, in the adolescents' group, 93 belonged to the high SES and 78 to the low SES group, while 300 of the adults belonged to high SES and 160 to low SES.

2.4. Statistical analyses

Statistical analyses were carried out separately for all three groups. We performed two-way ANOVAs for all groups to provide information about the role of musical classification and SES status regarding the dependent variable, perceptual language ability. For the adult participants, we ran a second two-way ANOVA using participants' educational status as a measure of SES as a comparison. Before conducting the two-way ANOVA, we first examined the correlation between musical status and socioeconomic status (SES) to assess whether a significant association existed between these factors. The correlation analysis indicated no significant positive relationship, supporting the assumption that musical status and SES are independent factors in our dataset.

Additionally, to ensure comparable and balanced groups among adults and adolescents, a random sampling procedure was applied during group formation. This procedure produced consistent results across samples, further validating the robustness and appropriateness of the two-way ANOVA for our analysis. Furthermore, gender was assessed as t-tests. Since previous research showed that gender had no influence on the perceptual language measures (Christiner 2020; Coumel et al. 2023; Groß et al. 2023), we provided them only in the supplementary material for transparency reasons (see table S2).

Additionally, we conducted correlational analyses between the speech perception measure and the singing variables, specifically, singing hours and singing self-estimation. Previous research has indicated an association between singing and foreign language pronunciation skills. However, we did not observe a relationship between singing variables and perceptual foreign language skills in previous study (Christiner, Bernhofs and Groß 2022).

3. RESULTS

3.1. Statistical results children

A two-way ANOVA was performed to provide information about the role of musical classification and SES status with regard to the dependent variable the perceptual language ability (see figure 1). The results of the two-way ANOVA revealed a significant main effect for the language perception score, showing a group difference between the participants when they are divided into high ($N= 47$) and low SES ($N= 30$); ($F(3, 76) = 7.97$, $p = 0.006$, partial $\eta 2 = 0.24$: High SES group ($M = 0.61$, $SD = 0.12$) than for the low SES group ($M = .58$, $SD = 0.12$). There was also a significant main effect for musical classification ($F(3, 76) = 7.11$, $p = 0.011$, partial $\eta 2 = 0.22$). The results revealed that children with musical training (children MT; $M = 0.60$, $SD = 0.019$); performed significantly better than the children without musical training (children NoMT; $M = 0.54$, $SD = 0.018$). However, there was no significant interaction between the musical classification of the children and the SES status ($F(3, 76 = 0.19$, $p = 0.66$; partial $\eta 2= 0.007$).

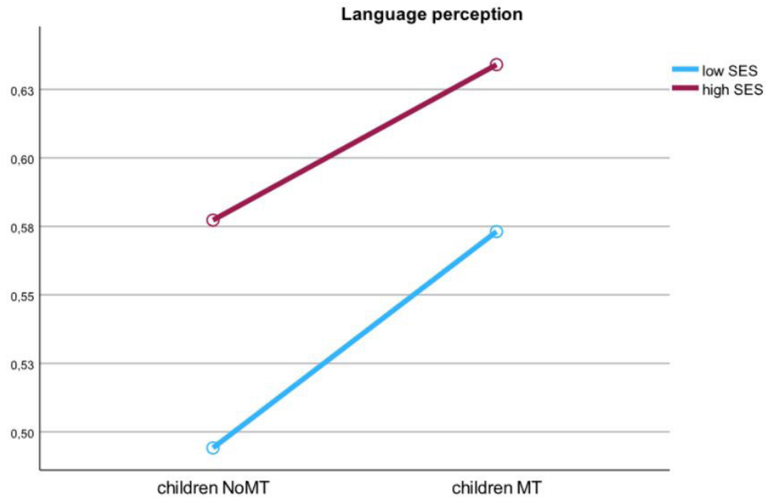

Figure 1 illustrates the mean values of the language perception measurement of the two groups (children with and without musical training) divided into high and low SES.

3.2. Statistical results adolescents

The statistical analyses of the adolescents included a two-way ANOVA to assess group differences for the music and language classification as well as the SES status (see figure 2). The results of the two-way ANOVA revealed a non-significant main effect for the language perception score, showing a group difference among the participants when they are divided into high (N= 93) and low SES (N= 78); ($F(9, 170) = 2.5$, $p = 0.117$, partial $\eta 2 = 0{,}006$. Despite the non-significant result, the means are higher for the High SES group ($M = 0.64$, $SD = 0.12$) than for the low SES group($M = .59$, $SD = 0.12$).

There was, however, a significant main effect for musical classification ($F(9, 170) = 8.81$, $p = 0.001$, partial $\eta 2 = 0.32$. As we had unequal group sizes, Gabriel-corrected post-hoc analysis was applied (see table S3). The results revealed that adolescents with musical training and no extensive foreign language training performed best (MT+NoEFL; $M = 0.67$, $SD = 0.11$), followed by adolescents with musical training and extensive foreign language capacity (MT+EFL; $M = 0.66$, $SD = 0.12$), adolescents without musical training and with extensive foreign language capacity (NoMT+EFL; $M = 0.64$, $SD = 0.10$), adolescents without musical training and no foreign language training (NoMT+NoEFL; $M = 0.57$, $SD = 0.12$) and individuals possessing ADHD (ADHD; $M = 0.52$, $SD = 0.11$). The difference was only significant between the groups with and without musical training. However, there was no significant interaction between the musical classification and the SES status ($F(9, 170) = 0.86$, $p = 0.49$; partial $\eta 2 = 0.04$.

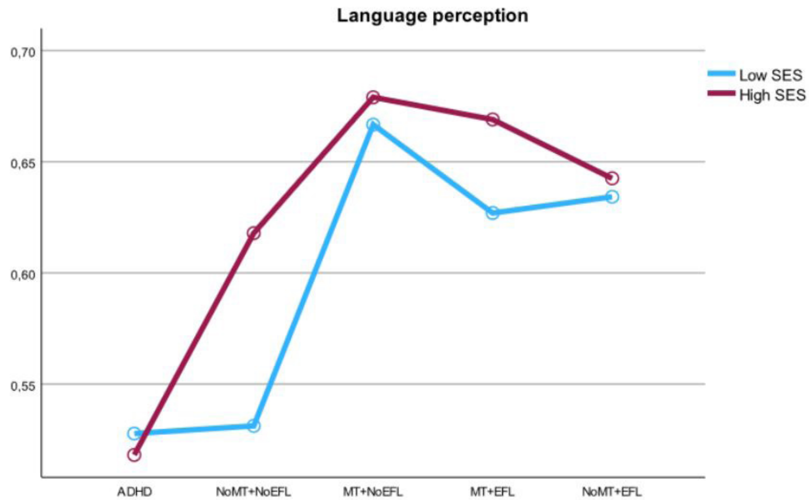

Figure 2 illustrates the mean values of the language perception measurement of the adolescents separated into high and low SES.

3.3. Statistical results adults

The statistical analyes of the adults follows the same rational idea than what we did for the adolescents. First, we performed a two-way ANOVA to assess group differences for the music and language classifications as well as the SES status based on parental education. In addition, we performed a second two-way ANOVA in which we replaced the parental SES of the participants by the participants own SES status to be able to compare both (compare with section 4 and figure S1 in the supplementary material).

The results of the two-way ANOVA revealed a significant main effect for the language perception score, showing a group difference among participants when they are divided into high and low SES ($F(11, 459) = 4.97$, $p = 0.026$, partial $\eta2 = 0.11$: High SES ($M = 0.68$, $SD = 0.12$ and low SES ($M = 0,64$, $SD = 0.12$).

There was also a significant main effect for musical classification ($F(11, 459) = 12.32$, $p = 0.001$, partial $\eta2 =0.23$). As we had unequal group sizes, Gabriel-corrected post-hoc analysis was applied (see table S4). The results revealed that adults with professional musical education performed best (PME; $M = 0.73$, $SD = 0.12$), followed by the adults with extensive foreign language and musical training (MT+EFL; $M = 0.70$, $SD = 0.11$) the adults with musical training with no extensive foreign language training (MT+NoEFL; $M = 0.69$, $SD = 0.10$), the adults with extensive foreign language without musical training (NoMT+EFL; $M = 0.64$, $SD = 0.10$), the adults without musical training with no extensive foreign language training (NoMT+NoEFL; $M = 0.62$, $SD = 0.14$) and the ADHD group (ADHD; $M = 0.54$, $SD = 0.10$). The difference was significant comparing the ADHD group to all other groups. In addition, the difference was also significant between the groups with and without musical training. However, there was no significant interaction between the musical classification and the SES status ($F(9, 459) = 0.59$, $p = 0.71$; partial $\eta2= 0.14$).

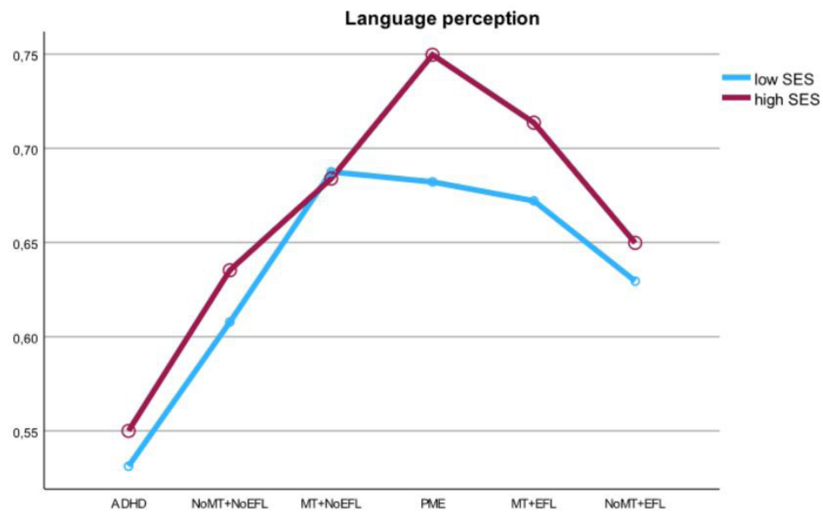

Figure 3 illustrates the mean values of the language perception measurement of the adult groups separated into high and low SES. Note that the PME group was not divided into individuals with and without EFL as the group would have been too small. We provided a t-test in the supplement showing that within the PME group, no differences between individuals with and without EFL were detected (see supplement table S1).

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3.4. Correlations of the language and singing variables for all groups

Previous studies have suggested a link between singing and the ability to pronounce foreign languages, but in previous research we did not find a link between singing factors and perceptual foreign language ability. This is why we also performed correlations between the language perception variable and the singing self-estimation variable and the amount individuals sang on average a week (see table 2).

Table 2 shows the correlations of the language perception measurement and the singing variables for the children group

	Singing hours per week	**Self estimation Singing**
Perceptual language ability		
children	0.032	-0.025
adolescents	0.078	0.066
adults	-0.001	0.049
Singing hours per week		
children	1	0.306**
adolescents	1	0.365**
adults	1	0.439**

*$p < 0.05$ (uncorrected, two-tailed). ** $p < 0.001$ (uncorrected, two-tailed).

4. DISCUSSION

The present study intentionally adopted an integrative, multifactorial design to examine the relative contribution of musical training, foreign language capacity, socio-economic status (SES), and ADHD within a unified framework. While each of these predictors could be investigated independently, our aim was to assess their comparative and combined influence on unfamiliar speech perception across age groups.

The outcomes of our study reveal that across the lifespan, the ability to discriminate against unfamiliar speech material is influenced by factors such as musical training/status, foreign language ability, and socioeconomic status (SES). In addition, as hypothesized, neither the amount of singing nor self-estimated singing ability was associated with speech perception performance. In light of the findings of this study, we will discuss the following aspects in more detail. First, we will shortly discuss singing and speech perception (Q4). Second, we will discuss the benefits of perceptual musical skills from the perspective of musicians and individuals with ADHD (Q1 and Q3). Third, we will discuss the impact of speaking more languages on a high level and its advantage related to the ability to discriminate against unfamiliar languages (Q2). Fourth, we will discuss the influence of SES on language ability also in the context of critical age factors (Q5).

Singing Variables and Speech Perception (Q4)

We included two singing variables in the research design, a self-estimation variable, and the amount of singing on average in a week. While musical training/status has been a predictive variable for explaining individual differences in unfamiliar speech perception, we observed that singing variables appear to be less effective in predicting perceptual language variables such as auditory pattern recognition. Previously, proficient singers showed enhanced musical discrimination and pronunciation skills, but no improvement in language perception (Christiner, Bernhofs and Groß 2022). Similar findings exist for professional musicians. Singers outperformed instrumentalists in foreign language pronunciation (Christiner and Reiterer 2015) showing that singing is a highly sensory training transferable to other forms of vocalization. As hypothesized (Q4), singing variables showed no association with speech perception. This null result carries important educational implications: while most music and language training prioritizes perceptual skills, curricula should equally emphasize productive abilities to foster comprehensive development.

Musical Training and ADHD (Q1 & Q3)

Perceptual studies examining the intersection of music and language have revealed that musical training can enhance both speech processing and speech perception (Besson, Chobert and Marie 2011; François et al. 2013; Kraus and Chandrasekaran 2010; Thompson, Schellenberg and Husain 2004). The present study confirms musical training's perceptual benefits for unintelligible foreign language material. Musically trained participants across all age groups outperformed controls in these language perception tasks. As expected, ADHD participants (adolescents and adults) showed reduced performance in language perception tasks compared to controls. Previous neurophysiological research has demonstrated that individuals with ADHD may show atypical auditory processing patterns, including alterations in early auditory evoked responses such as the P1 component (Christiner and Serrallach et al. 2022; Groß et al. 2022; Serrallach et al. 2016). These findings indicate differences in early-stage auditory processing in clinical populations. Although no neurophysiological measures were collected in the present study, the lower behavioral performance observed in the ADHD group is consistent with prior reports of auditory processing differences. However, the current data do not allow direct conclusions regarding underlying neural mechanisms (Serrallach et al. 2016).

Foreign Language Capacity (Q2)

The adolescent and adult participants were also divided into musically naïve participants with and without extensive foreign language capacity. Through extensive foreign language training, we mean that they spoke at least three languages at an advanced level. (Q2). The findings of the adolescents have shown that musically naïve participants with extensive foreign language capacity could not be distinguished from the two groups who were musically trained, while in the adult group, the professional musicians and the musically trained participants with extensive foreign language capacity performed significantly better than the adult group without musical training and extensive foreign language capacity (please compare figures 2 and 3 and tables S3 and S4).

It could be suggested that extensive foreign language and musical training both have a significant effect on the ability to discriminate against unfamiliar languages. However, the impact of extensive foreign language experience seems more pronounced during adolescence, whereas in adulthood, musical training appears to be the stronger predictor of such perceptual abilities. This finding also corresponds to the literature available. Scholars have proposed that phonetic ability is the only linguistic capacity subject to a critical period, typically declining after puberty (Moyer 2014). It is widely accepted that multilingual speakers are accustomed to perceiving and differentiating between diverse phonemes, which benefits them when encountering unfamiliar languages (Hell and Mahn 1997; Kaushanskaya and Marian 2009; Papagno and Vallar 1995). Individuals who speak more foreign languages are exposed to a broader range of acoustic features across languages. This exposure can make them more familiar with various sound patterns and accents, allowing them to adapt more quickly to novel phonetic structures (Spinu, Hwang and Vasilita 2023; Tremblay and Sabourin 2012). Thus, foreign language learning may exert an effect on perceptual skills, among others, comparable in strength to that of musical training during adolescence.

Although it is generally accepted that phonetic ability diminishes after puberty, a low number of individuals can reach native-like foreign language proficiency when they are adults (Selinker 1972). Professional musicians may fall into this category. Comparable to children and adolescents, adult musicians seem to retain a certain plasticity to adapt novel phonetic structures rather fast (Christiner 2020; Christiner and Reiterer 2013; Christiner and Reiterer 2015). Our findings of overlapping musical and speech perception abilities across the lifespan align with neuroscience evidence showing that lifelong musical training preserves musicianship-specific cortical characteristics – such as enhanced auditory cortex gyrification and broader network activation during tone perception – despite age-related atrophy (Rus-Oswald et al. 2022). Musicians also exhibit reduced age-related decline compared to non-musicians, particularly in auditory processing functions relevant to speech and music perception (Fostick 2019; Hanna-Pladdy and MacKay 2011). These findings suggest that musical training may help maintain elaborate perceptual skills across the lifespan.

Research has shown that engaging in active music-making encompasses a wide range of neural processes, including perception, cognition, brain connectivity, and behavior (Kraus and Chandrasekaran 2010; Tierney, Krizman and Kraus 2015) processing (Serrallach et al. 2016). While such findings provide an important theoretical framework for interpreting behavioral advantages in musicians, the present study was limited to behavioral measures and does not allow direct conclusions regarding neural normalization or neurological mechanisms.

Socioeconomic Status and Developmental Considerations (Q5)

Parental educational background served as our SES indicator, while participants' own educational attainment was analyzed separately. Parental SES significantly predicted language ability differences (high vs. low SES), whereas participants' educational status did not. SES demarcation followed ISCED-97 level 3a (A-levels equivalents), typically attained by adulthood. The findings show that family SES predicts language abilities. Studies have shown that higher SES of mothers and caretakers are positive predictors for language ability (Huttenlocher et al. 2010). Individuals belonging to low SES show poorer performance in language ability (Calvo and Bialystok 2014). The findings of our study provide similar information. While the SES differences were not significantly different in the adolescent group, those with high SES tended to score higher on average than those with low SES. This trend held true for the children and adults, with individuals from higher SES backgrounds consistently outperforming those with lower SES. Our study corroborates the findings of previous studies that provided evidence that the impact of socioeconomic disparities on language abilities may persist well into adulthood and affect academic achievement (Hoff 2013).

Our study also has limitations, and further research is needed to give more precise answers about the effect of foreign language capacity and musical ability. While SES appears to play a major role in early childhood and adulthood, this effect was less clear in our adolescent sample. Future studies should examine how early socioeconomic factors influence foreign language learning success in adulthood. Musical training was associated with beneficial effects across all age groups, suggesting it may be relevant across the lifespan. However, we cannot determine whether this reflects ongoing training, early acquired capacity, or both. Therefore, future research should also include a subgroup on "sleeping musicians (individuals who stopped training many years ago)" to address this in more detail. In addition, future studies with children should include individuals raised bilingually or multilingually to examine whether extensive early language exposure yields effects comparable to musical training. Future research using longitudinal designs would be required to determine whether the observed differences reflect developmental change over time.

5. CONCLUSIONS

Our study demonstrates that socioeconomic status (SES), musical training, and – to a lesser extent – foreign language proficiency is associated with speech perception abilities from childhood through adulthood, while singing parameters play a minor role. Given the cross-sectional nature of the design, the findings should not be interpreted as evidence of developmental trajectories. Musical training showed consistent associations with speech perception across all age groups. Extensive foreign language knowledge appeared particularly relevant during adolescence.

Compared to adolescents, musical training appeared to exert a more pronounced influence on unfamiliar speech perception in adulthood than foreign language capacity alone. Furthermore, the lower performance observed in adolescents and adults with ADHD suggests that differences in auditory processing may play a role in early stages of unfamiliar language perception.

These findings support the notion that individual differences in auditory expertise and cognitive processing capacities contribute to variability in unfamiliar speech perception. While musical training may be associated with enhanced perceptual sensitivity, individuals with clinically reported attentional and auditory processing difficulties may encounter additional challenges during the initial stages of foreign language learning.

However, as the present study relied exclusively on behavioral measures, interpretations regarding shared or overlapping neural mechanisms remain theoretical and require future investigation using combined behavioral and neurophysiological approaches.

Supplementary Materials: Table S1: independent t-tests for the perceptual language ability with and without extensive foreign language capacity for the adults with professional music education.; Table S2: independent t-tests for the perceptual language ability and gender for children, adolescents and adults; Tables S3 and S4: Gabriel-corrected post-hoc analysis for adolescents and adults; Figure S1: mean values of the language perception measurement of the adolescents separated into high and low SES.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the Medical Association of Riga (Latvia) 2-P ¯ EK-4/3/2022.

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Supplementary Materials: Table S1: independent t-tests for the perceptual language ability with and without extensive foreign language capacity for the adults with professional music education.; Table S2: independent t-tests for the perceptual language ability and gender for children, adolescents and adults; Tables S3 and S4: Gabriel-corrected post-hoc analysis for adolescents and adults; Figure S1: illustrates the mean values of the language perception measurement of the adolescents separated into high and low SES (personal education status).

1. Independent t-Test for the perceptual language ability with and without extensive foreign language capacity for the adults with professional music education

Table S1 shows the t-tests for perceptual language ability with (EFL) and without extensive foreign language capacity (NoEFL) for adults with professional music education (PME).

Variables	**Group comparisons and Means**	**Mean Difference**	***t***	**df**	***p***
Perceptual language ability	EFL (M= 0.74; SD= 0.13) NoEFL (M=0.74; SD=0.13)	-0.00	-0.056	47	0.96

2. Independent t-Test for Gender

Table S2 shows the t-tests of the perceptual language ability and gender for children, adults and adolescents.

Variable: Perceptual language ability	**Group**	**Group comparisons and Means**	**Mean Difference**	***t***	**df**	***p***
	children	female (M= 0.59; SD= 0.13) male (M=0.55; SD=0.10)	-0.05	-1.73	75	0.87
	adolescents	female (M= 0.60; SD= 0.13) male (M=0.62; SD=0.12)	0.02	1.08	214	0.28
	adults	female (M= 0.67; SD= 0.13) male (M=0.66; SD=0.12)	-0.00	-0.21	474	0.84

3. Gabriel post-hoc analyses

Table S3. Group differences in language perception capacity across the adolescent groups of this investigation.

Group	Means and standard deviation	Post-hoc comparisons	*Mean Difference*	*Std. Error*	*p*	95% Confidence Interval *Lower Bound*	95% Confidence Interval *Upper Bound*
ADHD	M = 0.52; SD = 0.11	vs. NoMT+NoEFL	-0.05	0.03	= .659	-0.01	0.14
		vs. MT+NoEFL	-0.15	0.03	< .001	-0.23	-0.07
		vs.MT+EFL	-0.13	0.03	< .001	-0.21	-0.06
		vs. NoMT+EFL	-0.12	0.03	< .001	0.03	0.19
NoMT+NoEFL	M = 0.57 SD = 0.12	vs. MT+NoEFL	-0.10	0.03	= .004	-0.18	-0.22
		vs. MT+EFL	-0.08	0.03	= .018	-0.16	-0.01
		vs. NoMT+EFL	-0.07	0.03	= .135	-0.14	0.01
MT+NoEFL	M = 0.67; SD =0.11	vs.MT+EFL	0.02	0.03	.999	-0.06	0.09
		vs. NoMT+EFL	0.04	0.03	.865	-0.04	0.11
MT+EFL	M = 0.66; SD =0.12	vs. NoMT+EFL	0.02	0.02	.998	-0.05	0.09
NoMT+EFL	M = 0.64; SD = 0.10						

PME = professional music education; EFL = with extensive foreign language capacity; NoEFL = without extensive foreign language capacity (only english as foreign language); MT = with musical training; NoMT = without musical training;

Table S4. Group differences in language perception capacity across the adult groups of this investigation.

Group	Means and standard deviation	Post-hoc comparisons	*Mean Difference*	*Std. Error*	*p*	95% Confidence Interval *Lower Bound*	95% Confidence Interval *Upper Bound*
ADHD	M = 0.54; SD = 0.10	vs. NoMT+NoEFL	-0.08	0.03	= .027	-0.15	-0.01
		vs. MT+NoEFL	-0.14	0.03	< .001	-0.22	-0.07
		vs.PME	-0.18	0.03	< .001	-0.26	-0.11
		vs.MT+EFL	-0.16	0.02	< .001	-0.22	-0.09
		vs. NoMT+EFL	-0.10	0.02	< .001	-0.17	-0.03
NoMT+NoEFL	M = 0.62 SD = 0.14	vs. MT+NoEFL	-0.06	0.02	= .022	-0.12	-0.01
		vs. PME	-0.11	0.02	< .001	-0.17	-0.05
		vs. MT+EFL	-0.08	0.02	< .001	-0.13	-0.03
		vs. NoMT+EFL	-0.02	0.02	.826	-0.07	0.03
MT+NoEFL	M = 0.69; SD =0.10	vs. PME	-0.04	0.02	.557	0.01	0.12
		vs. MT+EFL	-0.02	0.02	.997	-0.07	0.03
		vs. NoMT+EFL	0.04	0.02	.234	-0.01	0.10
PME	M = 0.73; SD = 0.12	vs.MT+EFL	0.03	0.02	.889	-0.08	0.03
		vs. NoMT+EFL	0.09	0.02	< .001	0.03	0.14
MT+EFL	M = 0.70; SD =0.11	vs. NoMT+EFL	0.06	0.01	< .001	0.02	0.10
NoMT+EFL	M = 0.64; SD = 0.10						

PME = professional music education; EFL = with extensive foreign language capacity; NoEFL = without extensive foreign language capacity (only english as foreign language); MT = with musical training; NoMT = without musical training; PME = with professional music education

4. Two-way ANOVA with high and low SES based on the participants educational status

A two-way ANOVA was performed to provide information about the role of musical classification and SES status of the participants according to their personal educational status with regard to the dependent variable of perceptual language ability. This two-way ANOVA was provided to show the contrasts to the parental education.

In marked contrast to the two-way ANOVA based on the educational status of the parents, when we use the participants highest level of education and use the cut off value of level 3a, the SES distinction is non-significant. ($F(11, 475) = 0.34$, $p = 0.56$, partial $\eta 2 = 0.008$: High SES ($M = 0.67$, $SD = 0.13$ and low SES ($M = 0,66$, $SD = 0.12$).

The results of the two-way ANOVA revealed a significant main effect for the musical classification ($F(11, 459) = 17.63$, $p = 0.001$, partial $\eta 2 =0.29$. The results revealed that adults with professional musical education performed best (PME; $M = 0.74$, $SD = 0.13$), followed by the adults with extensive foreign language and musical training (MT+EFL; $M = 0.70$, $SD = 0.11$), the adults with musical training with no extensive foreign language training (MT+NoEFL; $M = 0.68$, $SD = 0.10$), the adults with extensive foreign language without musical training (NoMT+EFL; $M = 0.64$, $SD = 0.10$), the adults without musical training with no extensive foreign language training (NoMT+NoEFL; $M = 0.60$, $SD = 0.14$) and the ADHD group (ADHD; $M = 0.54$, $SD = 0.10$). However, there was no significant interaction between musical classification and SES status ($F(9, 475) = 0.59$, $p = 0.71$; partial $\eta 2= 0.014$).

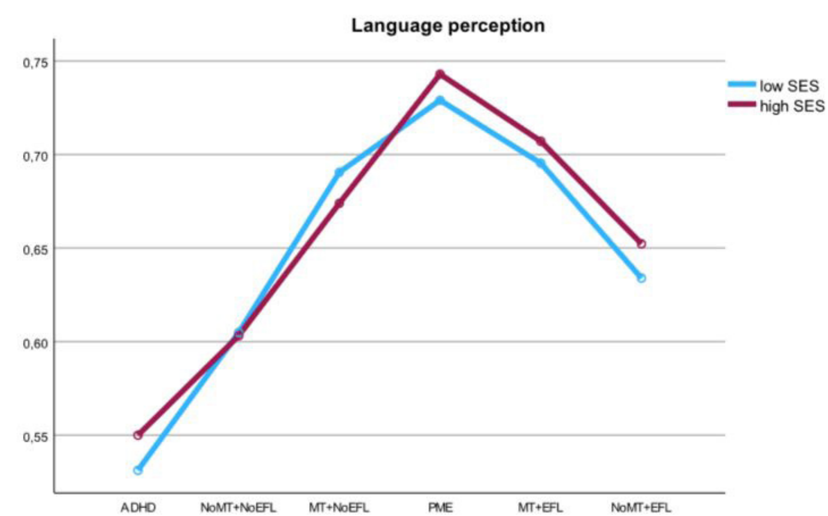

Figure S1 illustrates the mean values of the language perception measurement of adolescents separated into high and low SES (personal education status).

SASKARSME AR NEZINĀMO: INDIVIDUĀLO ATŠĶIRĪBU IZPĒTE NEPAZĪSTAMAS RUNAS UZTVERĒ DAŽĀDĀS GRUPĀS

Kristīne Grosa, Markuss Kristiners

KOPSAVILKUMS

Neirofizioloģiskie un biheiviorālie pētījumi ir uzrādījuši būtisku pārklāšanos starp mūzikas un valodas apstrādi, īpaši dzirdes informācijas atšķiršanas un fonoloģiskās jutības kontekstā. Muzikālā izglītība, svešvalodu pieredze, sociālekonomiskais statuss (SES) un neiroattīstības traucējumi, piemēram, uzmanības deficīta un hiperaktivitātes sindroms (UDHS), katrs ir saistīti ar individuālām atšķirībām ar valodas apguvi saistītās prasmēs. Tomēr šie faktori reti tiek analizēti vienotā, daudzfaktoru ietvarā. Šajā pētījumā tika izmantots daudzfaktoru šķērsgriezuma dizains, lai noskaidrotu, kā muzikālā izglītība, svešvalodu prasmes, SES un UDHS ir saistīti ar nepazīstamas runas uztveri dažādās vecuma grupās. Tika izvirzīti pieci pētnieciskie jautājumi par muzikālās izglītības, svešvalodu prasmju, UDHS, ar dziedāšanu saistīto mainīgo un sociālekonomiskā statusa ietekmi uz nepazīstamas verbālas informācijas uztveri bērniem, pusaudžiem un pieaugušajiem. Trīs vecuma grupu iekļaušana ļāva veikt šķērsgriezuma salīdzinājumus, taču pētījums nebija longitudināls.

Pētījumā piedalījās kopumā 724 dalībnieki (bērni, pusaudži un pieaugušie). Visi dalībnieki bija vācu valodas dzimtās valodas lietotāji; neliela apakšgrupa norādīja uz bilingvālu pieredzi. Nevienam nebija iepriekšējas pieredzes ar nepazīstamajām mērķvalodām (tagalu, mandarīnu, persiešu, japāņu valodu). Dzirdes stāvoklis un UDHS izpausmes tika novērtētas, izmantojot pašnovērtējumu. Nepazīstamas runas uztvere tika mērīta ar adaptētu vārdu atpazīšanas uzdevumu, kas simulēja agrīnos svešvalodas apguves posmus. Eksperiments tika veikts tiešsaistē, ievērojot standartizētas instrukcijas. Dalībnieki tika iedalīti grupās pēc muzikālās izglītības (tostarp profesionālās muzikālās izglītības), svešvalodu prasmēm, UDHS izpausmēm un sociālekonomiskā statusa, kas tika operacionalizēts, izmantojot ISCED-97 klasifikāciju par vecāku un pašu dalībnieku izglītības līmeni. Statistiskajā analīzē tika izmantotas divfaktoru dispersijas analīzes (ANOVA), neatkarīgo izlašu t-testi un *post-hoc* salīdzinājumi.

Muzikālā izglītība bija būtiski saistīta ar labāku nepazīstamas runas uztveri. Pieaugušie ar profesionālu muzikālo izglītību uzrādīja augstākos rezultātus, un pieaugušo grupā muzikālās izglītības ietekme bija spēcīgāka nekā svešvalodu prasmju ietekme. Plašas svešvalodu prasmes uzrādīja vājāku un mazāk konsekventu efektu salīdzinājumā ar muzikālo izglītību. Pusaudži un pieaugušie ar UDHS uzrādīja būtiski zemākus rezultātus nepazīstamas runas uztveres uzdevumos salīdzinājumā ar dalībniekiem bez UDHS. Vecāku SES būtiski prognozēja rezultātu atšķirības – augstāks SES bija saistīts ar labākiem rezultātiem, savukārt, pašu dalībnieku izglītības līmenis pieaugušo vecumā nebija statistiski nozīmīgs.

Kopumā rezultāti liecina, ka muzikālā izglītība un agrīnie sociālekonomiskie apstākļi ir saistīti ar individuālām atšķirībām nepazīstamas runas uztverē, un muzikālā izglītība izvirzījās kā īpaši spēcīgs faktors, it īpaši pieaugušo vecumā. Zemāki rezultāti dalībniekiem ar UDHS norāda, ka uzmanības regulācijas un dzirdes apstrādes īpatnības var ietekmēt svešvalodas uztveres agrīnos posmus. Ņemot vērā šķērsgriezuma un biheiviorālā pētījuma dizainu, nav iespējams izdarīt secinājumus par attīstības virzieniem vai neirālajiem mehānismiem. Lai noskaidrotu cēloņsakarības un attīstības dinamiku, nepieciešami longitudināli un neirofizioloģiski pētījumi.

FROM EAR TRAINING TO COGNITIVE EAR TRAINING: ESTABLISHING THE *CETra* FRAMEWORK

Valdis Bernhofs, Markus Christiner, Christine Gross

The article introduces *Cognitive Ear Training (CETra)* as a novel framework that reconceptualizes ear training as more than technical skill acquisition. While traditional approaches have emphasized pitch, rhythm, harmony, and sight-singing, they often overlook the cognitive prerequisites – such as attention, working memory, and executive control – that shape learning outcomes. *CETra* addresses this gap by integrating insights from cognitive neuroscience, music psychology, and pedagogy, positioning auditory training as both a musical and cognitive practice. Drawing on evidence from neural plasticity, music–language transfer, evolutionary and cross-cultural research, predictive coding, emotional engagement, and developmental studies, the paper demonstrates how *CETra* harnesses the interdependence of perception, attention, memory, self-regulation, and creativity. The framework is articulated through a Spotlight Model comprising seven interrelated dimensions – psychoacoustic, behavioral, psychoemotional, neurophysiological, physical, social, and pedagogical – each linking auditory processes with broader, cognitive functions. By reframing ear training as a multidimensional practice that cultivates transferable skills, *CETra* offers a paradigm shift for music education and establishes a foundation for future interdisciplinary research.

Keywords: Cognitive Ear Training (CETra), music education, auditory cognition

INTRODUCTION

Cognitive ear training is closely linked generally to the processes of perception and understanding. At its core, it emphasizes focus to cognitive functions such as perception, attention, memory, and creativity. Cognitive training refers to structured techniques designed to strengthen these components, thereby improving not only musical skills and knowledge about music, but also broader intellectual functions.

In research practice, there is a term *cognitive training*, widely used to describe interventions that aim to activate and reinforce specific cognitive components. Cognitive training has emerged as a promising approach to enhancing executive function and general cognition across diverse populations – from children to older adults (Bogataj et al. 2025; Diamond et al. 2016; Lampit et al. 2014; Simons et al. 2016). Evidence shows that such training can improve working memory, attention control, processing speed, and cognitive flexibility, while also promoting resilience against age-related decline and supporting neuroplastic changes in the brain. Well-designed training programs often generalize beyond task-specific skills, contributing to improvements in academic achievement, problem-solving, and everyday functioning (Jaeggi et al. 2011; Karbach et al. 2014). Even the cognitive training is widely broad it is not connected directly to sound material included in the training. Possible reasons will be discussed later.

In this article, *ear training* is used as a general umbrella term for pedagogical practices aimed at developing musical listening skills. The designation *traditional ear training*, most commonly associated with solfège-based approaches, does not refer to a formally standardized theoretical construct, but is used descriptively to denote historically established pedagogical practices that have been widely adopted in music education. These practices have typically been organized around solfège- and notation-based exercises, including interval and chord identification, melodic and harmonic dictation, and sight-singing within structured pitch and rhythmic systems.

These terminological distinctions provide a conceptual basis for positioning Cognitive Ear Training (*CETra*) as a framework that builds upon established ear-training practices while explicitly addressing the cognitive mechanisms underlying listening, perception, and learning processes.

Historically consolidated solfège-based ear training remains a deeply effective pedagogical tool, supported by its long pedagogical tradition as well as modern empirical validation. (Guido of Arezzo, ca. 1025/1978; Curwen 1870; Kodály 1974; Apfelstadt 1984; Demorest et al. 1995; Agbenyo 2021; Zhao 2024; Lumbantoruan et al. 2024). More than an exercise, solfège serves as a cognitive and expressive toolkit that bridges hearing, understanding, and performance – central to its enduring value in music education. Traditionally, ear training is organized into structured exercises in pitch recognition, interval identification, dictation of pitch and rhythm, and melodic-harmonic analysis. These activities foster not only musical literacy but also a distinctive form of cognitive training. Both pedagogical practice and empirical research indicate that solfège cultivates auditory discrimination, working memory, sustained and selective attention, and executive control – skills essential not only for musical performance but also for broader cognitive functioning (Schellenberg 2004; Tierney et al. 2013; Moreno et al. 2014). When focused on technical exercises – often modelled on stylistic conventions or style-imitative structures – traditional ear training can enhance cognitive capacities. By requiring learners to decode complex auditory input, retain musical phrases in memory, and anticipate structural patterns, ear training fosters neuroplastic adaptations that extend beyond music learning. Research indicates that such training can enhance linguistic processing, second-language acquisition, and general problem-solving abilities (Patel 2011; Besson et al. 2011). Furthermore, solfège exercises engage both convergent and divergent thinking, promoting creative flexibility while maintaining accuracy in auditory perception. Yet in practice, teachers often observe that learners encounter limitations: not all are equally able to process the curriculum. In fact, many of the very cognitive components that ear training aims to develop are already prerequisites for engaging with it effectively.

Based on our experience as teachers, we have observed that traditional ear training often places a narrow emphasis on the reproduction of intervals, chords, or dictations. Although these skills are essential, this approach may inadvertently foster a rigid mode of listening, in which students "train for the test", yet struggle to transfer their abilities to novel or creative contexts. In many music schools, vocational institutions, music academies or conservatory settings, ear training has traditionally emphasized musicianship through skills such as interval recognition, harmonic hearing, melodic dictation, and rhythmic accuracy. Although effective in developing technical proficiency, these practices often prioritize auditory recognition at the expense of domain-general processes that support flexible and robust listening. As a result, many students plateau in their progress because foundational capacities such as selective attention, short-term auditory memory, or cognitive flexibility are not sufficiently cultivated (Lehmann et al. 2007, 80–83, 141–147).

Integrating modern cognitive training principles into this long-standing pedagogical framework of traditional ear training may optimize its benefits, establishing a stronger foundation for both music learning and the development of transferable skills across educational and developmental contexts. This perspective reconceptualizes ear training as a structured platform for the cultivation of fundamental cognitive capacities, thereby enhancing the efficiency of the learning process and enabling individuals to mobilize their cognitive resources with greater depth and precision.

Despite these established connections, *cognitive ear training* as a targeted pedagogical construct has not yet been systematically conceptualized or applied. Traditional ear training continues to be framed primarily as a method for musical skill acquisition – emphasizing pitch, rhythm, harmony, and sight-singing – while its broader cognitive mechanisms remain largely under examined. To address this gap, we advance *cognitive ear training* as a novel framework: one that reconceptualizes auditory training not merely as a vehicle for musical development, but as a structured approach to cultivating cognitive components through the dynamic interplay of sound, silence, and spatial perception.

There are several possible reasons why this concept has not yet been used in research:

a) Historical framing. Ear training (solfège) has traditionally been seen as a pedagogical tool for musical literacy – interval recognition, melodic dictation, harmonic analysis – rather than as a cognitive intervention. As a result, research has emphasized practical knowledge and performance skills over cognitive outcomes (Karpinski 2000: ch. 1, Part I; McPherson et al. 2002, 99–115).

b) Terminology gaps. Music education and cognitive neuroscience operate within distinct disciplinary vocabularies. In pedagogy, the discourse centres on *aural skills* or *musicianship training* – implicitly engaging cognitive components such as perception and attention – whereas cognitive psychology emphasizes constructs like perception, working memory, executive function, and selective attention. This terminological divide has hindered the explicit conceptualization of ear training as a form of cognitive training, despite its reliance on the same underlying neural and cognitive systems (Patel 2011; Besson et al. 2011).

c) Methodological barriers. Cognitive training research typically employs controlled, quantifiable tasks with clearly measurable transfer effects (e.g., the *n*-back paradigm for assessing working memory). By contrast, ear training is inherently open-ended, context-dependent, and highly variable across institutions, which makes standardization and rigorous scientific measurement difficult (Simons et al. 2016; Diamond et al. 2016). Furthermore, ear training methodologies are often shaped less by empirical validation than by institutional traditions and the subjective pedagogical orientations of individual instructors. For example, in seminar settings, presenters often introduce new exercises for recognizing cadences; however, there is typically little consideration of the cognitive prerequisites for such tasks – namely, the foundational knowledge and cognitive flexibility required to process information efficiently and to transition fluidly between different musical contexts.

d) Research silos. Music cognition research often examines the effects of music training broadly – comparing musicians and non-musicians – without isolating ear training as a distinct component. This overlooks the possibility that ear training itself contributes uniquely to auditory attention, memory, and cognitive flexibility (Schellenberg 2004; Tierney et al. 2013).

e) Lack of an operational definition. To date, no clear framework for *cognitive ear training* has been articulated. In the absence of such a definition, ear training continues to function primarily as an educational construct rather than a scientifically grounded one. This conceptual gap highlights the need – and provides the opportunity – to advance *cognitive ear training* as an integrative framework that systematically bridges pedagogical practice with cognitive science.

In practice, the positive influence of musical training on cognition is widely recognized. Learning music and active music-making foster the development of attention, perception, and flexible thinking. Through ear training, students often encounter their cognitive limits, sharpening their pitch awareness, rhythmic sensitivity, and harmonic understanding. Yet, the connection between ear training and broader psychological processes remains insufficiently researched – a limitation that constrains its further development.

Cognitive Ear Training (*CETra*) reframes the concept of ear training by recognizing that musicianship and auditory perception rely on the integration of perceptual and cognitive processes. Rather than limiting training to reproduction, *CETra* emphasizes adaptability, problem-solving, and flexible listening strategies that prepare learners to engage actively and creatively with sound. Its structured exercises are designed to strengthen selective attention, working memory, prediction, and higher-order decision-making, while still incorporating the listening skills that remain central to musicianship. In this way, *CETra* extends the tradition of ear training by uniting technical mastery with cognitive development, fostering a more transferable and resilient foundation for musical learning. This reconceptualization provides the rationale for developing a structured framework in which ear training is organized into spotlights, each highlighting a distinct dimension of listening and learning that, taken together, support a more holistic philosophy and practice of ear training.

A key aspect of effective ear training is what we call *the freedom of hearing* – the ability to adapt to new contexts and apply previously acquired knowledge in unfamiliar situations. This involves the transfer of knowledge across domains, for example, connecting the recognition of classical harmonic progressions with the more complex structures of jazz. In our teaching practice we often use comparative exercises, such as asking students to notate the same melodic fragment in both classical and jazz notation, or to recognize harmonic substitutions across different styles. Such strategies strengthen cognitive flexibility and highlight that musical hearing is not fixed but can expand across genres and contexts. In this way, ear training fosters not only musicianship but also the cognitive agility to navigate diverse auditory environments.

The relevance of *CETra* is underscored by findings in neuroscience. Musical training is a robust driver of neuroplasticity: long-term practice induces structural and functional changes in the auditory and motor cortices, the corpus callosum, and networks supporting executive function (Gaser and Schlaug 2003; Hyde et al. 2009; Schlaug et al. 2009). These results suggest that *CETra* can deliberately harness neural plasticity to strengthen listening and learning. Beyond musicianship, such adaptations extend to language learning, auditory rehabilitation, and cognitive development across the lifespan – including children, adults, and older adults (Kraus et al. 2014; Moreno et al. 2009).

CETra also addresses practical needs. In music education, traditional exercises such as dictation or interval recognition can be insufficient for real-world performance demands that require rapid adaptation, improvisation, and integration of multiple auditory cues. In clinical contexts, cochlear-implant and hearing-aid users often struggle with speech-in-noise perception and subtle timbral distinctions. *CETra* proposes targeted tasks that train auditory filtering, rhythm–motor coordination, and cognitive flexibility to mitigate these challenges (Gohari et al. 2023; Shukor et al. 2020).

The concept of Cognitive Ear Training (*CETra*) must first be defined before turning to the supporting literature. *CETra* may be understood as a structured framework for the development and interconnection of core cognitive components through aural information, employing sound, silence, and spatial perception as its operative environment. By fostering integrated cognitive networks, *CETra* aims to enhance overall cognitive potential, grounded in the premise that dynamic correlations among perception, attention, memory, self-regulation, and creativity constitute essential prerequisites for meaningful musical experience and for the long-term acquisition of musical knowledge and skills.

MUSIC TRAINING AND COGNITIVE TRANSFER: TOWARD A NEW PARADIGM OF EAR TRAINING

Music training demonstrates wide-ranging transfer effects that form the conceptual foundation for the philosophy of *CETra*. Neuroscientific research has established that training reshapes both brain structure and function: musicians exhibit greater gray-matter density and stronger auditory–motor connections, while even short-term interventions yield measurable cognitive and perceptual gains in both children and adults (Gaser et al. 2003; Hyde et al. 2009; Moreno et al. 2009). At the functional level, training enhances neural phase-locking, predictive coding, and cortical tuning to pitch and timbre (Colverson et al. 2024; Kraus et al. 2014). Furthermore, music-evoked pleasure engages dopaminergic reward circuits that sustain motivation and consolidate learning (Zatorre et al. 2013a; Blood et al. 2001; Koelsch, 2014). For cognition, this plasticity translates into stronger auditory working memory, improved attentional control, and greater motivational resilience, capacities that support both musical performance and general learning.

Transfer effects extend across rhythm, timbre, and spatial dimensions. Rhythm-based training strengthens neural entrainment and temporal prediction, directly benefiting speech-in-noise perception and prosody recognition (Goswami 2022; Hennessy et al. 2022; Vuust et al. 2014). These processes enhance temporal attention, sequencing, and predictive monitoring – skills crucial for executive function and language processing. Timbre-oriented exercises refine fine-grained auditory discrimination and support emotional coding (McAdams 2008; Bellmann et al. 2024). Such training sharpens perceptual sensitivity, expands emotional awareness, and strengthens auditory categorization, thereby fostering flexible pattern recognition. Spatial-hearing tasks, meanwhile, enhance auditory scene analysis, stream segregation, and localization – skills critical for ensemble music-making and everyday listening (Maillard et al. 2023; Reis et al. 2021). Cognitively, these tasks train selective attention, multi-source information integration, and spatial working memory.

Music–language transfer adds another crucial dimension. Incorporating tonal language components, musical training has been shown to enhance phonological awareness, tonal language acquisition, and prosody perception, while linguistic expertise reciprocally refines pitch processing (Patel 2008, 356–378; Wong et al. 2007; Hennessy et al. 2022). Enhanced brainstem encoding of both linguistic and musical pitch patterns further illustrates experience-dependent plasticity (Krishnan et al. 2010). The cognitive benefits include strengthened verbal working memory, heightened auditory discrimination for speech, and increased cross-domain transfer between symbolic systems. In this context, language itself can serve as a valuable material for ear training.

Building on the evidence from music–language transfer, it is equally important to recognize that the foundations of ear training extend beyond formal music education into evolutionary and cross-cultural domains. This perspective underscores that music training draws not only on learned symbolic systems, such as language, but also on deeply ingrained human predispositions for rhythm, coordination, and collective practice. Evolutionary and anthropological research demonstrates that music leverages these innate capacities as mechanisms of social bonding and communication (Mehr et al. 2019; Savage et al. 2020). At the cognitive level, such collective engagement promotes joint attention, synchronization, and social cognition, which in turn enhance cooperative problem-solving and emotional regulation. Predictive coding studies further reveal that musical prediction errors activate neural systems for adaptive processing, thereby cultivating tolerance for uncertainty and cognitive flexibility (Koelsch et al. 2019; Ueno et al. 2024). These mechanisms strengthen error monitoring, adaptive updating, and resilience to ambiguity – core components of higher-order executive function. Emotional engagement and group participation also sustain motivation and consolidate memory (Zatorre et al. 2013a; Savage et al. 2020), contributing to affective learning, long-term retention, and persistence in complex tasks.

Developmental evidence highlights the importance of early interventions: sensitive periods facilitate accelerated growth of auditory, cognitive, and linguistic capacities (Hyde et al. 2009; Moreno et al. 2009). Engaging in *CETra* during these windows enhances neuroplasticity, scaffolds metacognitive awareness, and builds enduring foundations for learning. Complementing these findings, large-scale data demonstrate that psychosocial skills – such as grit, self-efficacy, and prosocial behaviour – are significant contributors to musical development alongside cognitive and technical abilities (Voitova et al. 2025). These traits reinforce self-regulation, perseverance, and collaborative learning, extending the cognitive reach of ear training into broader developmental domains.

Taken together, these strands of evidence articulate a paradigm of transfer in which *CETra* is grounded. Music training operates not only as a vehicle for technical development but as a multidimensional practice that leverages neuroplasticity, language transfer, evolutionary predispositions, predictive processing, emotional engagement, developmental timing, and psychosocial growth. Within this paradigm, *CETra* organizes its approach into a Spotlight Framework: seven interrelated spotlights, each illuminating a distinct but interconnected dimension of listening and learning.

In practice, *CETra* can be implemented across education, therapy, and technology: from studio pedagogy that embeds adaptive dictations and rhythmic flexibility (Berkowitz 2010), to classroom games that strengthen entrainment and phonological awareness (Goswami 2022), to AI-driven tools and VR simulations that personalize auditory training and expand access (Reis et al. 2021; Han et al. 2024). Clinical applications demonstrate improvements in speech-in-noise perception, timbre recognition, and spatial listening for cochlear-implant and hearing-aid users (Shukor et al. 2020; Dornhoffer et al. 2024).

TOWARD A MULTIDIMENSIONAL SCIENCE OF EAR TRAINING: THE SPOTLIGHT FRAMEWORK

The Spotlight Framework addresses this need by articulating seven interrelated dimensions of listening and learning that collectively define *CETra*. Each spotlight illuminates a distinct domain – spanning psychoacoustic precision, social interaction, behavioural regulation, psychoemotional engagement, neurophysiological grounding, physical embodiment, and pedagogical design. Viewed through these multiple lenses, *CETra* reframes ear training from a narrow focus on technical reproduction to a holistic practice that unites knowledge with pleasure, accuracy with creativity, and discipline with motivation.

1. Psychoacoustic Spotlight: From Acoustic Cues to Cognitive Interpretation

The psychoacoustic spotlight examines how listeners perceive, discriminate, and interpret the fine-grained acoustic features of environmental and musical sounds, emphasizing the integration of perceptual, attentional, and memory processes that support auditory mechanisms. A particularly important component is sound density, as the layering and overlap of spectral information directly affect clarity and perceptual load in both musical and ecological contexts. Research on timbre perception demonstrates that subtle spectral and temporal cues – such as attack transients, spectral centroid, and harmonic inharmonicity – enable individuals to reliably distinguish between instruments and sound sources, even when pitch or rhythm remain constant (McAdams 2008). Neuroimaging studies further reveal that these discriminations recruit bilateral auditory cortices as well as higher-order networks related to working memory and decision-making, indicating that psychoacoustic processing is inherently cognitive and distributed across neural systems (Koelsch 2014). Behavioural evidence supports this account: musicians consistently outperform non-musicians in tasks requiring micro-interval discrimination and spectro-temporal analysis, reflecting experience-driven sharpening of auditory representations and enhanced attentional control. Parallel findings show that both musical training and tone-language experience enhance subcortical pitch encoding, underscoring the plasticity of the auditory system (Wong et al. 2007; Krishnan et al. 2010).

Training interventions that target psychoacoustic acuity – such as adaptive timbre contrast paradigms, micro-interval dictations, and spectro-temporal masking tasks – improve not only accuracy and just-noticeable-difference (JND) thresholds but also transfer meaningfully to real-world contexts such as speech perception in noise and the interpretation of subtle timbral nuances in repertoire (Hennessy et al. 2022; Bellmann et al. 2024). Taken together, these findings position psychoacoustic training as a cornerstone of *CETra*, particularly in the early stages of musical development, where improvements in auditory precision are reinforced by cognitive engagement and validated through their transfer to ecologically relevant performance domains.

In traditional ear training, this dimension is often overlooked,, as instruction quickly prioritizes explicit knowledge of pitch, interval, and harmony. This emphasis risks neglecting the acoustic discrimination processes necessary for robust auditory representations and for the neural foundations of higher-order cognitive and musical skill functions.

Infants as young as 3 and 7 months can reliably detect fine-grained changes in pitch (F0) and timbre, performing on par with musically trained adults and even surpassing untrained adults (Lau et al. 2021). This evidence suggests that sensitivity to microtonal distinctions emerges early, yet such perceptual capacities are rarely cultivated in music schools or vocational curricula, which typically focus on tempered pitch systems. Integrating microtonal training into ear training could therefore harness and extend these innate psychoacoustic abilities.

By reinstating the psychoacoustic dimension as a primary focus, *CETra* ensures that ear training does not leap prematurely into symbolic domains, but rather develops from the perceptual bedrock that enables both musical literacy and broader cognitive flexibility.

2. Social Spotlight: Collaborative Dimensions of Auditory Learning

The social spotlight emphasizes how auditory training extends beyond individual perception into the dynamics of interaction, coordination, and communication. Cognitive domains central to this area include attention, language, problem-solving, and creativity, which are recruited when individuals make music or communicate together. Research on ensemble synchronization demonstrates that musicians develop superior skills in maintaining temporal alignment with others, even under conditions of uncertainty or without external cues (Vuust et al. 2014). Such coordination depends on attentional networks (Markett et al.2022) and rapid adjustment, highlighting the cognitive flexibility required for successful group performance. Beyond music, these capacities contribute to turn-taking in conversation and cooperative problem-solving, underscoring the transfer value of social listening skills (Savage et al. 2020).

Evidence further shows that conversational prosody – the rhythm and intonation of speech – is closely tied to the same auditory mechanisms that underlie musical synchronization. Neurocognitive studies reveal that training in rhythmic entrainment enhances sensitivity to speech boundaries and improves comprehension in noisy environments (Goswami 2022). Ensemble and call-and-response paradigms, therefore, not only strengthen musical timing but also reinforce language processing skills. This connection is particularly relevant in early childhood, where collective music-making accelerates both linguistic and social-emotional development (Moreno et al. 2009). Furthermore, it is useful to incorporate different cultural models of interaction, including rhythmic frameworks derived from non-Western scales and tonal language patterns. Research shows that tone-language speakers exhibit enhanced pitch sensitivity and prosodic awareness compared to non-tonal language speakers, highlighting the potential value of cross-cultural integration in *CETra*-based training (Krishnan et al. 2010).

Embedding training in collaborative activities further enhances motivation and creativity, as learners engage more deeply when they are required to interact, co-create, and respond dynamically to peers (Berkowitz 2010; Savage et al. 2020). By situating *CETra* in group environments, the social spotlight demonstrates how auditory training can simultaneously strengthen cognitive flexibility, communicative competence, and social bonding. This emphasis on interaction is reinforced by recent findings that psychosocial skills such as prosocial behaviour and perseverance predict listening ability outcomes in musically gifted adolescents (Voitova et al. 2025).

3. Behavioural Spotlight: From Practice Habits to Cognitive Flexibility in Ear Training

The behavioural spotlight focuses on how learners regulate their listening strategies, consciously manage cognition, and monitor progress during training. Unlike the psychoacoustic or social dimensions, this spotlight emphasizes metacognitive processes – awareness and control of one's own learning strategies – as well as the adaptive regulation of effort. Key cognitive domains include attentional sustainment, working memory, and decision-making. In music education, research shows that expert performers rely on deliberate practice strategies and active self-monitoring to refine their skills, often verbalizing or annotating errors to guide subsequent improvement (Lehmann et al. 2007). Such metacognitive behaviours have been strongly linked to accelerated skill acquisition and long-term retention. Cross-sectional evidence further demonstrates that constructs such as grit and hope interact with practice behaviours and listening skills, suggesting that strategic regulation cannot be separated from broader psychosocial capacities (Voitova et al. 2025).

Empirical findings highlight the importance of adaptive learning in auditory training, particularly under noisy conditions where sustained attention and distractor filtering are critical (Sridhar et al. 2025). Similarly, adaptive systems that adjust task difficulty in real time foster sustained engagement by keeping learners within an optimal zone of challenge and success. Evidence from musical training suggests that tasks which stretch working memory capacity without overwhelming it can strengthen attentional control and decision-making in complex auditory contexts (Román-Caballero 2023).

Another crucial behavioural dimension concerns how individuals respond when faced with novel or unpredictable contexts. The ability to transfer knowledge to unfamiliar circumstances depends on acceptance of uncertainty, flexible strategy generation, and the capacity to reorganize prior knowledge in light of new demands. Research on *far transfer* and adaptive expertise shows that musicians who develop such flexible habits are better able to cope with unexpected performance conditions and apply learned skills in new environments (Hatano et al. 1986, 262–272; Barnett et al. 2002). These findings resonate with educational psychology, where adaptive learning and self-regulated strategy use are seen as predictors of resilience and long-term achievement (Zimmerman 2002; Veenman et al. 2006).

Studies of musical performance in adolescents with ADHD, ADD, and dyslexia have highlighted not only neurophysiological differences but also motivational and self-regulatory benefits (Groß et al. 2022). These findings underscore the value of ear-training interventions in fostering self-efficacy, attentional control, and emotional engagement – especially for learners with neurodevelopmental diversity.

CETra incorporates these principles through dual-task dictations, which require learners to divide attention between melody and rhythm or between listening and notating under time constraints. Self-explanation protocols encourage students to articulate their listening strategies, reinforcing metacognitive awareness, while error-tagging tasks train learners to recognize and categorize mistakes systematically. By cultivating flexible listening strategies and reflective learning habits, the behavioural spotlight ensures that *CETra* is not merely about perceptual sharpening but also about equipping learners with lifelong skills for self-directed learning, adaptability, and problem-solving – even in completely new and unexpected contexts.

4. Psychoemotional Spotlight: Emotional Engagement as a Catalyst for Learning

The psychoemotional spotlight addresses the interplay between affective responses, motivational states, and auditory listening and learning. Cognitive domains central to this spotlight include attention, memory, creativity, and decision-making, all of which are influenced by emotional engagement. Research has consistently shown that music-evoked pleasure engages the brain's reward circuitry, particularly dopaminergic pathways in the ventral striatum, leading to enhanced motivation and reinforcement of learning (Zatorre et al. 2013a; Blood et al. 2001). Emotional arousal not only sustains attention but also promotes stronger memory consolidation, thereby linking affective engagement directly to the efficiency of ear training (Koelsch 2014). Empirical results from Latvia confirm that psychosocial skills play a greater role for musically gifted pupils than musical training alone, underscoring how affect, motivation, and perseverance influence not only practice but measurable listening abilities (Voitova et al. 2025).

Affective and motivational processes also play an important role in group music-making, where social bonding enhances persistence and enjoyment. Collective music-making, such as choir singing or ensemble performance, has been shown to elevate endorphin release and increase social cohesion (Savage et al. 2020). These positive affective states in turn improve learners' willingness to persist through challenges and regulate their cognitive effort. In the *CETra* framework, leveraging affect is not peripheral but central: emotionally engaging tasks stimulate reward-based learning mechanisms that amplify both the effectiveness and the sustainability of auditory training.

CETra operationalizes these principles through blueprint tasks designed to link perception with affective response. For example, emotion-labelling exercises train learners to detect subtle timbral or microtiming shifts that evoke distinct feelings, while personalized repertoire tasks allow students to work with music that resonates with their own preferences, thereby strengthening intrinsic motivation. This motivational dimension is critical: learners who engage with material that is personally meaningful show higher persistence, deeper processing, and greater long-term retention (Ryan et al. 2020; Evans et al. 2012). Assessment within this spotlight combines subjective and objective measures, including self-reported valence and arousal, persistence indicators such as practice duration, and behavioural performance under stressors (e.g., dictation in noise or under time pressure).

By embedding affect, motivation, and reward into ear training, *CETra* transforms auditory practice into a psychoemotional spotlight – a framework that not only sharpens perceptual acuity but also activates the very emotional and motivational circuits that sustain lifelong musical engagement. Neuroscientific evidence confirms that dopaminergic reward pathways engaged during pleasurable music listening reinforce both learning and habit formation (Zatorre 2013b; Salimpoor et al. 2011). Educational psychology likewise demonstrates that intrinsic motivation fuels resilience, creativity, and sustained effort in skill acquisition (Ryan and Deci 2020). Within *CETra*, these insights converge: emotionally rewarding training experiences generate motivational momentum, which in turn elevates practice quality and consolidates learning. In this way, *CETra* establishes a self-reinforcing cycle where success breeds further success – a virtuous loop fundamental to both musical growth and cognitive development.

5. Neurophysiological Spotlight: Brain Mechanisms and Plasticity in Auditory Learning

The neurophysiological spotlight emphasizes the biological mechanisms that support ear training, with particular attention to how neural systems adapt to the demands of auditory learning. Core cognitive domains include perception, attention, prediction, and expectation, all of which depend on the precision and flexibility of neural coding. Pitch and rhythm serve as especially powerful activators within this system.

A central mechanism is neural phase-locking – the capacity of neurons to synchronize their firing with rhythmic auditory input. Research demonstrates that musicians show enhanced phase-locking in auditory brainstem responses, which supports superior rhythm perception and temporal prediction (Colverson et al. 2024; Wong et al. 2007). This neural synchronization not only enables rhythmic accuracy in music but also facilitates speech processing in noisy environments, underscoring the close relationship between music training and broader auditory cognition.

Another line of evidence highlights cortical tuning to pitch and timbre, which becomes increasingly refined through musical training. Functional imaging studies demonstrate that musicians exhibit sharper frequency tuning in auditory cortex as well as stronger engagement of auditory–motor networks, reflecting the integration of perceptual processing with motor planning (Schlaug et al. 2009; Hyde et al. 2009). These findings underscore the brain's remarkable capacity for plasticity: intensive auditory practice reshapes cortical representations, yielding long-lasting improvements not only in musical performance but also in language-related auditory tasks. This plasticity provides a biological rationale for uniting sound, cognition, and training within a single framework, thereby grounding pedagogical interventions in well-documented neurophysiological processes. Practically, it can be understood as the brain's readiness to reconfigure itself by applying previously acquired knowledge to novel auditory models. At the same time, it must be acknowledged that networks shaped through repetitive pattern training are not easily generalized to new contexts. *CETra* therefore emphasizes a dual approach: stepwise reinforcement that strengthens neural coding through repeated exposure, combined with opportunities for flexible transfer that encourage learners to reapply and reorganize neural resources in unfamiliar auditory environments.

Decades of neuroscientific work show that both structural predispositions and training shape the auditory cortex. A seminal study demonstrated that morphology of Heschl's gyrus is associated with enhanced activation in musicians compared to non-musicians (Schneider et al. 2002). Later, structural and functional asymmetries in the lateral Heschl's gyrus were shown to correlate with pitch perception preferences, such as fundamental versus overtone dominance (Schneider et al. 2005). More recently, a 12-year longitudinal study confirmed that musicians exhibit distinct neuroanatomical dispositions, maturational changes, and robust training-induced plasticity compared to non-musicians (Schneider et al. 2023). Complementary evidence indicates that even short-term active listening training can elicit measurable neuroplastic changes in auditory processing (Schneider et al. 2022).

CETra translates these mechanisms into training tasks such as rhythm oddball paradigms, which require learners to detect deviations in expected rhythmic patterns; beat prediction tasks under tempo jitter, which strengthen predictive coding mechanisms; and polyrhythm switching spatial exercises, which engage both auditory and motor systems in managing complex temporal structures. Evaluation relies on metrics including prediction error rates (how often learners miss deviations), synchronization stability (variability in entrainment to a beat), and switch costs (time or accuracy penalties when changing between rhythmic patterns). By embedding training in tasks that directly engage neural prediction and motor coupling, the neurophysiological spotlight ensures that *CETra* not only develops perceptual skills but also harnesses the brain's biological substrates for lasting auditory and cognitive benefits.

6. Physical Spotlight: Auditory–Motor Integration and Rhythmic Entrainment

The physical spotlight underscores the fundamental role of the body in shaping auditory learning, with pitch and rhythm serving as primary media for bodily activation. These auditory parameters are not merely abstract musical constructs, but dynamic triggers for movement and neural coordination – enabling learners to transform sound directly into embodied experience. Importantly, this spotlight interrogates how rapidly individuals can perceive acoustic information and translate it into movement, as speed of auditory–motor integration critically determines the alignment of perception, prediction, and action.

These embodied processes extend into real-world contexts: bodily engagement with rhythm enhances attention, prediction, and adaptability, contributing to speech segmentation and coordination in social settings. Gerry et al. (2012) found that children who engaged in rhythmic movement while listening show stronger retention of melodies and rhythms. Similarly, adult studies reveal that coordinated movement stabilizes beat perception and improves tempo adaptation (Phillips-Silver and Trainor 2005).

Recent studies add depth to this understanding. For example, low-pitched rhythms significantly stabilize spontaneous movement entrainment compared to high-pitched alternatives, a finding supported by evidence that both pitch and tempo systematically affect the strength and stability of movement synchronization with auditory rhythms (Varlet et al. 2020). Meanwhile, pitch influences the timing of sensorimotor synchronization – suggesting pitch can adjust the perceived timing structure of rhythm itself (Pazdera et al. 2025). Additional evidence shows that entrainment capacity varies across individuals, with some demonstrating more precise auditory–motor synchronization than others – a variability that Mares et al. (2023) trace to both individual traits and acoustic features of the stimuli.

In practical terms, *CETra* operationalizes these insights through tasks such as body-percussion polyrhythms, gait-clapped synchronization, and sensorimotor timing exercises of increasing complexity. These activities not only engage working memory – as learners juggle multiple rhythmic layers – but also accelerate auditory–motor mapping via pitch-guided gesture (e.g., contour-driven movement). Performance is assessed through metrics like movement-beat asynchrony, variability in synchronization consistency, and endurance across challenging tempi.

By weaving physical movement into auditory learning, the physical spotlight ensures that *CETra* leverages embodied cognition – reinforcing auditory precision through motor integration and embedding abstract listening skills in the lived experience of the body.

7. Pedagogical Spotlight: Integrating Cognitive, Emotional, and Social Dimensions in Ear Training

The pedagogical spotlight highlights how *CETra* principles can be systematically embedded into curriculum design, ensuring that the benefits of acoustic, social, behavioural, psychoemotional, neurophysiological, and physical training are integrated into structured educational pathways. Unlike the other spotlights, this one encompasses all eight cognitive domains, since teaching design inherently requires balancing perception, attention, memory, prediction, creativity, decision-making, timing, and motor engagement. Research in adaptive curricula demonstrates that individualized pacing and scaffolded learning pathways yield stronger outcomes than uniform, one-size-fits-all models, aligning with evidence that musical training confers cognitive benefits across the lifespan (Román-Caballero 2023). Within this context, adaptive technologies provide one powerful means of implementation: digital platforms and AI-driven systems enable teachers to calibrate task difficulty dynamically, maintaining learners in an optimal challenge zone that fosters both motivation and measurable growth (Reis et al. 2021).

Evidence also underscores the importance of early sensitive periods in musical training. Longitudinal studies reveal that structured music education in early childhood not only accelerates auditory discrimination but also confers lasting benefits for language development, working memory, and attentional control (Schlaug et al. 2009; Moreno et al. 2009). This suggests that *CETra*-informed curricula should strategically embed auditory-cognitive training from the earliest stages of education. Beyond childhood, curricula remain crucial for older learners and professionals, as spiral models of instruction – where concepts such as rhythm, timbre, and auditory scene analysis are revisited at progressively deeper levels – promote long-term mastery and transfer (Bruner 1960, 12–13, 141). Recent studies in music education reinforce this approach: Fautley and Daubney describe a spiral-based curriculum structured around interconnected strands such as singing, composing, improvising, playing, and critical engagement, all of which are revisited with increasing complexity to support experiential learning (Fautley and Daubney 2019). Similarly, models such as the Swanwick–Tillman spiral emphasize developmental transformations through the repeated revisiting of musical concepts within a growth trajectory (Leveridge 2022; Philpott 2022). Empirical evaluations further show that spiral curriculum designs enhance retention and deepen understanding, with students reporting stronger consolidation and fewer misconceptions when prior knowledge is revisited in structured, layered ways. A spiral curriculum for rhythm, timbre, and auditory analysis ensures recurring engagement with core auditory domains, reinforcing and expanding skills over time. Classroom group entrainment games integrate social and rhythmic learning while supporting attentional and behavioural development. Emerging VR-based spatial listening labs provide immersive environments where learners can train auditory scene analysis and spatial perception in realistic yet controllable contexts (Han et al. 2024).

Longitudinal and cross-sectional research indicates that auditory cortex size and synchronization predict not only musical skills but also literacy and attentional abilities in children (Schneider et al. 2014). The AMseL longitudinal findings (Schneider et al. 2023) support *CETra*'s spiral-curriculum approach, integrating perception, cognition, and emotion across development. Moreover, short-term training studies (Schneider et al. 2022) show how adaptive, individualized methods can quickly enhance auditory discrimination and attention, making the case for personalized ear-training design.

Going one step further, *CETra* can also function as a tool for balancing cognitive resources for learners across diverse fields who face high levels of stress and performance pressure. Research shows that musical engagement reduces stress and enhances resilience, with structured music training lowering performance anxiety and perceived stress in student populations (Nwokenna et al. 2022). These effects are not merely emotional but also cognitive: by strengthening self-regulation, attentional control, and working memory under challenging conditions, musical practice equips learners to maintain cognitive efficiency when demands are high.

CETra can incorporate evidence-based self-control techniques for optimizing cognitive resources under stress. Controlled breathing and rhythmic entrainment have been shown to stabilize physiological arousal (Pozzato et al. 2025) and improve attentional focus (Jha et al. 2007). Mental rehearsal and imagery, widely used in performance psychology, reduce cognitive load by pre-activating relevant neural networks before execution (Lotze et al. 2006). Metacognitive strategies such as self-monitoring and reflective journaling enhance awareness of attentional lapses and support adaptive allocation of effort (Efklides 2011). Cognitive reappraisal – reframing stress as challenge rather than threat – promotes greater working memory efficiency and resilience during demanding tasks (Jamieson et al. 2013).

Success in pedagogical spotlight interventions can be measured using metrics such as course-level mastery paths, which track longitudinal progression across competencies, and standardized listening transfer tests, which assess the extent to which classroom training generalizes to authentic musical and communicative contexts. By uniting evidence-based strategies with scalable instructional design, the pedagogical spotlight ensures that *CETra* is not only a set of isolated practices but a coherent, progressive, and transformative approach to music and cognitive education. These results align with the pedagogical case for explicitly integrating psychosocial skills into music curricula. While traditional programs rarely teach these skills, emerging evidence suggests that systematically cultivating them may substantially support musical giftedness education (Voitova et al. 2025).

Within the pedagogical spotlight, these considerations underscore that *CETra* is not intended as a catalogue of prescriptive exercises but as a conceptual framework. Detailed examples and training protocols are intentionally reserved for future work directed at practitioners and specific learner groups. Here, the aim has been to articulate principles that allow readers and instructors to critically reflect on their current practice, to recognize where traditional approaches converge with *CETra*, and to identify points of divergence.

Illustrative directions highlight this interface. Solmization systems – whether perfect or relative – can be complemented, or in some cases reoriented, toward interval-based labelling, enabling learners to internalize absolute intervallic structures rather than anchoring them solely within a tonal framework. Research suggests that interval-focused encoding fosters more durable auditory schemas and enhances transpositional flexibility (Halpern 1989). Similarly, memorization strategies may shift from reproduction to generative activity: learners might be invited to compose and retain their own melodic material within multi-voice textures, a process shown to deepen memory consolidation and strengthen transfer (Fiorella et al. 2015). Finally, the balance between harmonic and non-harmonic material can be calibrated to the learner's level of experience, consistent with evidence that graded exposure to increasing complexity supports perceptual acuity and cognitive resilience (Bigand et al. 2006).

In this way, the pedagogical spotlight brings *CETra* into dialogue with established practice, while also extending beyond it. This provides a natural bridge to the conclusion, where the broader implications of *CETra* – as both a framework and a reorientation of ear training – can be articulated.

CONCLUSION

Taken together, the spotlight framework illustrates that ear training is not a narrow technical exercise but a multifaceted process grounded in cognitive, emotional, social, and physiological dimensions. It is important to broaden and enrich ear training by respecting all of these perspectives. For example, beginners benefit from being given time to explore the qualities of sound in diverse musical contexts, fostering curiosity and perceptual sensitivity before more advanced technical demands are introduced. Psychoacoustic training sharpens attention to detail, while social and behavioural approaches cultivate adaptability, collaboration, and reflective practice. Psychoemotional strategies ensure that motivation and affect remain central to sustained engagement, whereas neurophysiological and physical spotlights remind us that listening is embodied, predictive, and deeply rooted in brain–body networks. Finally, the pedagogical spotlight highlights the importance of curriculum design in weaving these strands together across developmental stages, from early childhood through professional musicianship.

The philosophy that emerges from this framework is that ear training must balance structure with exploration, discipline with creativity, and technical precision with emotional resonance. At its core, the most important element is the circulation between gaining knowledge and experiencing pleasure: progress in auditory skills should generate aesthetic enjoyment, and that enjoyment, in turn, fuels further learning. Effective practice strategies should therefore target not only measurable outcomes such as accuracy or memory retention but also the cultivation of joy, attentional flexibility, resilience, and cooperative listening. By uniting evidence-based methods with an openness to cultural diversity, embodied practice, and evolving technologies, *CETra* establishes a holistic model of ear training – one that prepares learners not only to master musical repertoire but also to listen, interact, and create with greater depth, imagination, and satisfaction throughout their lives.

Ultimately, *CETra* demonstrates that ear training is not merely a narrow exercise in technical listening, but a gateway to broader cognitive development and enriched communication. It reframes ear training from a specialized drill into a dynamic, integrative model of human learning. By aligning knowledge with pleasure, precision with creativity, and discipline with social and emotional engagement, *CETra* outlines a path for twenty-first-century music education. As research continues to refine its methods and document transfer effects, *CETra* is positioned to play a pivotal role in bridging music, neuroscience, and education – ensuring that ear training produces not only skilled musicians but also more attentive, adaptive, and connected human beings. Above all, *CETra* remains inherently open to interdisciplinarity, inviting dialogue across fields and reaffirming music education as a site of innovation, integration, and cognitive growth.

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NO DZIRDES TRENIŅA UZ KOGNITĪVI ORIENTĒTU DZIRDES TRENĒŠANU: *CETra* IETVARA PAMATOJUMS

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Raksts analizē kognitīvā dzirdes treniņa (*Cognitive Ear Training* – *CETra*) koncepciju kā jaunu, starpdisciplināru ietvaru, kas paplašina uz mūzikas stilos balstītu dzirdes trenēšanu (pedagoģiskajā praksē tiek konceptualizēts kā solfedžo) no tehnisku muzikālu prasmju apguves līdz mērķtiecīgai kognitīvo komponentu attīstībai. Autori uzsver, ka dzirdes treniņš vēsturiski tiek fokusēts uz toņaugstumu, ritmu, intervālu, harmoniju un dažādu modeļu precīzu atpazīšanu un reproducēšanu, taču bieži nepietiekami ņem vērā kognitīvos priekšnosacījumus, kas nodrošina mācīšanās procesu: uztveri, uzmanību, darba atmiņu, izpildfunkcijas, domāšanu, pašregulāciju un motivāciju.

Rakstā *CETra* tiek definēta kā strukturēta pieeja, kurā skaņa, klusums un telpiskā uztvere tiek izmantoti kā vide kognitīvo komponentu savstarpējai sasaistīšanai un nostiprināšanai. Šī pieeja balstās uz pierādījumiem kognitīvajā neirozinātnē, mūzikas psiholoģijā, valodas–mūzikas pārneses pētījumos, neiroplastiskuma teorijā. Tā tostarp iekļauj prognozējošo kodēšanu, kas raksturo smadzeņu spēju **nepārtraukti veidot prognozes** par to, kas notiks tālāk, un salīdzināt šīs prognozes ar reālo sensorisko ievadi. Tā iekļauj arī emocionālo un sociālo aspektu iesaisti mācīšanās procesā. Autori argumentē, ka dzirdes trenēšana jau pēc būtības darbojas kā kognitīvo komponentu treniņa forma, taču šī pieeja līdz šim nav bijusi sistemātiski konceptualizēta vai mērķtiecīgi strukturēta.

Svarīga raksta daļa ir veltīta tam, kāpēc kognitīvais dzirdes treniņš līdz šim nav nostiprinājies kā atsevišķs pētniecības jēdziens. Kā galvenie iemesli minēti vēsturiskais skatījums uz solfedžo kā mūzikas teorētisku (tehnisku) disciplīnu, terminoloģiskā plaisa starp mūzikas pedagoģiju un kognitīvo zinātni, metodoloģiskās grūtības standartizēt tādus dzirdes uzdevumus, kas nav saistīti ar mūzikas teoriju, pētījumu fragmentācija un skaidras praksē lietojamas definīcijas trūkums. *CETra* tiek piedāvāta kā iespējama šī brīža atbilde.

CETra teorētiskais kodols ir starmešu ietvars, kas ietver septiņas savstarpēji saistītas dimensijas: 1) psihoakustisko, 2) sociālo, 3) uzvedības, 4) psihoemocionālo, 5) neirofizioloģisko, 6) fizisko (ķermenisko) un 7) pedagoģisko. Katra no šīm dimensijām izgaismo atšķirīgu klausīšanās un mācīšanās aspektu – no smalkas akustisko pazīmju (veido pamatu tam, ko vēlāk smadzenes interpretē kā fonēmas, vārdus, melodijas vai ritmus) atšķiršanas un neirālās sinhronizācijas līdz kopmuzicēšanai, emocionālajai motivācijai, metakognitīvai pašregulācijai un mācību dizainam. Kopā tās veido holistisku skatījumu, kur dzirdes trenēšana vairs netiek uztverta kā mūzikas teorētisku uzdevumu kopums, bet gan kā dinamiska sistēma, kas attīsta pārnesamas prasmes arī ārpus mūzikas konteksta.

Rakstā īpaši uzsvērta **zināšanu pārnese** – gan no mūzikas uz valodu, gan uz uzmanību, atmiņu, sociālo kognīciju un problēmrisināšanu. Tiek aplūkoti pētījumi par ritma nozīmi runas uztverē, tembra un telpiskās dzirdes lomu auditorajā analīzē, kā arī emocionālā gandarījuma un neirālo mehānismu nozīmi motivācijas uzturēšanā. *CETra* tiek pozicionēta kā pieeja, kas apzināti izmanto neiroplastiskumu un prognozējošos mehānismus, vienlaikus veicinot kognitīvo elastību un radošu klausīšanos.

Noslēgumā autori secina, ka *CETra* piedāvā paradigmas maiņu mūzikas izglītībā: dzirdes treniņš tiek pārorientēts uz daudzdimensionālu kognitīvas attīstības modeli, ne tikai mūzikas izglītības ietvaros. Šī pieeja ļauj apvienot precizitāti ar radošumu, zināšanu pārnesi ar gandarījumu, individuālu darbu ar sociālu mijiedarbību, kā arī paver iespējas pielietojumam izglītībā, terapijā un tehnoloģiski balstītās mācību vidēs. *CETra* tiek piedāvāta kā atvērts, starpdisciplinārs ietvars turpmākiem pētījumiem un praktisku uzdevumu izstrādei, kas stiprina saikni starp mūziku, kognīciju un cilvēka mācīšanās potenciālu kopumā.

THE IMPACT OF MULTILINGUALISM ON MUSICAL ABILITIES

Maria Schneider, Christine Groß, Markus Christiner

Research has shown that musical ability influences language capacity across multiple domains. In this study, we reversed this perspective by investigating whether the degree of multilingualism – measured as the number of foreign languages spoken at B2 level – impacts musical ability. We recruited 176 participants who completed perceptual musicality, singing, foreign language pronunciation, and short-term memory (STM) tasks, and self-reported their educational status. As expected, results revealed significant correlations among all variables examined. We conducted conventional regression models with degree of multilingualism as the dependent variable, followed by the reverse model predicting musicality from language-related predictors. Both models successfully accounted for variance in their respective outcome variables. Critically, the reverse model showed that degree of multilingualism and STM capacity jointly predict musical ability (R^2 = 17%), suggesting bidirectional rather than unidirectional influences between these auditory domains. This suggests that musicality and foreign language training engage similar underlying mechanisms applicable across both domains.

Keywords: musicality, musical perception, musical production, foreign language learning.

INTRODUCTION

The relationship between musicality and language abilities has been a subject of extensive research, and studies investigating the overlaps between both domains are increasingly recognized as a promising resource for developing innovative approaches for both language and music learning. The rationale behind this development is well-founded, as music and language share a number of fundamental characteristics, particularly in terms of rhythm and pitch (Jackendoff and Lerdahl, 2006, 161). Pitch is the most prominent aspect in language and music (Liu and Kager 2017, 56). In both, speech and music, the pattern of pitch over time, also referred to as pitch contour, is relevant. Research has postulated that perception of pitch changes in spoken language is enhanced following musical training, suggesting a transfer effect whereby auditory processing skills acquired through musical practice facilitate improved language abilities (Schön et al. 2004, 387). Another key feature shared by language and music that is most relevant is rhythm: In language it helps to group sounds and pauses into meaningful units such as words, and sentences, while in music, it serves to organize phrases and motives into coherent sequences (Roncaglia-Denissen et al. 2018, 2).

As Aniruddh Patel p. 141 notes, words are often grouped into "rhythmic chunks" (Patel 2003, 140–143). The presence of parallel rhythmic structures in music and speech may thus contribute to deeper cognitive and neural links between these two domains. These shared features of rhythm and pitch contour support the assumption that musical abilities may exert a positive transfer effect on linguistic processing, potentially enhancing skills such as speech perception, imitation and pronunciation in foreign language learning (Christiner and Reiterer 2018; Milovanov et al. 2010).

Musicality is not only linked to enhanced perceptual abilities, but also to performance skills. It could be assumed that individuals with strong perceptual capacities are likewise more proficient in musical performance or singing. While this tends to be the case, research has also demonstrated the opposite: accurate perception does not necessarily translate into accurate performance, either in phonetic language tasks or in music (Golestani and Pallier 2007; Christiner and Reiterer, 2019; Christiner and Reiterer 2015; Christiner et al. 2022a). To more comprehensively capture the construct of musicality and its relation to language, it is essential to assess both music perception and production abilities. Including both dimensions allows for a more complete representation of an individual's musical skills. Singing is one of the most accessible tasks for assessing productive musical skills, as it measures musical training and can be applied to both professionals and non-professionals (Dalla Bella et al. 2007, 99; Dalla Bella and Berkowska 2009, 105).

Singing in particular – as a form of musical-linguistic expression – demonstrates promising overlaps with productive linguistic skills, including aspects such as (foreign language) pronunciation and the ability to mimic accents (Coumel et al. 2023, 5; Christiner et al. 2022b). Relatedly individuals who perceive certain languages as more melodic tend to retrieve and pronounce melodic-sounding utterances more accurately (Christiner et al. 2021, 15). Recent research also suggests that the ability to produce intelligible utterances in unfamiliar languages is related to singing ability (Christiner et al. 2023, 14). The findings of this study suggests that both musical perception and singing ability correlate with the intelligibility of newly acquired utterances. However, when entered together into regression analyses, singing aptitude emerges as the stronger predictor, while perceptual measures no longer account for unique variance. This pattern indicates that singing constitutes the more decisive factor in explaining early L2 speech production (Christiner et al. 2023, 11).

Studies investigating singing have also shown that singing new vocabulary enhances memorization (Ludke et al. 2014, 51), which may clarify the connection between singing ability and foreign language pronunciation (Christiner 2020; Christiner and Reiterer 2018, 11) as well as vocabulary acquisition (Thiessen and Saffran 2009). This emphasizes the close connection between productive musical skills such as singing abilities and language acquisition and demonstrates the value of conducting more in-depth research in this area.

On the other hand, research on perceptual musical ability has revealed positive transfer effects to language perception, highlighting substantial overlaps that imply shared cognitive and neural mechanisms supporting auditory processing in both the musical and linguistic domains. Musicians exhibit perceptual enhancements in various language-specific abilities, including phonological processing (Anvari et al. 2002), verbal memory (Chan et al. 1998), verbal intelligence (Moreno et al. 2011), as well as voice pitch discrimination (Bidelman and Krishnan 2010) and tone syllable perception in Mandarin (Christiner et al. 2022b). Musicians also show sensitivity to prosodic cues and improved second language proficiency (Slevc and Miyake 2006). Moreover, musical training has been shown to improve the neural processing of speech (Besson et al. 2011; Parbery-Clark et al., 2012; Intartaglia et al. 2017). More recent research has shown that musically trained participants exhibit superior auditory–phonological pattern recognition, particularly for longer speech sequences with low linguistic content (Christiner and Groß 2025, 9). Here "pattern" refers to the comparable perceptual ability to retain short melodies and unfamiliar multi-syllabic phrases in memory – suggesting that musical auditory skills facilitate the processing of both musical and phonological sequences. Following the above discussion, musicality emerges as a multifaceted construct. When assessing musicality, measuring perceptual abilities alongside singing ability offers a comprehensive approach to capturing its complexity.

In studies examining the relationship between language and music, STM – a subcomponent of working memory (WM) capacity – plays a crucial role and should therefore always be assessed, as STM capacity influences both language and musical abilities. In language research, STM and WM capacity has been shown to be one of the most important predictors that influence mastery in first and second language capacity (Wen et al. 2017; Wen et al. 2019). More recent research demonstrates that music and language rely on overlapping STM and WM resources, particularly verbal rather than visuospatial subsystems. The aforementioned study revealed that musicians tend to achieve higher accuracy on WM tasks involving verbal and musical material, consistent with an enhanced verbal WM capacity associated with musicianship (Bugos et al. 2021, 7).

Numerous studies have demonstrated that musical ability predicts language functions, while considerably less research has examined the relationship in the opposite direction or conceptualized it as a bidirectional process. For instance, bidirectional transfer effects have been demonstrated for pitch experience, from speech to music and vice versa (Bidelman et al. 2011, 432). This study demonstrates that neural mechanisms recruited for both musical and linguistic pitch processing are sharpened by years of active listening to complex pitch patterns, contributing to bidirectional transfer effects between the domains (Bidelman et al. 2011, 432). Consistent with this view, neuroscientific research demonstrates that both musicians and bilinguals exhibit increased grey matter volume (Mechelli et al. 2004, 757; Schneider et al. 2055, 388), which is associated with musical ability (Schneider 2002, 688) and enhanced language learning capabilities (Mechelli et al. 2004, 757).

Building on these behavioral and neuroscientific parallels, the mostly considered unidirectional transfer from music to language warrants reconsideration as bidirectional. Notably, the number of languages spoken predicts further language learning aptitude (Christiner et al. 2021), paralleling how proficiency across multiple instruments facilitates additional musical skill acquisition (Christiner 2020). Both multilingualism and musicality also enhance unfamiliar language learning (Christiner and Groß 2025) – raising the question of whether extensive multilingual experience might likewise boost musical performance. See figure 1 for the directions of influence.

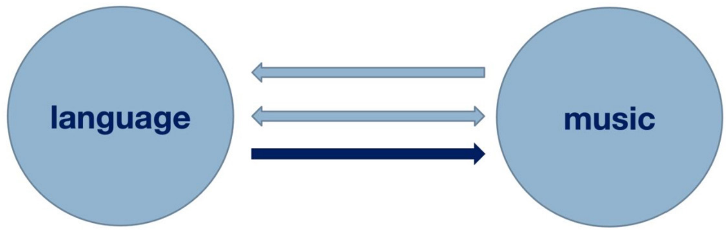

Figure 1. Depicts the influence from the musical domain to the linguistic domain (light blue arrow), the bidirectional direction in which the domains influence each other (second light blue arrow with two arrowheads), and the direction hypothesizing the influence of linguistic abilities to musical abilities (dark blue arrow).

This study addresses three main hypotheses. First, we examine whether multilingualism – measured as the number of foreign languages spoken at B2 level or higher – is positively associated with musicality. Second, since previous research has found positive associations between multilingualism, STM, and pronunciation skills, we included a pronunciation task and a STM measure as control variables. This approach allowed us to verify whether our variable capturing the degree of multilingualism aligns with established findings linking foreign language proficiency to enhanced STM capacity and pronunciation ability. Third, since individuals with higher education levels are more likely to have learned musical instruments and thus may perform better on musicality measures, we considered education as a confounding variable to assess whether it influences the relationship between musicality and the degree of multilingualism.

METHODS

Participants

The study included a total of 176 German native speakers (95 women, 81 men; M = 24.23 years, SD = 11.48). The recruitment criteria were designed to include native German speakers with an interest in foreign languages, who, however, were neither able to comprehend nor speak Mandarin, the language used in the L0 production tasks. Additionally, participants were expected to have achieved at least a B2 proficiency level in at least one foreign language, indicating a fluent command capable of understanding complex texts, engaging in spontaneous conversation with native speakers, and expressing detailed viewpoints on a variety of topics. Based on these recruitment criteria, 187 participants were originally invited to take part in the study. However, 11 were excluded from the final sample, because they did not complete the tests. All participants provided informed consent before the test session and took part voluntarily. The study was approved by the Rīga Stradiņš University (RSU) Research Ethics Committee (2-PĒK-4/3/2022).

To collect detailed data about the participants' language and musical background, and to verify that they met the recruitment criteria, participants were invited to complete a self-report questionnaire and were also interviewed. The questionnaire and interview responses showed that all participants were German native speakers who had been raised in primarily monolingual environments. Besides German, the participants could speak other foreign languages such as English, French, Italian, Spanish, Portuguese or Dutch. While 57 participants reported never having learned to play a musical instrument, 119 participants reported having learned to play a musical instrument at some point in their lives.

Testing procedure

Prior to testing, participants' suitability for participation in the study (e.g. language background) was assessed. If participants fulfilled the inclusion criteria, they were provided with login data and completed all measures, except for the singing and language pronunciation tasks, online, as all tests and questionnaires were computer-based. First, participants filled in the questionnaire, which was followed by the musicality and STM measures. Finally, the singing and language pronunciation tasks were recorded in the lab.

Musicality tests and language assessment

Gordon's Advanced Measures of Music Audiation (AMMA)

We used the Advanced Measures of Music Audiation (AMMA; Gordon 1989) to assess individual differences in musical aptitude. It measures an individual's ability to perceive and discriminate tonal and rhythmic patterns. The AMMA consists of rhythm and tonal discrimination tasks, in which participants must determine whether the second excerpt is the same as the first or differs in tonality or rhythm. In the tonal part, excerpts differ in pitch/tonality but have the same rhythm. In the rhythm part, excerpts differ in tempo, meter or duration, but have the same tonality. The AMMA assessment is made up of 33 items in total, yet the first 3 items are familiarization tasks that are excluded from the ultimate data analysis. The AMMA provides a measure of innate musical aptitude, considered a strong predictor of potential for musical achievement and learning. This assessment is recognized for its role in predicting musical achievement and learning potential. It is widely employed in both educational and professional contexts to evaluate individuals musical abilities. The AMMA's design and implementation enable a nuanced understanding of participants' perceptual competencies in music, contributing valuable insights into their capabilities and areas for development.

Singing ability (Happy Birthday) and rating criteria

To test singing ability, the participants were asked to sing “Happy Birthday” as well as they could, using a key that they found most comfortable and enjoyable for their own singing voice. We chose a singing task to measure musical production because singing is a universal activity accessible to nearly everyone. Additionally, it is a skill that both professional musicians and non-professionals can perform, allowing us to obtain a musical production score from all participants, including those who do not play an instrument. Since singing ability improves with training, it is not solely an innate skill. This evaluation approach has been applied in several previous studies (Christiner 2013; Christiner and Reiterer 2013; Christiner et al. 2018, 2021; Christiner 2020). The singing performances of the participants were then rated and evaluated by a panel of singing experts, consisting of two male and two female raters. The raters were provided with detailed instructions regarding their tasks and the specific criteria for their assessments, namely evaluating the participants’ melodic and rhythmic abilities. Melodic singing ability was defined as the accuracy with which participants reproduced the melody of the original song, whereas rhythmic singing ability referred to the accuracy of reproduction of the original song’s rhythm. These two criteria were then combined into a single overall score for each participant. Specifically, the raters were instructed to evaluate the participants’ performances on scales ranging from 0 (lowest score) to 10 (highest score). To ensure the reliability of the ratings, intraclass correlation coefficients (ICCs) were calculated. The results demonstrated that the ratings provided by the expert panel were reliable, exceeding the commonly accepted threshold of 0.7. The AMMA score, measuring perception and the singing score, measuring musical production, were z-standardized and then added together to receive a valid musicality score (“musicality complex”) which comprises both musical perception as well as musical production.

Assessing Foreign Language Proficiency: Foreign Language Pronunciation Task

The study involved a speech production task where participants were asked to repeat three phrases of varying lengths (7, 9, and 11 syllables) of an unfamiliar language (Mandarin). This type of measurement has high ecological validity, as it resembles a language learning situation in the initial learning stages when individuals hear phrases for the first time (Christiner 2020; Christiner et al. 2021). Previous research has shown that individuals imitating unfamiliar, typologically different languages perform well regardless of the specific language repeated, suggesting that when language material is unfamiliar, its typological characteristics do not influence performance. Factor analyses have further demonstrated that short sequences of typologically diverse unfamiliar languages load onto the same factor, indicating that they measure general pronunciation ability (Christiner 2020, 155). Therefore, we selected Mandarin – a language typologically distant from the participants’ native (German) and foreign languages – to minimize educational and sociolinguistic biases, ensuring a reliable assessment of general speech imitation skills (Christiner and Reiterer 2013, 5). The original phrases of the Mandarin samples were spoken by native speakers. The participants listened to each sample three times before they had to imitate it. The assessment procedure followed previous research: the participants' recordings were normalized for loudness and then evaluated by five native speakers. The evaluators were tasked with assessing how well the participants preserved the rhythmical structure, melodic aspects, completeness of the sentence material, and the overall performance. They provided a score ranging from 0 to 10 for each of these four criteria, which were then combined into a single score. The inter-rater reliability of the evaluations was assessed using an intra-class coefficient analysis. The results demonstrated that the ratings provided by the expert panel were reliable, exceeding the commonly accepted threshold of 0.7.

Educational Status

The educational status of the participants revealed a diverse range of educational backgrounds. 50 participants completed the main general secondary school, 27 the apprenticeship, technical and vocational school, 54 the secondary academic school (general qualification for university entrance), 19 had a bachelor's degree, and 26 had obtained a master's or doctoral degree. The educational level scoring system used in this study, ranging from 2 to 6, was applied following previous research to reflect the hierarchical educational attainment levels from main general secondary school to master's or doctoral degrees (Christiner 2021).

The level of education of the participants should be taken into account, because education generally has an influence on other domains and can be seen a confounding variable: It is important to consider that people who have received a higher level of education are more likely to learn to play a musical instrument.

Degree of Multilingualism: Number of foreign languages (Level B2)

The number of languages spoken was assessed via a self-report questionnaire in which participants were asked to report only those languages they could speak at a B2 proficiency level or higher (i.e., "I can speak and understand most things without difficulties" or above). The maximum number of languages spoken at this level was four. Based on this information, a multilingualism score was calculated to quantify the degree of multilingual proficiency among participants.

Short-Term Memory (STM)

To assess the STM capacity of participants, the Wechsler Digit Span test (Wechsler, 1939) was employed. This assessment consists of two parts: the forward digit span (STMF) and the backward digit span (STMB). Conducted online, the test presented auditory stimuli, requiring participants to repeat sequences of digits in either forward or backward order. The forward span included sequences ranging from 3 to 9 digits, while the backward span involved sequences from 2 to 8 digits. Participants received individual scores for each task, based on the number of digits they accurately recalled, with a maximum possible score of 14. Previous research indicates that adult participants typically achieve average scores of 7 to 8 on the forward span, while scores for the backward span are generally about one point lower (Christiner 2020, 275; Christiner et al. 2021). STM has been found to influence language competences (Dörnyei 2005; Wen and Skehan 2011; Wen et al. 2017). Therefore, when assessing language abilities, the capacity of STM should also be examined. In this study, STM capacity was assessed as a composite score of forward and backward digit spans.

RESULTS

Statistical Analysis

First, we calculated descriptive statistics and conducted correlational analyses to explore the relationships between the variables of interest, refer to Table 1 for more information. Next, we applied two regression models: the first representing the conventional approach, in which musicality beside other variables is treated as an independent variable and the degree of multilingualism as the dependent variable, examining which musical and other predictors explain multilingual abilities. In the second model, we reversed this direction by using musicality as the dependent variable to investigate whether language-related variables predict individual differences in musicality. Finally, we assessed whether the association between musicality and multilingualism might be confounded by participants' educational background.

Table 1. Descriptive statistics provide the descriptives of the variables under consideration

Variables	M	SD
Degree of Multilingualism	1.78	0.794
Education	3.68	1.378
Musicality Complex	0.00	0.81
Foreign Language Imitation	3.14	1.23
STM	13.50	3.14

Correlational Analysis

We conducted correlational analyses to examine the relationships among the variables of interest. All variables showed significant positive correlations with degree of multilingualism, confirming our hypothesis. Our initial objective was to identify which specific variables showed positive correlations with this degree of multilingualism. These patterns indicate that cognitive and perceptual skills underpin multilingual success, with education emerging as the strongest contributor and musicality as the second most prominent factor. Consistent with our hypotheses, the results confirmed that each variable under investigation was positively correlated with multilingualism to varying extents, see table 2 for details.

Table 2. Results of the correlational analysis.

	Degree of Multilingualism	Musicality Complex	Foreign Language Imitation	STM	Education
Degree of Multilingualism	1	.309**	.243**	.164*	.337**
Musicality Complex	.309**	1	.255**	.308**	.281**
Foreign Language Imitation	.243**	.255**	1	.244**	-0.026
STM	.164*	.308**	.244**	1	.251**
Education	.337**	.281**	-0.026	.251**	1

** *means that p<0.01 (uncorrected, two-tailed)*

* *means that p<0.05 (uncorrected, two-tailed)*

Partial Correlations

Given that individuals with higher education levels are more likely to have received training in playing musical instruments which may enhance performance on musicality measures, and are also more likely to have received extensive foreign language education, we treated education as a potential confounding variable in our analyses. To assess whether education influences the relationship between musicality and the degree of multilingualism, we conducted partial correlation analyses. These controlled for educational attainment while examining the associations between language proficiency scores, musicality measures, and the degree of multilingualism. Our approach allowed us to isolate the unique contribution of musicality to multilingualism beyond the shared variance explained by education. The original correlation between the degree of multilingualism and the music complex was r =0.309, p (two-tailed) < 0.01. The partial correlation, controlling for education, revealed a reduced but still significant association, r =0.237, p (two-tailed) < 0.01. This indicates that while the relationship between multilingualism and musicality diminishes when accounting for educational attainment, it remains statistically significant.

Regression analysis

While previous research and our introduction have emphasized that the connection between musicality and language may not be unidirectional, but rather reciprocal, our analyses were designed to examine both possible directions of influence.

Following inspection of the correlation matrix, two sets of regression analyses were conducted. In the first analysis, the degree of multilingualism was entered as the dependent variable. Only predictors that correlated significantly with this variable ($p < 0.05$; change in F) were included in the model. Results indicated that highest level of education, foreign language imitation, and the musicality complex together accounted for 20% of the variance in the degree of multilingualism. For further details, see Table 3.

Given the theoretical possibility that these associations could also operate in the opposite direction, a second regression analysis was performed with musicality as the dependent variable, and linguistic predictors (including degree of multilingualism, imitation ability, STM, and education) as independent variables. This approach allowed examination of whether musicality can also be predicted by linguistic variables in addition to the reverse, providing a more comprehensive understanding of the interrelationships between language and musical abilities. Details are provided in Table 4.

Table 3. Regression models explaining the variance in the degree of multilingualism

Predictor	**Partial correlation (pr)**	***p*-Value**
Dependent variable: *Degree of Multilingualism* $R = 0.34$, $F(1, 174) = 22.35$, $p < 0.001$		
Education	0,34	< 0.001
Dependent variable: *Degree of Multilingualism* $R = 0.42$, $F(1, 173) = 13.30$, $p < 0.001$		
Education	0,35	< 0.001
Foreign Language Imitation (production)	0,27	< 0.001
Dependent variable: D*egree of Multilingualism* $R = 0.45$, $F(1, 172) = 5.55$, $p = 0.026$		
Education	0,30	< 0.001
Foreign Language Imitation (production)	0,22	< 0.001
Musicality Complex	0,18	0.020

Table 4. Regression models explaining the variance in musicality complex

Predictor	**Partial correlation (pr)**	**p-Value**
Dependent variable: *Musicality Complex* R = 0.31, F(1, 174) = 18.33, p < 0.001		
Degree of Multilingualism	0,31	< 0.001
Dependent variable: *Musicality Complex* R = 0.41, F(1, 173) = 14.12, p < 0.001		
Degree of Multilingualism	0,31	< 0.001
STM	0,31	< 0.001

Discussion

In this study, we aimed to investigate whether musical capacity can be predicted by the degree of multilingualism – specifically, whether individuals who speak more languages also exhibit enhanced musical skills – contrary to many previous studies that predominantly examined the influence in the opposite direction.

In order to examine the impact of foreign languages on musical ability, a multifaceted approach was employed. This involved the measurement of musical ability and linguistic abilities, the assessment of STM and educational status, and the number of foreign languages spoken at a B2 level, resulting in the degree of multilingualism. Subsequently, correlational analyses, partial correlations, and regression analyses were conducted. As expected, correlational analyses revealed that all variables under consideration were significantly associated with the degree of multilingualism. Building on these correlational findings, we further explored the predictive relationships by conducting two regression models. The first followed the conventional approach by treating the degree of multilingualism as the dependent variable. This model demonstrated that multilingualism could be predicted by education level, musicality, and foreign language imitation skills – predictors validated by numerous prior studies as relevant for foreign language proficiency (Christiner et al. 2022b; Christiner et al. 2023, 2). We performed this approach for reasons of transparency but will not discuss the results in detail, as they have been addressed in multiple previous investigations (Slevc and Miyake 2006; Wong et al. 2007; Anvari et al. 2002).

Reversing this approach, we used musicality as the dependent variable. The results showed that both the degree of multilingualism and STM capacity significantly predicted musical ability (see Table 4), suggesting a potential bidirectional positive transfer between music and language faculties. To further confirm this relationship beyond the preceding analyses, partial correlation analyses were conducted controlling for educational attainment as a potential confounding factor in the multilingualism–musicality link. These analyses indicated that the strength of the association slightly decreased but remained statistically significant, suggesting that the capacity to speak multiple languages independently contributes to musical ability. In light of these findings, the roles of multilingualism degree and STM capacity as predictors of musicality are discussed.

WM encompasses Baddeley's multicomponent model – including the phonological loop, visuospatial sketchpad, central executive, and episodic buffer – that combines storage with active manipulation and attentional control (Cowan 2008, 326), whereas STM represents simple temporary storage without these processing elements (Baddeley 2012, 4). STM capacity is one of the most extensively studied predictors of individual differences in language ability (Dörnyei 2005; Wen and Skehan 2011; Wen et al. 2017). In contrast, the relationship between musicality and STM capacity remains less well studied. Same studies suggest that auditory STM processing of musical and verbal sounds overlaps only minimally (Williamson et al. 2010, 172), while more recently evidence has been provided for the relationship between musical training and improved STM and WM capacity (Groussard et al. 2020). In this study, we found that STM capacity also predicts variance in musical ability performance. The reasons why STM and the degree of foreign language capacity predict musical ability could be a result of different mechanisms. First, STM capacity is trained by language learning and may enhance sequence memory in music, while musical training likely boosts STM capacity in return – suggesting bidirectional pathways across these auditory domains rather than a unidirectional model.

Second, the relationships between musicality, STM, and multilingual proficiency may stem from their shared perceptual-cognitive nature. STM capacity is closely associated with the ability to recall larger phonological units and emerges as a key cognitive predictor of advanced language skills in multilinguals (Christiner 2020, 80). Research shows that auditory phonological pattern recognition of unfamiliar languages correlates with both the number of foreign languages spoken and musical ability (Christiner and Groß 2025). Common to all three – STM (measured via increasing digit spans in this study), musicality tests (short musical sequences), and larger auditory phonological patterns (multi-syllabic stimuli) – is the core demand of retaining and repeating increasingly complex auditory sequences.

Third, memory is central to auditory processing: when listeners encode unintelligible utterances they rely chiefly on phonological features rather than semantic content (Baddeley 2003, 832). Musical experience bolsters this phonological/auditory coding and retention, with research showing that musicians outperform non-musicians on STM tasks (Tierney et al. 2008 Christiner and Reiterer 2013).

Multilingual exposure and musical training likely enhance this shared sequence retention capacity, facilitating bidirectional transfer across domains: prosodic patterns from diverse languages generalize to melodic structures and digit strings, rather than unidirectional effects. This mechanism accounts for the observed predictive relationships, where STM capacity and degree of multilingualism jointly explain variance in musicality performance.

Our findings contribute to the existing body of literature on multilingualism and musical abilities by illustrating the interplay between productive musical skills and foreign language proficiency. Unlike the majority of previous studies, which primarily explore the influence of musicality on linguistic skills, our research emphasizes the impact of linguistic capabilities on musical competencies. This study provides preliminary evidence for bidirectional associations between linguistic and musical abilities.

The results of our study suggest that research should move beyond unidirectional models when addressing overlaps between musicality and language ability. Similarly, given evidence of bidirectional training effects between these faculties, music and language education warrant integration to maximize cognitive transfer benefits.

However, the exclusively German-native sample limits generalizability. Future studies should test whether these bidirectional relationships hold across typologically diverse populations while controlling for language-specific influences (e.g., tonal vs. non-tonal systems). Future studies should test whether these bidirectional relationships between degree of multilingualism, STM capacity, and musicality hold across typologically diverse populations while controlling for language-specific influences (e.g., tonal vs. non-tonal systems).

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DAUDZVALODĪBAS IETEKME UZ MUZIKĀLAJĀM SPĒJĀM

Marija Šnaidere, Kristīne Grosa, Markuss Kristiners

KOPSAVILKUMS

Šī pētījuma mērķis bija izpētīt daudzvalodības ietekmi uz muzikālajām spējām. Izglītība un īstermiņa atmiņa tika uzskatīti par kontrolējošiem mainīgajiem. Tika pārbaudītas trīs hipotēzes par saikni starp svešvalodu prasmi un muzikālajām spējām.

Pirmkārt, tika pārbaudīts, vai vairāku svešvalodu zināšanas B2 vai augstākā līmenī ir saistītas ar muzikālajām spējām. Otrkārt, tā kā daudzvalodība ir spēcīgs indikators indivīda spējai apgūt jaunas valodas, pētījumā tika iekļauts izrunas uzdevums kā kontroles mainīgais, lai noteiktu, vai vairākās valodās runājoši indivīdi demonstrē labākas izrunas prasmes. Šī saikne pamato atziņu, ka vienas valodas zināšanas sekmē spēju apgūt citas valodas. Treškārt, tā kā indivīdi ar augstāko izglītību biežāk ir apguvuši kāda mūzikas instrumenta spēli un tādējādi var sasniegt labākus rezultātus mūzikas testā, izglītība tika uzskatīta par kontrolējošo mainīgo, lai novērtētu, vai tā ietekmē saikni starp muzikālajām spējām (novērtētas pēc dziedāšanas spējām un kopējā AMMA rezultāta) un daudzvalodības pakāpi.

Pētījumā kopumā piedalījās 176 vācu valodā runājoši cilvēki, kuriem tā ir dzimtā valoda. Dalībnieki aizpildīja anketu par savu valodas un mūzikas pieredzi un izglītību. Lai novērtētu muzikālās spējas, pētījumā tika iekļauti šādi mērinstrumenti: Gordona *Mūzikas audiācijas padziļinātais tests* (AMMA), kas mēra mūzikas uztveri, kā arī dalībnieku ieraksti, dziedot "Happy Birthday". Ierakstos tika vērtēta intonatīvā un ritmiskā precizitāte, ko izteica punktos. Lielāks punktu skaits korelēja ar augstāku muzikalitātes pakāpi. Abu mūzikas uztveres testu rezultāti tika standartizēti, aprēķinot z-vērtības, kur katra individuālā vērtība tika izteikta attiecībā pret izlases vidējo un standartnovirzi.

Svešvalodu prasmi novērtēja, izmantojot uzdevumu, kurā dalībniekiem bija jāatkārto trīs frāzes nepazīstamā valodā. Svešvalodu prasmes novērtēja speciālisti, kuriem uzdevumā iekļautā valoda ir dzimtā valoda.

Īstermiņa atmiņa tika novērtēta, izmantojot Vekslera *Skaitļu amplitūdas testu*, kurā dalībnieki atkārtoja un atcerējās skaitļus no 3 līdz 9, secīgā un apgrieztā secībā.

Tika veikta korelācijas analīze mūzikas un valodas mainīgajiem, īstermiņa atmiņai un izglītības rezultātiem, kā arī daļējās korelācijas.

Pētījumā tika izvērtēta korelācija starp valodas un muzikālajām spējām un izglītības līmeni. Tika konstatēta pozitīva korelācija starp daudzvalodības pakāpi un muzikālajām spējām, kuru raksturotāji bija dziedāšanas sniegums un AMMA testa rezultāti. Iegūtie rezultāti liecina par pozitīvu saistību starp daudzvalodības pakāpi un dziedāšanas

spējām, kā arī mūzikas uztveri. Turklāt, tika konstatēta korelācija starp daudzvalodības pakāpi un īstermiņa atmiņas kapacitāti, kas liecina, ka daudzvalodība var būt saistīta ar veiksmīgāku īstermiņa notikumu apstrādi. Turklāt tika novērota korelācija starp muzikālo spēju rezultātiem un spēju imitēt svešvalodu.

Attiecībā uz daļējām korelācijām tika konstatēts, ka muzikālās spējas korelē ar izglītību. Tika secināts, ka korelācija starp valodas imitāciju un izglītību nav nozīmīga. Jāatzīmē, ka pastāv arī korelācija starp īstermiņa atmiņu un izglītību, kas liecina, ka indivīdiem ar labāku īstermiņa atmiņas kapacitāti ir lielākas izredzes sasniegt augstāku izglītības līmeni. Šie secinājumi uzsver attiecības starp valodas apguvi un muzikālajām spējām un to ietekmi uz izglītības rezultātiem.

NEURODIVERGENT SOUNDSCAPES: PROFILING MUSICAL STRENGTHS IN ADHD, ADD, AND DYSLEXIA

Christine Groß, Bettina L. Serrallach, Valdis Bernhofs, and Markus Christiner

This article introduces the concept of the Neuro-Auditory Profile, a multimodal framework for describing musical abilities in neurodivergent populations, with a particular focus on children and adolescents with Attention Deficit Hyperactivity Disorder (ADHD), Attention Deficit Disorder (ADD), and dyslexia. Drawing on a series of studies conducted between 2014 and 2023, the model integrates four dimensions: neuroanatomical structures, functional timing parameters (e.g., magnetoencephalography (MEG) latencies), psychoacoustic and musical performance, and metacognitive self-evaluation. Findings indicate that, despite documented perceptual deficits, adolescents with ADHD and ADD perform on par with control groups in improvisational and expressive musical tasks. This suggests that musical creativity and expressiveness may represent preserved or even enhanced domains of functioning. The results carry both theoretical and profiling implications, encouraging a shift away from deficit-oriented perspectives toward a differentiated understanding of musical potential. For music education, the model highlights new opportunities to support individual strengths in inclusive learning environments. Finally, the article outlines perspectives for the further development of the framework, emphasizing the need for validated instruments and ecologically valid performance tasks to enable more precise characterization of musical creativity in neurodivergent populations.

Keywords: Neuro-Auditory Profile; musical creativity; neurodiversity; ADHD; ADD; dyslexia; auditory processing; MRI; MEG; improvisation and expression; inclusive music education.

1. INTRODUCTION

Over the past decade, systematic musicology has increasingly engaged with questions of individual variability in auditory processing and musical behaviour, driven by advances in auditory neuroscience and developmental psychology. This shift reflects a growing recognition of the complex interplay between neurobiological, cognitive, and experiential factors that shape musical perception and production (Zatorre 2013; Müllensiefen et al. 2014). For example, individual differences in pitch perception, rhythm synchronization, and timbre discrimination have been linked to variations in auditory cortical structures and connectivity (Schneider et al. 2005; Schnupp, Nelken and King 2011; Hyde et al. 2009). At the same time, developmental studies underscore the role of early auditory and musical experiences in shaping neural plasticity and musical behavior across the lifespan (Trainor et al. 2009; Putkinen, Tervaniemi and Huotilainen 2013). Consequently, systematic musicology has begun to incorporate methods and models from differential psychology and cognitive neuroscience to better understand the roots and implications of inter-individual variability in musicality (Mosing et al. 2014; Gingras, Honing and Peretz, 2015).

Building upon this shift in focus toward individual variability in musical behavior and auditory processing, the concept of the Neuro-Auditory Profile has been introduced as a multimodal framework. It integrates neuroanatomical features, neurophysiological timing measures, and behavioural indicators of musicality to account for the complex relationship between auditory processing and musical expression. This research is essential not only for clarifying the mechanisms underlying the beneficial effects of musicality on auditory processing, but also for establishing a conceptual framework to examine the inverse pathway – that is, the development and characteristics of auditory deficits. Over the past decade, empirical research suggests that neurodevelopmental conditions such as Attention Deficit Hyperactivity Disorder (ADHD), Attention Deficit Disorder (ADD), and developmental dyslexia are associated with distinct auditory processing and anatomical patterns, some of which correlate with enhanced musical improvisation and expressive fluency, rather than deficits (Groß et al. 2022; Seither-Preisler et al. 2014; Serrallach et al. 2016).

The Neuro-Auditory Profile is a multimodal construct that integrates (1) neuroanatomical parameters – specifically the volume and ratio of Heschl's gyrus (HG) and the planum temporale (PT), (2) functional timing characteristics derived from auditory-evoked fields (such as hemispheric P1 latency asymmetries measured via MEG), and (3) psychoacoustic and musical performance indicators, including pitch discrimination and rhythm reproduction. It was designed to distinguish auditory phenotypes in children, including those associated with developmental disorders, with the goal of linking these profiles to behavioural capacities in music-making (Groß et al. 2022; Serrallach et al. 2016).

Studies have shown that children with ADHD, for example, often exhibit delayed P1 latencies in the left hemisphere and advanced responses in the right, accompanied by atypical HG/PT ratios and reduced auditory synchronization – especially in the absence of musical training (Seither-Preisler et al. 2014; Serrallach et al. 2016). Despite neurofunctional deviations, adolescents with ADHD and ADD performed on par with controls in rhythmic improvisation and musical expression. These findings challenge purely deficit-oriented perspectives on neurodevelopmental disorders, suggesting that divergent auditory processing does not necessarily impede, and may even coexist with, intact creative and expressive musical abilities (Groß et al. 2022, 12–16).

This shift in perspective calls for an expansion of the musicological framework. Rather than evaluating musicality solely on the basis of accuracy or reproduction (e.g., pitch matching or sight-reading), the Neuro-Auditory Profile proposes a broader view that includes temporal processing, behavioural flexibility, and metacognitive insight as further elements.

The empirical convergence of neurophysiological auditory markers and domain-specific musical strengths – especially in adolescents with ADHD and ADD – demonstrates the heuristic value of the Neuro-Auditory Profile not only for differentiated profiling of musical potential, but also for the theorization of musical potential as a dynamic and context-dependent phenomenon. Through the development of the Musical Performance Assessment Scale (MuPAS), musical behaviour was operationalized along six interrelated dimensions: rhythmic reproduction, rhythmic improvisation, pitch reproduction, pitch improvisation, musical expression, and auditory memory. These behavioural profiles could be statistically correlated with timing parameters, such as P1 latencies and hemispheric synchronization patterns, revealing that shorter latencies and reduced asymmetries in neurodivergent groups often co-occur with elevated improvisational fluency and expressive flexibility (Groß et al. 2022, 13-14).

Taken together, this growing body of research underscores the complexity of individual auditory and musical development. Existing research has provided robust evidence for individual variability in auditory cortical morphology (e.g., HG/PT ratios), neurofunctional timing parameters (e.g., hemispheric P1 latency asymmetries), and auditory perception in both neurotypical and neurodivergent populations (e.g., Seither-Preisler et al. 2014; Serrallach et al. 2016, 2022). However, this body of work has predominantly examined these markers in isolation, with limited integration of functional musical behavior – particularly creative and expressive performance – into the interpretation of auditory processing differences.

Consequently, there is an absence of models that have been iteratively developed across multiple studies and age groups, integrating structural, functional, behavioral, and metacognitive dimensions of auditory–musical processing over an extended research period.

The present manuscript addresses this gap by introducing and synthesizing the Neuro-Auditory Profile. Rather than reporting isolated findings, this article traces the longitudinal development of the model across successive empirical studies and demonstrates its epistemological relevance as a profiling approach.

The aim of this article is twofold: 1) to provide a chronologically structured synthesis of peer-reviewed studies conducted by the author's research group between 2014 and 2023 that contributed to the development and empirical grounding of the Neuro-Auditory Profile; and 2) to analyze the epistemological implications of this framework for systematic musicology, with particular attention to the identification of musical strengths in children and adolescents with ADHD, ADD, and dyslexia. Special emphasis will be placed on how the Neuro-Auditory Profile can inform inclusive practices in music education.

This multidimensional concept is illustrated in Figure 1. The subsequent sections will elaborate on these components in detail, drawing on empirical findings that establish the foundation of the model.

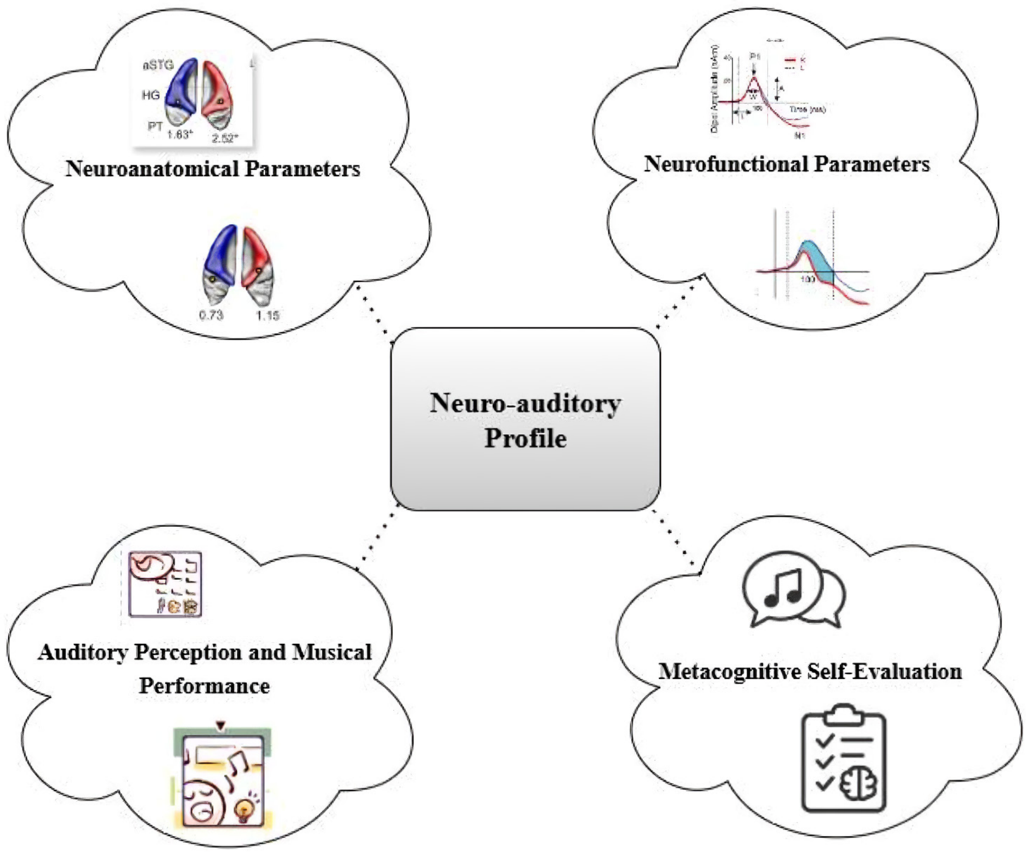

Figure 1. The Neuro-Auditory Profile. The concept of the Neuro-Auditory Profile integrates four dimensions: 1) neuroanatomical parameters (Heschl's gyrus (HG) / planum temporale (PT) ratio), 2) functional timing characteristics (e.g., P1 latency asymmetries), 3) psychoacoustic and musical performance (e.g., Musical Performance Assessment Scale (MuPAS)), and 4) metacognitive self-evaluation in musical and speech-related tasks. Own illustration based on previous research (Seither-Preisler et al. 2014; Serralach et al. 2016, 2022; Groß et al. (2022, 2023).

2. CHRONOLOGICAL OVERVIEW OF CORE RESEARCH

2.1 Chronological synthesis of empirical studies (2014 – 2023)

To enhance transparency regarding the development of the Neuro-Auditory Profile, this subsection provides a chronological synthesis of the empirical studies conducted between 2014 and 2023. The overview highlights how successive studies contributed distinct structural, neurofunctional, behavioural, and metacognitive dimensions to the evolving framework. This synthesis serves as an orientation for the subsequent subsections, which discuss the individual components of the profile in greater detail.

Table 1 Chronological development of the Neuro-Auditory Profile (2014–2023) across successive empirical studies cited in the present manuscript

Period	Study / Reference	Sample (N, age)	Design & Methods	Core contribution to the Neuro-Auditory Profile
2014	Seither-Preisler et al., 2014	N = 132 children (controls and children with AD(H)D), mean age 8.6–8.9 years	Cross-sectional; structural MRI (HG, PT), MEG (P1 latency, hemispheric synchrony), psychoacoustic test battery	Identification of stable neuroanatomical (HG/PT ratios) and neurofunctional timing markers (P1 latency/ asynchrony) linked to musical, literacy, and attention skills
2016	Serrallach et al., 2016	N = 147 children, 8–12 years (controls, ADHD, ADD, dyslexia)	Cross-sectional + longitudinal subsample; MRI, MEG, extended auditory perception battery	Differentiation of ADHD, ADD, dyslexia, and controls based on distinct auditory cortical morphologies and latency profiles
2022	Serrallach et al., 2022	N = 82 adults, mean age 35.6-42.6 (controls, ADHD, ADD)	Cross-sectional; MRI, MEG	Differentiation of ADHD, ADD, and controls in adults based on distinct auditory cortical morphologies and latency profiles
2022	Groß et al., 2022	N = 96 adolescents, 12–18 years (controls, ADHD, ADD, dyslexia)	Cross-sectional; MEG, MuPAS (behavioural musical performance), psychoacoustics	Shift from perceptual deficits toward expressive and improvisational musical strengths; introduction of the behavioral dimension
2023	Groß et al., 2023	N = 75 (3×25), 20–21 years (controls, ADHD)	Cross-sectional; complex auditory and musical tasks, self-evaluation measures	Integration of metacognitive self-assessment as an additional dimension, revealing dissociations between perceived and actual performance

This chronological synthesis illustrates how the Neuro-Auditory Profile evolved iteratively, with each research phase contributing a distinct dimension to the emerging framework.

Abbreviations: HG = Heschl's gyrus; PT = planum temporale; MRI = magnetic resonance imaging; MEG = magnetoencephalography; MuPAS = Musical Performance Assessment Scale.

2.2 Structural Markers of the Auditory Cortex

As illustrated in Figure 1, structural parameters represent one of the four key dimensions of the Neuro-Auditory Profile, providing the morphological scaffold for subsequent functional and behavioral analyses. The Neuro-Auditory Profile includes structural magnetic resonance imaging (MRI) findings comprising specific volumetric and asymmetry-based markers in auditory cortex regions. Seither-Preisler et al. (2014) demonstrated that children with musical training had enlarged Heschl's gyri (HG) compared to non-musicians, while those with AD(H)D showed reduced volumes of Heschl's gyri and enlarged volumes of the plana temporalia. Morphometric deviations in children diagnosed with AD(H)D and dyslexia were systematically explored in Serrallach et al. (2016), where HG/PT ratios served as indicators differentiating patients with ADHD, ADD, and dyslexia from controls. In this study all three disorder subgroups showed smaller HG and enlarged PT volumes in the left hemisphere, resulting in smaller left HG/PT ratios as compared to controls. In the right hemisphere, HG/PT ratios were generally higher and similar in controls and children with ADD, but clearly decreased in children with ADHD and dyslexia. Extending this research into adulthood, Serrallach et al. (2022) found that these structural differences persist in adults with ADHD and ADD, highlighting enduring reductions in left HG volumes, resulting in diminished left HG/PT ratios and distinct hemispheric patterns, with patients with ADHD showing lower right HG/PT ratios and patients with ADD a similar right HG/PT ratio compared to controls. Together, these structural features form a morpho-anatomical scaffold for the Neuro-Auditory Profile.

2.3 Neurofunctional Timing and MEG Latency Profiles

Across above mentioned studies, magnetoencephalography (MEG) served as a core methodology to assess auditory-evoked fields (AEFs), particularly focusing on the P1 component of the auditory-evoked response (P1 latency). Seither-Preisler et al. (2014) observed that musical training in children enhances bilateral P1 synchronization and accelerates latency, while children with AD(H)D showed delayed left-hemispheric latencies and premature right-hemispheric responses, indicative of inter-hemispheric asynchrony. Serrallach et al. (2016) extended this finding by linking diagnostic subtypes to distinct latency patterns. Controls showed well-balanced bilateral responses, with a mean absolute P1 asynchrony of 3.7 ± 1.6 ms. In disorder subgroups (ADHD, ADD and dyslexia), asynchronies were about fivefold larger and accompanied by distinct source waveform profiles. Dyslexics showed an enlarged P1 peak in the right hemisphere, ADHD children displayed temporally expanded responses in the left and reduced amplitude in the right, and ADD children exhibited bilaterally similar but temporally shifted waveforms. These findings were further supported in adults (Serrallach et al., 2022), where asynchrony patterns partially persisted but were less pronounced, potentially reflecting maturational or compensatory mechanisms.

2.4 Auditory Perception and Musical Performance

The behavioral dimension of the Neuro-Auditory Profile (see Figure 1) captures psychoacoustic and musical performance, which is further specified through measures such as MuPAS. Auditory perception and musical performance have been investigated in neurodivergent populations through increasingly refined methodological frameworks revealing fundamental differences between subgroups (ADHD, ADD, dyslexia) and neurotypical controls in both elementary psychoacoustic skills and complex musical capacities.

Seither-Preisler et al. (2014) found that children who spent more time practicing a musical instrument showed enlarged Heschl's gyri and increased right–left hemispheric synchronization of the primary evoked response (P1) to harmonic complex sounds. These anatomical features were positively correlated with performance in frequency discrimination, reading, and spelling skills.

When examining the auditory profiles of children diagnosed with ADHD, ADD, and dyslexia using a battery of psychoacoustic tasks, including basic sound processing (frequency, intensity, onset ramp, and tone duration discrimination) and complex auditory pattern recognition (meter, rhythm, melody, and pitch perception), distinct group differences emerged (Serrallach et al. 2016). Compared with the neurotypical control group, children with dyslexia performed significantly worse than all other groups on both elementary and complex auditory tasks. Moreover, they showed a relative predominance of spectral/timbral aspects in pitch perception in the Auditory Ambiguity Test (AAT). In contrast, children with ADHD were characterized by lower scores in the rhythmic and melodic subscales of the Intermediate Measures of Music Audiation (IMMA), whereas children with ADD exhibited no auditory deficits. These findings indicate that while dyslexia and ADHD are associated with measurable perceptual limitations, ADD may preserve auditory functions. This pattern supports the hypothesis that ADD may be characterized not by a generalized deficit, but by a neurocognitive style conducive to internal audiation, flexible attention, and creative auditory imagination, factors that may underlie superior performance in improvisational and expressive musical tasks.

In contrast to earlier studies that focused primarily on elementary auditory perception, Groß et al. (2022) introduced the Musical Performance Assessment Scale (MuPAS) for evaluating complex musical behavior in adolescents aged 12 to 18. This instrument comprises six subtests that assess both reproductive and generative dimensions of musical ability: rhythmic reproduction, rhythmic improvisation, pitch reproduction, pitch improvisation, musical expression, and rhythmic and pitch memorization. The MuPAS thus enables a multidimensional evaluation of musical competence, encompassing both accuracy-based performance and creative fluency.

Improvisation and Expression: Adolescents with ADHD and ADD performed on par with controls in rhythmic improvisation and musical expression. This is a novel finding, given that previous research has documented perceptual deficits – particularly in rhythm and melody perception – for ADHD. The results indicate that, despite such perceptual limitations, adolescents with ADHD and ADD can achieve musical performance levels in these creative and expressive domains comparable to those of unaffected peers.

Pitch Reproduction: Both ADHD and ADD groups performed similarly or slightly below controls in pitch reproduction, suggesting that their enhanced performance in improvisational domains is not driven by superior pitch accuracy but rather by expressive, perhaps compensatory, neural mechanisms. Auditory Memory: No significant group differences were found in rhythmic and pitch memorization tasks, possibly due to task constraints and ceiling effects. Rhythmic improvisation was negatively correlated with P1 and N1 latencies, indicating that earlier cortical responses predicted better improvisational performance. This supports the notion that temporal efficiency in auditory processing facilitates creative musical behaviour. This finding suggests that impaired auditory perception does not necessarily constrain creative musical performance. Beyond musical performance, melodic perception in speech has been shown to correlate with both language performance and musical abilities, underscoring that musicality may scaffold broader cognitive domains such as prosodic processing and linguistic competence (Christiner, Groß, Seither-Preisler and Schneider, 2022).

The empirical findings Seither-Preisler et al. (2014), Serrallach et al. (2016), and Groß et al. (2022) demonstrate a multilayered association between the structural morphology of the auditory cortex, neurofunctional timing parameters, and musical behaviour in both neurotypical and neurodivergent individuals (Seither-Presiler at al. 2014; Serralach et al. 2016; Groß et al. 2022). While earlier studies reported associations between these neural characteristics and superior psychoacoustic performance – such as rhythm reproduction and frequency discrimination – in the current dataset (Groß et al. 2022, 12-14) the neurofunctional enhancements, namely reduced P1 latency asynchrony and earlier P1/N1 latencies, were specifically associated with better rhythmic improvisation performance.

Building on previous findings, Groß et al. (2022) shifted the focus from auditory perception to the expressive dimensions of musicality, thereby addressing an often-overlooked facet of neurodivergent musical behaviour.

Crucially, these results emphasize the need to differentiate between at least three functionally distinct domains of musicality:

- Perceptual accuracy, reflected in pitch or frequency discrimination tasks;
- Temporal processing, as measured by latency and synchrony parameters (e.g., MEG P1 latencies);
- Expressive fluency, operationalized through generative tasks like improvisation and emotional expression.

This multidimensional framework supports a more nuanced view of musical ability that accounts for compensatory mechanisms and divergent neurodevelopmental trajectories. In practical terms, it suggests that conventional profiling instruments – focused predominantly on accuracy and reproduction – may overlook key indicators of musical potential in neurodivergent populations, particularly those whose strengths manifest in open-ended, creative contexts.

2.5 Metacognitive Self-Evaluation in Musical and Speech Perception Tasks

This section addresses the metacognitive dimension of the Neuro-Auditory Profile (Figure 1). Building upon the structural, functional, and behavioural dimensions of the Neuro-Auditory Profile, a recent study Groß et al. (2023) investigated the metacognitive aspect of musical and speech perception performance in young adults with ADHD (Groß et al. 2023). While previous research had demonstrated perceptual and timing-related deviations in this group, the question remained whether individuals with ADHD are aware of such differences in performance and how self-assessment processes interact with their rated competence. To address this, the study employed a multi-domain diagnostic battery comprising both musical and language-based listening tasks of varying complexity, alongside standardized assessments of short-term memory and subjective self-evaluation. Three groups participated: musically naïve individuals, participants with formal musical training, and individuals diagnosed with ADHD. The results revealed a consistent pattern across tasks: although participants with ADHD performed significantly worse than the control groups in complex auditory tasks – such as melodic discrimination and foreign language prosody identification, their self-assessments were markedly inflated. In contrast to the musically naïve group, who rated their own abilities more conservatively, the ADHD group judged their competence to be on par with musically trained peers, despite objective evidence to the contrary. This discrepancy was especially evident in open-ended tasks requiring complex auditory integration, rather than in simple perceptual discrimination tasks, where no significant group differences emerged.

Importantly, no short-term memory (STM) impairments were observed in the ADHD group, suggesting that previously reported STM limitations in children may not persist into adulthood or may be compensated by alternative strategies (Schmidt, Hesse, Loo, and Thome, 2020). The most distinctive marker, however, was the dissociation between perceived and actual competence. This aligns with prior findings on the positive illusory bias in ADHD (Hoza et al., 2004), where inflated self-evaluations may function as a psychological coping mechanism in the face of inconsistent performance.

Discriminant analyses supported these observations by revealing two orthogonal components: one reflecting actual performance (musical discrimination, STM, language tasks), which clearly separated ADHD participants from both control groups; and a second component reflecting self-perception variables, which grouped ADHD participants with musically trained individuals. This convergence of self-evaluation profiles – despite divergent actual performance – suggests that individuals with ADHD may internalize high competence beliefs independent of feedback accuracy.

These findings have direct implications for music education and training. Since individuals with ADHD tend to systematically overestimate their own performance, self-report measures alone provide limited insight into actual abilities. Thus, pedagogical interventions should combine objective performance assessments with structured feedback to support realistic self-monitoring. Moreover, targeted metacognitive training may help students with ADHD calibrate their self-assessments, fostering more accurate goal-setting, adaptive learning strategies, and effective feedback integration – all of which are critical for sustained progress in complex auditory learning environments (Groß et al. 2023, 12-13).

3. THEORETICAL AND PROFILING IMPLICATIONS

In the present context, the term profiling refers to the systematic characterization of auditory–musical strengths and processing patterns and does not imply clinical diagnosis in the sense of DSM or ICD classification. The findings presented across the examined studies substantiate a theoretical reframing of musicality in neurodivergent populations. Rather than conceptualizing neurodevelopmental conditions such as ADHD, ADD, or dyslexia primarily as deficit-based, the Neuro-Auditory Profile provides a differentiated and integrative multidimensional model.

Especially in individuals with ADD and ADHD, distinctive strengths in improvisation and expressive performance have been observed, capacities that are not well predicted by traditional measures of musical aptitude such as pitch reproduction or STM. These creative strengths correlate with shortened latencies in MEG-based auditory evoked fields (P1, N1) and, as shown in Section 2.5, with elevated self-confidence in auditory performance, even in the absence of objective superiority.

Crucially, the findings underscore the importance of distinguishing between at least three functionally distinct domains of musicality: perceptual accuracy, temporal processing, and expressive fluency. Perceptual accuracy refers to abilities such as pitch and frequency discrimination, while temporal processing encompasses parameters like auditory-evoked latencies and hemispheric synchrony (e.g., P1 latencies measured via MEG). Expressive fluency, by contrast, is reflected in generative musical behaviors such as improvisation and emotional expressiveness. This multidimensional conceptualization offers a more differentiated understanding of musical ability, one that takes into account compensatory mechanisms and divergent neurodevelopmental trajectories. From a practical perspective, it highlights the limitations of conventional profiling tools, which often prioritize accuracy and reproduction, and may therefore fail to identify crucial indicators of musical potential – especially in neurodivergent individuals whose strengths emerge most clearly in open-ended, creative contexts.

4. PERSPECTIVES FOR SYSTEMATIC MUSICOLOGY

The Neuro-Auditory Profile offers systematic musicology a novel epistemological lens through which musical ability is reconceptualized as a dynamic interplay of brain-based timing, perceptual precision, expressive fluency, and metacognitive reflection. Through the combined analysis of morphological (HG/PT ratios), functional (MEG latencies), behavioural (MuPAS subscales), and metacognitive (self-assessment) data, musicality can be understood not as a fixed trait but as a multifactorial, developmentally sensitive process.

This reconceptualization carries significant implications for music education. In inclusive pedagogical environments, diagnostic profiles that highlight individual creative strengths – such as improvisational fluency or expressive modulation – can inform personalized instructional design. For example, learners with ADHD who struggle with pitch accuracy may thrive in generative, less structured musical settings, where their auditory-motor integration capacities are better utilized.

Methodologically, the Neuro-Auditory Profile challenges musicology to expand its scope to include neurophysiological measurement techniques (e.g., EEG/MEG), realworld performance assessments (e.g., ratings of a familiarsong singing task and brief improvisations recorded under typical classroom/clinic conditions), and psychometrically grounded coding frameworks such as MuPAS. Incorporating metacognitive measures (selfestimates alongside objective performance) adds a profiling and educational layer consistent with current research on neurodiversity and learning.

5. CONCLUSIONS AND FUTURE DIRECTIONS

5.1 Main findings and current state of the Neuro-Auditory Profile

The present manuscript synthesized a series of empirical studies conducted between 2014 and 2023 to document the development of the Neuro-Auditory Profile as an integrative framework for understanding auditory–musical processing in neurodivergent populations.

Structural and neurofunctional markers of the auditory cortex-hemispheric asymmetries and timing-related parameters-were reliably associated with individual differences in musical, literacy-related, and attentional skills in children with ADHD, ADD, and dyslexia. Notably, these auditory processing characteristics were linked not only to perceptual performance but also to expressive and improvisational musical strengths, highlighting the functional significance of efficient internal auditory timing.

Findings from adolescent and young adult samples further demonstrated systematic dissociations between objective auditory-musical performance and subjective self-evaluation, indicating a distinct metacognitive dimension that complements neurophysiological and behavioural indicators. Taken together, the available evidence supports the Neuro-Auditory Profile as a multimodal, strength-oriented profiling framework that captures heterogeneous auditory–musical processing patterns across developmental stages, rather than reducing neurodivergence to deficit-based classifications.

5.2 Implications and future research directions

While the Neuro-Auditory Profile is empirically grounded in several peer-reviewed studies, future research is required to further refine and extend the framework. This includes the systematic validation of profiling dimensions across larger and more diverse samples, as well as the examination of their developmental stability using longitudinal designs.

Future work integrating neurophysiological, behavioural, and self-report measures within ecologically valid research paradigms may further elucidate how differentiated auditory–musical profiles can inform inclusive approaches in music education and related applied contexts, provided that the strength-oriented character of the framework is preserved

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NEIRODIVERĢENTAS SKAŅAINAVAS: MUZIKĀLĀ PROFILA ĪPATNĪBAS PERSONĀM AR UDHS, UDS UN DISLEKSIJU

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Atslēgvārdi: dzirdes neirālais profils, muzikālās dotības, neiroatšķirība, UDHS, UDS, disleksija, mūzikas radošums, improvizācija, MRT, MEG, iekļaujoša mūzikas izglītība.

Rakstā dzirdes neirālais profils tiek aplūkots kā integrēta, daudzdimensionāla sistēma, kas raksturo dzirdes un mūzikas apstrādes īpatnības personām ar neiroatšķirīgu attīstību. Īpaša uzmanība pievērsta cilvēkiem ar uzmanības deficīta hiperaktivitātes sindromu (UDHS), uzmanības deficīta sindromu (UDS) un attīstības disleksiju. Atšķirībā no atsevišķu empīrisku rezultātu analīzes, raksts apkopo un integrē recenzētos pētījumus, kas veikti laika posmā no 2014. līdz 2023. gadam, izsekojot dzirdes neirālā profila attīstībai dažādos vecumposmos un secīgos pētījumos.

Dzirdes neirālais profils apvieno četras savstarpēji saistītas dimensijas. Pirmkārt, tiek analizēti strukturālie neiroanatomiskie rādītāji dzirdes smadzeņu garozā, īpaši apjoma attiecību un pusložu asimetrijā Hešla krokā (HG) un deniņu daivas virsmā (*planum temporalis*, PT). Otrkārt, aplūkoti neirofunkcionālie laika raksturlielumi, kas iegūti ar magnētiskās encefalogrāfijas (MEG) palīdzību, koncentrējoties uz P1 latencēm un starppusložu sinhronizāciju. Treškārt, iekļauti psihoakustiskie un mūzikas apstrādes pamata un kompleksie rādītāji, kas aptver gan precizitātes, gan radošus un adaptīvus uzdevumus. Ceturtkārt, analizēts metakognitīvais pašnovērtējums attiecībā uz muzikālo un runas sniegumu.

Sākotnējie pētījumi liecina, ka stabilas dzirdes garozas strukturālās un funkcionālās īpatnības ir cieši saistītas ar individuālām atšķirībām muzikālajās prasmēs, lasītprasmes attīstībā un uzmanības regulācijā bērnībā. Bērniem ar UDHS, UDS un disleksiju tika konstatēti atšķirīgi HG/PT attiecību modeļi, kā arī izteiktas pusložu latences asimetrijas, kas norāda uz netipisku dzirdes laika apstrādes un sinhronizācijas mehānismu darbību. Šīs īpatnības saglabājas arī pieaugušā vecumā, liecinot par noturīgiem neiroattīstības profiliem, nevis tikai *pārejošu attīstības fāzes efektu.*

Vēlākajos pētījumos būtiska nozīme piešķirta mūzikas biheiviorālajai analīzei. Izmantojot muzicēšanas novērtēšanas skalu (MuPAS), tika konstatēts, ka pusaudži ar UDHS un UDS ritmiskās improvizācijas un muzicēšanas uzdevumos sasniedz līdzvērtīgus rezultātus neirotipiskajiem vienaudžiem, neraugoties uz iepriekš dokumentētajiem uztveres ierobežojumiem ritma vai toņaugstuma apstrādē. Neirofizioloģiskā laika apstrādes efektivitāte, kuru raksturo īsākas P1 un N1 latences, bija cieši saistītas ar improvizēšanas komponentu. Tas norāda, ka radošs muzikāls izpildījums vairāk korelē ar temporālo apstrādi, kā ar uztveres precizitāti.

Dzirdes neirālā profila paplašinājums ietver arī metakognitīvā pašnovērtējuma dimensiju. Jauniešiem ar UDHS tika novērota sistemātiska neatbilstība starp objektīvo sniegumu un subjektīvo pašnovērtējumu, jo īpaši sarežģītākos mūzikas un runas uztveres uzdevumos. Lai gan faktiskais sniegums bieži bija zemāks nekā kontroles grupai, pašnovērtējums bija ievērojami augstāks un līdzinājās mūzikas izglītību ieguvušu dalībnieku vērtējumam. Šis metakognitīvais modelis veido neatkarīgu profila dimensiju, kam ir tieša nozīme izglītības, vērtēšanas un atgriezeniskās saites procesos.

Kopumā rakstā integrētie rezultāti rosina pārskatīt muzikālo dotību izpratni neiroatšķirīgās populācijās. Muzikālās spējas nav iespējams adekvāti novērtēt, balstoties tikai uz precizitātes rādītājiem, jo tās veidojas no uztveres precizitātes, temporālās apstrādes, muzikālās izteiksmības un metakognitīvās apziņas savstarpējās mijiedarbības. Dzirdes neirālais profils piedāvā uz stiprajām pusēm vērstu, indivīda attīstībai adaptētu pieeju, kas pārsniedz normnovirzēs balstītas klasifikācijas un ļauj diferencētāk izprast individuālo muzikālo potenciālu.

No sistemātiskās muzikoloģijas skatpunkta dzirdes neirālā profilēšana piedāvā integrētu epistemoloģisku modeli, kas apvieno neirofizioloģiskās metodes, ekoloģiski pamatotus muzikālās izpildes uzdevumus un reflektīvu skatījumu uz muzikas rosinātu uzvedību. Raksts noslēdzas ar turpmāko pētījumu virzienu izklāstu, uzsverot nepieciešamību turpināt profila dimensiju validāciju, veikt ilgtermiņa pētījumus un attīstīt šīs pieejas izmantošanu iekļaujošas mūzikas izglītības praksē.

HARMONIZING GROWTH: EXPLORING MUSICAL DEVELOPMENT THROUGH PSYCHOSOCIAL SKILLS IN ADOLESCENT EDUCATION

Tatjana Voitova

Psychosocial skills – often referred to as psychosocial competence, soft skills, or non-cognitive strengths – are particularly crucial during adolescence, a period characterized by substantial changes across neurobiological, physical, cognitive, and socio-emotional domains. Adolescence represents a pivotal phase of life during which the capacities for achieving full human potential are most profoundly developed. Given that psychosocial skills are malleable and continue to develop throughout life, it is important to prioritize their cultivation – especially during adolescence. Consistent support from key individuals, particularly during the school years, plays a vital role in strengthening adolescents' psychosocial competence.

This article emphasizes the need for research on the role of psychosocial skills in education, an area that remains unexplored in Latvia. Latvia's unique music education system not only nurtures young musical talent but also reinforces national identity. Given this, it is essential to investigate adolescent musical development through psychosocial dimensions. The diversity of music education opportunities in Latvia provides a valuable context for both theoretical and, more importantly, empirical research, whose evidence-based findings could be implemented in educational practice through collaboration among all stakeholders. Accordingly, this article aims to provide an overview of the construct of psychosocial skills in adolescence and to examine the Latvian music education system as a context for research. Furthermore, it argues for the integration of psychosocial skill development into music education.

Keywords: psychosocial skills, adolescents, music education in Latvia, musical development

INTRODUCTION

In recent years, increasing attention has been directed toward mental health, well-being, and the development of psychosocial competence. This growing interest is reflected in various international initiatives and research efforts dedicated to incorporating psychosocial skills into educational policies and practices. For example, in 2021, France launched a national strategy aimed at developing psychosocial competencies in all children and young people aged 3 to 25 (Lamboy et al. 2022, 1). Similarly, the World Health Organization (WHO 2023) emphasizes the importance of fostering emotional and social well-being in schools as part of its Health-Promoting and Child-Friendly Schools framework.

Promoting the socio-emotional well-being of young people is vital. This involves fostering supportive environments and deliberate cultivating psychosocial skills, which are essential for positive personal development. The school context is particularly important in this regard, as adolescents spend a significant part of their lives in educational settings, where they face various social, emotional, and academic challenges, among others. These experiences influence not only their cognitive development but also shape emotional regulation, intra- and interpersonal skills, self-identity, and overall well-being.

Psychosocial skills are now widely recognized as strong predictors of academic, professional, and overall life outcomes (Lipnevich, Preckel, and Roberts 2016, 376). Moreover, these skills are considered especially crucial during adolescence, a period marked by major transformations in goal setting, learning attitudes, and ability development (Voitova et al. 2025, 184). In the context of education – particularly in Latvia – psychosocial skills have thus far received limited attention. However, interest in this area has increased in recent years. For example, in 2022, the General Education Law in Latvia was amended to require general education program implementers to provide learners with systemic support for the development of social and emotional competencies (Saeima 2022). Similarly, studies have emerged addressing socio-emotional and behavioural issues among adolescents, alongside their well-being within the school context (see Bezborodovs 2024; Cāzere-Pakalne and Svence 2020).

However, there is a lack of studies on the relationship between psychosocial skills and musical development or musically gifted education in Latvia. Moreover, these skills have not been systematically incorporated into advanced music curricula (Voitova et al. 2025, 198). Thus, this paper advocates for the integration of psychosocial skills into music education and employs the Latvian music education system as a research context to identify strengths and barriers. To contextualize the research focus, the subsequent sections explore the concept of psychosocial skills and examine the structure and characteristics of the Latvian music education system.

1. PSYCHOSOCIAL SKILLS

1.1. Terminology and definitions

The literature presents a wide range of terms used to define and describe the concept of *psychosocial skills*. Moreover, numerous alternative terms appear throughout the literature and are often used interchangeably, including soft skills, noncognitive factors, personal qualities, and non-intellectual strengths, among others (Kyllonen et al. 2014, 4; Voitova et al. 2025, 185). For example, Dixson et al. (2016) use the terms psychosocial factors and variables synonymously, while Subotnik et al. (2011) use them interchangeably with skills, abilities, and components. Other authors refer to psychosocial competence or psychological capacity (Basak 2022, 60).

As stated in the Dictionary of Psychology of American Psychological Association, the term *psychosocial factors* is defined as:

> "social, cultural, and environmental phenomena and influences that affect mental health and behaviour. These influences include social situations, relationships, and pressures, such as competition for education, health care, and other social resources" (APA n.d.).

This definition encompasses various components of psychosocial competence, emphasizing that mental health is not solely a personal matter but is profoundly shaped by external factors, including the social relationships and environments in which we live.

Other authors also highlight the dual intra- and interpersonal dimensions of psychosocial competence, asserting that "psychosocial factors refer to motivational constructs that are affected by both psychological and social contexts" (Dixson et al. 2016, 67).

More specifically, referring to health promotion, behaviour, and the ability to cope with difficulties, Basak defines *psychosocial competence* as "the ability to exercise control over one's life, to effectively deal with specific difficulties, and to create adjustments to one's behaviour and environment" (Basak 2022, 63).

This represents only a limited selection of existing definitions. However, a unifying factor across these and other definitions – as well as a key distinction from cognitive or so-called hard skills – is that psychosocial skills are closely linked to mental health and well-being, behavioural and socio-emotional capacities, and positive personality development. This is particularly important in today's rapidly changing world, where individuals must continuously adapt to complex social dynamics. The development of psychosocial skills becomes even more crucial during adolescence – a life stage widely recognized as a sensitive period.

1.2. Psychosocial skills in adolescence

According to the World Health Organization, "adolescence is the phase of life between childhood and adulthood, from ages 10 to 19. It is a unique stage of human development and an important time for laying foundations of good health" (WHO n.d.).

It is also claimed that adolescence "ends with physiological and neurobiological maturity, shown in neuro-scientific research to extend to at least age 20" (APA n.d.).

This makes adolescence a particularly vulnerable and dynamic phase of personality development, as it involves significant physical, cognitive, and socio-emotional changes that influence brain function, behaviour, self-identity, emotional intelligence, among others. This complex developmental process is primarily shaped by social environments, as adolescents' self-identity changes in response to interactions with peers, family, and school (Raufelder et al. 2021, 1). The quality of social relationships plays a critical role in supporting healthy psychosocial development, highlighting the importance of consistent emotional support from the various communities surrounding adolescents during this formative stage.

Although personality has traditionally been viewed as fixed, recent studies emphasize that the development of psychosocial skills is a lifelong process (Basak 2022, 63), and that personality and psychosocial skills – like many other skills – can be developed and improved across the lifespan (Burrus and Brenneman 2016, 20; Kyllonen et al. 2014, 2). Moreover, these skills are malleable and continue to evolve over time (Burrus and Brenneman 2016, 20; Dixson et al. 2016, 74; Kyllonen et al. 2014, 2; Subotnik et al. 2011, 7). Furthermore, it is argued that the malleability of personality development is particularly pronounced during adolescence (Jebb et al., 2006, 126). In the case of children and adolescents, these skills can – and should – be deliberately taught and cultivated by educators, parents, and other influential figures (Dixson et al. 2016, 74; Subotnik et al. 2011, 7). This underscores the importance of a supportive environment provided by the community surrounding the adolescent, including the school, family, and other social institutions.

1.3. Psychosocial skills and (music) education

As school is an integral part of young people's lives, it is important to recognize its role not only in their academic development but also in promoting their overall well-being, as well as in preparing them for adult life by equipping them with skills to navigate personal and professional challenges. Alongside cognitive abilities, a growing emphasis nowadays is placed on psychosocial skills. Numerous studies have shown that psychosocial skills, e.g., self-discipline, hope, grit, motivation, and a growth mindset, play a crucial role in education (Dixson et al. 2017, 1; Kyllonen et al. 2014, 3). These skills not only support effective learning but also correlate with higher academic outcomes (Basak 2022, 61; Burrus & Brenneman 2016; Yeager and Walton 2011, 268). Achievement in educational environments undoubtedly enhances motivation, confidence, self-efficacy, and perseverance, which are key components of psychosocial competence, particularly in adolescence. Indeed, academic success and psychosocial strength are mutually reinforcing, with positive educational outcomes contributing significantly to the development of psychosocial skills, and vice versa. Therefore, teaching psychosocial skills should be a deliberate goal of education (Kyllonen et al. 2014, 10; Lipnevich, Preckel, and Roberts 2016, 381).

It is widely recognized that music training not only enhances musical abilities but also positively influences cognitive abilities (Hallam 2010, 270; Müllensiefen and Harrison 2020, 234). However, a growing body of research also highlights the beneficial impact of music on psychosocial competence and well-being (Hallam 2010, 270; Müllensiefen and Harrison 2020, 224). This is particularly significant in the domain of gifted education, as talented pupils often face greater pressure and various difficulties and therefore require a specialized approach that not only nurtures their cognitive abilities and professional skills in a particular domain but also supports their overall well-being.

Authors have identified psychosocial skills as key contributors to successful talent development (Subotnik et al. 2011, 7). Additionally, it is claimed that these skills are malleable and must be deliberately cultivated in gifted education (Dixson et al. 2016, 74). Similarly, the initial findings of Voitova et al.'s study on the influence of psychosocial skills on musical ability development demonstrate that these skills play a significant role in fostering musical abilities during adolescence, suggesting that the introduction psychosocial competence in earlier stages of gifted education should be considered essential (Voitova et al. 2025, 198). Undoubtedly, this requires the involvement of multiple stakeholders – including family support, specialized qualifications and competencies among educators, and positive environment, among others.

Having outlined the concept of psychosocial skills and their relevance in adolescence, we now explore their integration within the framework of Latvian music education. This examination reveals where psychosocial skills are currently fostered and uncovers existing gaps. The following section provides an overview of an exclusive music education system in Latvia, whose distinctive features particularly emphasize the special needs of learners, suggesting a tailored approach to instruction as well as the involvement of the adolescents' surrounding social environment. Before that, an exploration of the historical background and recent developments in musical heritage is presented to contextualize the origins of the system.

2. LATVIA'S UNIQUE MUSIC EDUCATION SYSTEM: A NURTURING ENVIRONMENT FOR THE DEVELOPMENT OF TALENT

2.1. Historical context and contemporary developments

It is important to emphasize that music education in Latvia is deeply intertwined with the nation's strong musical heritage. Latvia is highly regarded for its rich musical traditions, especially in choral singing and folk music, as well as in performing arts. Latvia hosts a variety of nationally and internationally recognized music events – festivals, competitions, concert series. One of the most prominent music events is the The Nationwide Latvian Song and Dance Festival (*Vispārējie Latviešu Dziesmu un Deju svētki*) which was inscribed in 2003 on UNESCO's List of the Masterpieces of the Oral and Intangible Heritage of Humanity (Vispārējie Latviešu Dziesmu un Deju Svētki n.d.). There are also a number of other music events, such as the Liepāja International Piano Stars Festival (*Starptautiskais Pianisma zvaigžņu festivāls*), the Latvian Composers' Union festival "Latvian New Music Days" (*Latvijas jaunās mūzikas dienas*), Jāzeps Vītols International Piano Competition (*Jāzepa Vītola Starptautiskais pianistu konkurss*) etc. A special place holds the annual international competition Talents of Inese Galante (*Ineses Galantes talanti*), as it aims to discover and nurture emerging talent by providing a platform for young musicians to be heard and supported in their professional musical careers. The majority of these and other events are linked to Latvia's state-supported music education system, as participation is often an integral part of a student's musical training, particularly within specialized music education institutions or with their support.

The close relationship between musical practice and music education has fostered a comprehensive system that nurtures both artistic proficiency and cultural awareness from early childhood. In Latvia, cultural education (*kultūrizglītība*) occupies a prominent and well-established position within the broader educational framework. As stated in the Cultural Policy Guidelines 2022-2027 "Cultural State",

> "the cornerstone of a cultural education system is vocationally oriented cultural education focused on talent development that involves a large number of learners, thereby allowing to identify and deliberately develop new talents" (Ministru kabinets 2022).

This means that the cultural education system has a significant impact on the cultural, professional, and psychosocial development of young people. It not only supports the development of individual musical skills but also serves as a vital means of preserving and transmitting national identity as well as cultural continuity.

The cultural education system includes vocationally oriented, secondary vocational, and higher vocational education programs in various fields of the creative industries within the thematic area of education titled "Arts" (*Mākslas*), including music, dance, visual arts, design and applied arts, and more (LNKC 2021). The policy was developed by the Latvian Ministry of Culture (*Latvijas Kultūras ministrija*), while its implementation is administered by the Latvian National Centre for Culture (LNKC, *Latvijas Nacionālais kultūras centrs*). Cultural education in Latvia is delivered through a network of institutions founded by the Latvian State, municipal governments, and private educational institutions. It can be acquired through formal education, delivered via structured education programs within accredited institutions, as well as through non-formal education, which includes interest-based activities such as extracurricular clubs, youth centres, courses, seminars etc.

According to data provided by LNKC, a total of 151 educational institutions in Latvia implemented accredited vocationally oriented education programs in 2024–2025. These included 7 state-founded, 135 municipal, and 9 privately established institutions, involving 28,237 enrolled learners (LNKC 2024). Within secondary vocational cultural education, there were 23 educational institutions, comprising 18 state-founded, 3 municipal, and 2 private educational entities operating in the thematic area of "Arts", educating a total of 4,452 learners.

An important role in cultural education is played by the "Latvian School Bag Program" (*Latvijas skolas soma*), a nationwide, state-funded cultural educational initiative (LNKC n.d.a.). The program was launched in the 2018–2019 academic year as part of the Latvian centenary celebrations, and since 2022 it has been administered by LNKC.

It offers every student in Latvia – from the beginning of primary to the end of secondary education, in both general and vocational education – the opportunity to attend high-quality cultural and art events free of charge as part of the educational curriculum. Therefore, it promotes cultural awareness, promotes a sense of national identity and belonging through cultural values, enhances educational outcomes, as well as reduces socio-economic inequalities. In addition, as stated in the program's research report covering the years 2018–2023, participation in artistic events contributes to the psychosocial development of youth. It promotes emotional well-being and mental health, and supports the resolution of important social issues among young people, especially in light of the harmful consequences of the COVID-19 pandemic and recent geopolitical developments (LNKC n.d.b.).

2.2. An overview of vocational music education programs in Latvia

Vocational education in art comprises various educational programs with the unifying name Music and the Performance Art (*Mūzika un skatuves māksla*). The music education framework is both well-established and distinctive, characterized by an extensive nationwide network of music schools and a multi-level structure spanning early childhood through higher education. Notably, music education is predominantly financed by the state, though parental co-payments may be necessary depending on municipal contributions. Vocational music education in Latvia is a fundamental component of cultural education, bridging long-standing traditions with contemporary educational practices. It is regulated by the state, and it is voluntary. The framework of the vocational education in general is governed by the Vocational Education Law (*Profesionālās izglītības likums*) aligned with European standards.

Specifically in the context of music education, three levels of vocational education must be highlighted:

1) vocationally oriented education (*profesionālās ievirzes izglītība*);

2) vocational secondary education (*profesionālā vidējā izglītība*);

3) vocational higher education (*profesionālā augstākā izglītība*).

Since adolescence typically covers the age range of approximately 12 to 20 years, the following will focus on the levels of basic and secondary education.

According to Regulation No. 762 in the State Standard for Vocationally Oriented Education in the Arts – including music, art, and dance – the aim of vocationally oriented education is to develop learner's talents and skills in the chosen field of art, as well as to provide opportunities to acquire professional competencies for continuing education at a higher level (Ministru kabinets 2023). There are two educational programs within vocationally oriented education: **20V** and **30V**.

The program 20V represents the first step towards professional music education. It is delivered concurrently with general basic education. Pupils around the age of seven, typically in grade 1 or 2 in general school, are admitted to this program with or without prior musical knowledge. During the admission process, applicants usually are assessed for their sensitivity to pitch and rhythm, as well as their ability to repeat simple melodic and rhythmic patterns.

In 2024–2025, 23 different educational programs were offered, including instrument playing as well as choral singing, contemporary rhythm music and even rock music. Throughout their studies, pupils develop musical perception, creativity, and general intellectual and analytical skills related to music, through both group and individual lessons. The program lasts eight years. Upon completion, pupils receive a certificate of vocationally oriented education and are eligible to continue their studies at the next level of vocational education.

The program 30V is delivered concurrently with secondary education in another educational institution. In this program, pupils are admitted with prior musical experience, typically at the age of 16. During the 2024–2025 academic year, 24 different educational programs were offered, including all of the previously mentioned programs, with the addition of solo singing. The duration of this educational program is three years. By completing the program, pupils receive a diploma of vocational secondary education and may proceed to the next level of vocational studies, most commonly, at the Jazeps Vitols Latvian Academy of Music (JVLMA, *Jāzepa Vītola Latvijas Mūzikas akadēmija*).

According to Regulation No. 332 in the State Standard for Vocational Secondary Education, the strategic goal of vocational educational programs is to prepare learners for professional careers by equipping them with specific skills, knowledge, qualification, and attitudes that enhance employability and adaptability to changing socio-economic conditions. These programs also aim to support personal growth, civic engagement, and contribute to competitiveness, sustainability, and innovation both in Latvia and across Europe (Ministru kabinets 2020).

Program 33, implemented in specialized music schools for musically gifted individuals, plays an important role in nurturing musical talent and supporting the professional development of young musicians. This highly selective program integrates intensive music education with a comprehensive general education curriculum. Admission to this program requires applicants to have completed basic education and have prior musical experience. In addition, candidates must pass an entrance examination, usually consisting of two parts: a performance assessment in their chosen specialization and an evaluation of their music theory knowledge. The duration of this educational program is three or four years.

A key feature of the program is the emphasis on individual instruction. This is complemented by classes in music theory disciplines, typically delivered in small groups up to 10–12 pupils. As a result, the program ensures both individual artistic growth and professional preparation through a highly specialized and student-centred curriculum. During their studies, learners receive a scholarship based on their academic performance. Additionally, some schools provide accommodation in dormitories for those students who come from more remote areas of Latvia. These two aspects provide both financial and social support, allowing students to focus more on their learning and personal development. Also, this reduces socio-economic barriers and geographical inequalities, enabling pupils from all regions of Latvia to access education in these schools.

Upon completion of this program, students are awarded a diploma of vocational secondary education and obtain a professional qualification in their chosen specialisation. Graduates may pursue employment in the arts field and / or continue their studies at a higher music education institution, most commonly at the JVLMA.

2.3. Summary

Music education in Latvia is extensive and multifaceted, playing a vital role in strengthening national identity and preserving cultural heritage. Predominantly state-funded, it is delivered through a well-structured and diverse system that includes both interest-based education and vocational education. As such, the system is designed to be accessible and inclusive, ensuring that children and adolescents from diverse socio-economic backgrounds and geographical areas have the opportunity to develop their musical talents and pursue professional pathways in music. This comprehensive and uniquely structured framework provides a strong foundation and a supportive environment for nurturing young people. Moreover, it presents a valuable context for academic exploration of musical development within the psychosocial dimensions during adolescence.

CONCLUSION AND FUTURE DIRECTIONS

This article is the first to highlight the need for further research on the role of psychosocial skills in (gifted) education. In Latvia, as in many other countries, psychosocial skills have not been systematically integrated into educational curricula. Only in recent years has this issue begun to receive increased attention through various training courses, workshops, surveys, and educational initiatives.

The educational system should not only focus on the development of academic or professional competence but also integrate psychosocial support as a core component of the curriculum at all stages. This is particularly important in gifted education, especially during the critical developmental period of adolescence. At this stage, students often exhibit heightened sensitivity, face intense workloads, and encounter various personal, academic, and professional challenges – such as maintaining motivation and perseverance, managing self-discipline and competition, coping with setbacks, and dealing with performance-related issues, including performance anxiety.

Undoubtedly, teachers must initially complete various courses and seminars to acquire the necessary competencies. Since the topic is relatively new in Latvia, it would be beneficial to invite the appropriate specialists or offer exchange programs abroad, allowing teachers to gain new skills and experiences. On one hand, social well-being and a sense of belonging could be nurtured through various social activities, such as group music performances, debates, or collaborative projects. On the other hand, it is equally important to focus on developing emotional and physical health. Therefore, it would be valuable to introduce new courses, such as various types of therapy or self-care practices, or at least integrate relevant components into existing curricula. These could include stress management, emotional regulation, as well as body awareness, breathing techniques, among others.

This requires joint collaboration among stakeholders, as well as in-depth scientific research, the results of which could – and should – be integrated into practice. Therefore, it is hoped that psychosocial competence could introduce a new dimension to education, particularly within the unique Latvian music education system as a nurturing environment for talent development. Such efforts would contribute to holistic personal growth and support mental health alongside cultivating academic and professional skills.

In conclusion, this paper highlights key aspects of the concept of psychosocial skills, with particular attention to their relevance in adolescence. Additionally, by examining the Latvian music education system, the study identifies strengths and challenges that may contribute to future directions. As such, it provides a conceptual foundation for further empirical research and practical implementation.

LIMITATIONS

Despite the contributions to the field, the present article is constrained by certain limitations. First, it employs a non-empirical design, aiming to contextualize the current situation and highlight key conceptual perspectives. Therefore, future empirical research is necessary to validate the proposed arguments and to examine their applicability within diverse educational settings. It must also be acknowledged that several enablers must be considered and addressed, including staffing, teacher capacity, and the availability of specialized training. Additionally, issues related to resources, funding, curriculum flexibility, and institutional support are essential for the effective implementation of such initiatives.

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HARMONISKA IZAUGSME: MUZIKĀLĀS ATTĪSTĪBAS IZPĒTE CAUR PSIHOSOCIĀLAJĀM PRASMĒM PUSAUDŽU IZGLĪTĪBĀ

Tatjana Voitova

KOPSAVILKUMS

Pēdējā laikā arvien lielāka uzmanība tiek pievērsta cilvēku mentālajai veselībai, labbūtībai un psihosociālās kompetences attīstībai, jo īpaši mūsdienu strauji mainīgajā pasaulē. Šie aspekti ir īpaši nozīmīgi pusaudžu vecumposmā (12–20 gadi), kad norisinās būtiskas pārmaiņas neirobioloģiskajā, fiziskajā, kognitīvajā un sociāli emocionālajā attīstībā. Ir svarīgi apzināties, ka psihosociālās prasmes ir maināmas un attīstāmas dzīves laikā, turklāt tiek uzsvērts, ka šo prasmju attīstības potenciāls ir īpaši izteikts pusaudžu vecumposmā. Tāpēc ir būtiski šīs prasmes mērķtiecīgi mācīt un attīstīt, izstrādājot atbalsta programmas, rīkojot pasākumus un nodrošinot sistemātisku pieeju jauniešu psihosociālajai izaugsmei.

Arī izglītības jomā arvien vairāk tiek uzsvērta nepieciešamība pievērst uzmanību ne tikai akadēmiskajām un kognitīvajām spējām, bet arī sociāli psiholoģiskajiem aspektiem, jo tie kļūst arvien nozīmīgāki mūsdienu realitātē. Tā kā jaunieši ievērojamu savas dzīves daļu pavada skolā, ir būtiski veidot atbalstošu un iekļaujošu skolas vidi, kas sekmē emocionālo drošību, pozitīvu mikroklimatu, uzticamas attiecības ar nozīmīgām personām un harmonisku personības attīstību.

Latvijā ir izveidota spēcīga un ilgtspējīga kultūrizglītības sistēma, kas ietver daudzpakāpju struktūru formālās izglītības ietvaros, kā arī dažādus neformālās izglītības veidus – tostarp interešu izglītības pulciņus, jauniešu centrus un dažādus kursus. Šī sistēma nodrošina secīgu un mērķtiecīgu muzikālo prasmju attīstību, kā arī jauniešu radošuma un pašizpausmes pilnveidi. Būtiski uzsvērt, ka mūzikas izglītība ir cieši saistīta ar valsts kultūrpolitiku – tā nodrošina plašu pieejamību visos Latvijas reģionos, sekmējot aktīvu pilsonisko līdzdalību un stiprinot nacionālo identitāti.

Profesionālā mūzikas izglītība Latvijā ir būtiska kultūrizglītības sastāvdaļa, kas apvieno senas un spēcīgas tradīcijas ar mūsdienu tendencēm. Pusaudžu vecumposmā jāmin profesionālās ievirzes un profesionālās vidējās izglītības programmas. Profesionālās ievirzes programmas **20V** (mācību ilgums – 8 gadi) un **30V** (mācību ilgums – 3 gadi) ir paredzētas prasmju apguvei, kas nepieciešamas turpmākai profesionālās izglītības turpināšanai izvēlētajā specialitātē. Šīs programmas tiek apgūtas paralēli vispārējai izglītībai un tiek īstenotas pašvaldību mūzikas skolās un profesionālās ievirzes mūzikas skolās. Profesionālajā vidējā mūzikas izglītībā īpaša nozīme ir programmai **33** (mācību ilgums 3–4 gadi), kas paredzēta audzēkņu sagatavošanai profesionālai karjerai mūzikā. Tā apvieno intensīvu instrumentu spēles vai dziedāšanas apmācību ar visaptverošu teorētisko zināšanu apguvi.

Šī raksta mērķis ir sniegt pārskatu par psihosociālo prasmju konceptu pusaudžu vecumposmā (kas Latvijā ir salīdzinoši jauna tēma), kā arī aplūkot Latvijas mūzikas izglītības sistēmu. Papildus tam tiek uzsvērta un pamatota nepieciešamība veikt pētījumus – gan teorētiskos, gan empīriskos – par psihosociālo prasmju nozīmību, tostarp mūzikas izglītības jomā. Tā kā Latvijā ir unikāla mūzikas izglītības sistēma, kas piedāvā plašas un daudzveidīgas iespējas jauniešu muzikalitātes attīstībā, tas veido labvēlīgu un radošu vidi šādu pētījumu veikšanai. Sadarbojoties dažādām institūcijām un personām, kas iesaistītas jauniešu attīstības procesā, pētījumu rezultātos balstītus secinājumus varētu integrēt izglītības praksē.

Neapšaubāmi, vispirms ir jānodrošina pedagogiem atbilstoša profesionālā pilnveide, lai viņi iegūtu nepieciešamās kompetences – piemēram, piedaloties kursos, semināros, iepazīstoties ar labās prakses piemēriem, kā arī iesaistoties pieredzes apmaiņas programmās. No vienas puses, sociālo labbūtību un piederības sajūtu var veicināt, audzēkņiem piedāvājot dažādas sociālās aktivitātes, piemēram, grupu muzicēšanu, diskusijas, sadarbības projektus. No otras puses, tikpat būtiski ir pievērst uzmanību jauniešu emocionālās un fiziskās veselības stiprināšanai. Tādēļ mācību procesā būtu vērtīgi ieviest dažādu veidu terapijas prakses, emocionālās pašregulācijas un stresa pārvaldības tehnikas, kā arī fiziskās aktivitātes.

Tādējādi psihosociālo prasmju sistemātiska iekļaušana mācību procesā visos izglītības posmos varētu ieviest jaunu un būtisku dimensiju izglītībā, vienlaikus ar kognitīvo un profesionālo spēju attīstību veicinot arī pusaudžu vispusīgu un harmonisku personības izaugsmi un vispārējo labbūtību.

LINKING SINGING SKILL DEVELOPMENT TO LIFE SATISFACTION: EVIDENCE FROM BOYS' CHOIRS

Reinis Maurītis, Valdis Bernhofs

Although singing has been shown to affect life satisfaction, little is known about children's choir contexts. This study examines the interplay between the development of singing skills and the level of life satisfaction in children and adolescents, with a particular focus on the context of boys' choirs. Collective music-making, including singing in choirs, is a multifaceted activity that simultaneously involves musical, cognitive, emotional, and social competencies, contributing significantly to the personal development and quality of life of children and youth. Although a substantial body of research addresses the impact of singing on adults' emotional well-being, the relationship between singing skills and life satisfaction among children and adolescents especially in the choral context remains underexplored.

Highlighting the relevance of this study, it must be noted that regular and structured participation in school choirs not only fosters vocal and musical skills but also promotes emotional balance, social integration, and the enhancement of cognitive functions. Thus, singing may serve as an important psychosocial and pedagogical instrument in the lives of students, helping to reveal how musical activities influence young people's subjective well-being and life satisfaction.

To achieve the aims of the study, an adapted online testing platform, *LongGold Latvia*, was employed. This platform integrates standardized and customized instruments to assess singing skills, musical perception, and levels of life satisfaction. Such an approach provides comprehensive and quantitatively comparable data, enabling the analysis of the associations between singing and musical abilities and the life satisfaction of children and adolescents. The study thereby offers valuable contributions to both the field of music pedagogy and the exploration of youth psychological well-being. Findings indicate that choir participants demonstrated higher rhythmic singing ability than non-participants, while no significant differences were observed in life satisfaction between the two groups. This suggests that structured choral singing may support musical development, although its direct relationship with well-being requires further investigation.

Keywords: singing, singing skills, boys' choir, life satisfaction, collective music-making

INTRODUCTION

Singing, particularly collective music-making in various types of choirs, such as boys', mixed, and other choral groups, constitutes one of the oldest and most universal forms of human musical expression. It encompasses several interrelated components, including vocal skills, musicality, as well as emotional, cognitive, and social competences.

The experience of collective music-making in childhood and adolescence not only fosters the development of technical singing abilities but also affects emotional well-being, social interaction skills, and self-esteem (Clift & Hancox, 2010; Welch, 2011). Previous research has demonstrated that regular singing enhances emotional self-regulation, reduces stress, and promotes a more positive outlook on life (Kreutz et al., 2004; Gick, 2011; Pearce et al., 2016). However, these findings have predominantly been derived from studies with adults and older populations, while the context of children's and adolescents' choirs remains largely underexplored.

In view of this research gap, the Latvian boys' choir tradition provides a unique opportunity to analyze the impact of collective singing on the development of children and adolescents within a pedagogical and cultural environment. This tradition, which has long been closely connected with the national Song Festival movement, remains a vital part of Latvia's cultural identity and music education system. As such, it represents not only an artistic practice but also a pedagogical and social institution that shapes children's musical, emotional, and social development. These choirs represent a significant pedagogical, social, and emotional context for students, making it possible to systematically assess both the development of singing skills and students' life satisfaction, particularly when employing contemporary quantitative assessment methods. Such research is essential for better understanding how music, and collective singing in particular, influences students' emotional well-being, social integration, and cognitive development.

The starting point of this study lies in the need to systematically investigate the interrelations between the development of singing skills and subjective well-being during childhood and adolescence. By focusing on boys' choirs, the research offers the possibility to analyze the multidimensional effects of collective singing (i.e., vocal, musical, social, cultural, pedagogical, and psychological aspects) in a real educational context, while also expanding the academic literature that has thus far primarily addressed either musical development or emotional well-being in isolation. Understanding these interactions is crucial in both music pedagogy and child and adolescent psychology, as it enables the development of more effective educational and musical activities that foster both vocal skills and students' subjective well-being.

Characterizing collective music-making, for example in boys' choirs, it must be emphasized that this is a complex process in which all the aforementioned dimensions of singing (vocal, musical, emotional, cognitive, social, and pedagogical – interact dynamically and contribute to the overall artistic and developmental outcomes) can be developed and reinforced. Research indicates that regular singing improves emotional self-regulation, reduces stress levels, and supports the development of positive self-esteem (Milošević, 2024). The social dimension is particularly significant during adolescence, a developmental stage in which identity formation and the sense of belonging to a group are critical. Collective music-making strengthens cooperation skills, responsibility, and social integration, all of which are directly correlated with life satisfaction and subjective well-being (Shen & Yang, 2025).

In addition to its emotional and social dimensions, singing stimulates cognitive development. Systematic and regular music-making enhances concentration, musical memory, and learning efficiency (Moreno et al., 2009; Schellenberg, 2004; Schlaug et al., 2005; Hyde et al., 2009). These factors, in turn, influence self-esteem and overall quality of life, creating a multi-layered positive effect on individual well-being.

The present research builds upon a previous study examining stress and its management, particularly the extent to which such competencies are incorporated into higher education and the practical strategies applied to cope with stress (Maurītis, 2022). This article expands the thematic scope by examining the development of singing skills and their correlation with life satisfaction within the real pedagogical setting of general education. The study focuses on how processes of musical and emotional development that occur through collective singing influence the subjective well-being of children and adolescents, particularly their level of life satisfaction. In this way, the research continues previous inquiries in a more specific educational context and age group.

The development of singing skills in boys' choirs is not solely a musical phenomenon, but also a psychosocial and cognitive one. Its investigation provides a significant contribution to both music pedagogy and the study of youth psychological well-being, offering theoretical and empirical insights into the correlation between musical skill development and life satisfaction. This perspective forms the basis of the study's relevance particularly in Latvia, where the relationship between singing skills and life satisfaction in the boys' choir context has thus far received little scholarly attention. The article is grounded in the methodological framework of the international *LongGold* project and the author's practical experience. At the same time, the study contributes to the broader international discourse, as the *LongGold* project will be expanded with new research and Latvian data, thereby enabling cross-national comparisons and enriching the global understanding of this research problem.

In the following sections, the author presents evidence indicating that singing skills may be positively associated with students' overall life satisfaction. Previous research by other authors has highlighted that regular engagement in musical activities, such as choir singing, contributes significantly to emotional well-being, social cohesion, and cognitive development. Building on these findings, growing attention has been directed toward understanding how singing abilities develop during childhood and adolescence, as well as the potential benefits that structured collective music-making experiences in school settings may provide. The present study aims to examine the associations between students' life satisfaction and their musical skills, with a specific focus on the development of singing abilities throughout childhood and adolescence. Furthermore, it investigates whether boys who regularly and systematically participate in school choir activities demonstrate higher levels of life satisfaction and enhanced musical skill development compared to peers who do not engage in choir singing. To address these objectives, three central research questions were formulated:

(1) Are singing skills in school-aged children positively related to indicators of life satisfaction?

(2) Does participation in school choir singing, as a structured and regular form of collective music-making, influence students' life satisfaction?

(3) Do boys who participate in school choirs differ significantly from their non-singing peers in both singing skills and life satisfaction?

1. MUSIC-MAKING AT SCHOOL AND IN BOYS' CHOIRS: HISTORICAL, PEDAGOGICAL AND PSYCHOSOCIAL CONTEXTS

Music-making in schools is a multifaceted activity that encompasses educational, creative, social, personal development, and cultural dimensions. It not only provides musical experience, but also fosters children's and adolescents' personal growth, emotional balance, social skills, and a sense of belonging to the collective, the school, and the broader culture (Hallam, 2010; Welch & McPherson, 2018; Rickard et al., 2013). The school environment serves as a key setting in which singing acquires both pedagogical and cultural value, integrating music education with the goals of emotional and social development.

From a historical perspective, the evolution of singing in Ancient Egypt, Greece, and Rome demonstrates its multifunctional role in society, where it was purposefully employed in religious, educational, and social communication contexts (Ma, 2024). Over time, singing has manifested in diverse forms and stylistic traditions, maintaining ties with traditional values while expanding opportunities for creative expression (Batovska et al., 2022). Collective music-making enables children to express their thoughts, build relationships, and enhance emotional well-being (Van Der Sandt, 2025).

Children's choirs have long been an essential part of music education, particularly in school settings, and this tradition continues today. In Latvia, various types of choirs exist – boys', girls', and mixed – each with their own pedagogical particularities. Boys' choirs possess a rich cultural history closely connected with schools and the work of national educators. Choral singing holds an important place in Latvia's musical heritage, developing alongside the formation of national culture and continuing through traditions such as the General Song and Dance Celebrations and the School Youth Song and Dance Festivals (Daugavietis, 2015; Latvian National Centre for Culture, 2018; UNESCO, 2003).

Even today, boys' choirs provide a unique environment that combines artistic expression, discipline, and a sense of community, while simultaneously offering social and emotional support. Within this environment, students develop a sense of belonging, responsibility, self-confidence, and collaboration skills. Unlike mixed or girls' choirs, boys' choirs face specific challenges related to upbringing, motivation, and voice development, which require tailored pedagogical approaches and individualized work with singers (Periodika.lv, n.d., *Rīgā un visā Latvijā – pasaules zēnu balsis*[1]).

This multidimensional perspective, encompassing historical, pedagogical, and psychosocial factors, provides a framework for understanding how school-based singing not only offers music education but also promotes the emotional, social, and cognitive development of young people. Such a context is particularly relevant for analyzing the development of singing skills and life satisfaction, as it demonstrates how collective music-making creates an integrated pedagogical and psychosocial experience for students.

2. THE DEVELOPMENT OF SINGING SKILLS IN SCHOOLS AND BOYS' CHOIRS AND THE SIGNIFICANCE OF STUDYING SUBJECTIVE WELL-BEING IN THE SCHOOL CHOIR CONTEXT

Singing is one of the oldest and most universal forms of musical expression, centered on the human voice. It combines intonation, rhythm, articulation, emotional expression, and communication skills, which develop gradually and are closely linked to physiological, cognitive, emotional, and social factors (Welch, 2005; Welch, 2006). Within general and cultural education, singing serves not only as a foundation of aesthetic and creative education but also as an important driver of personal development and social interaction (Wicks, 2014).

In Latvia, singing skills are systematically acquired in general education schools, where music classes provide both practical music-making and theoretical knowledge (*Metodiskie ieteikumi skolotājiem mācību satura īstenošanai mūzikā 1.–9. klasei*, n.d.[2]). This process is characterized by systematicity, continuity, concentric progression, and practical application. Regular singing enhances students' musical hearing, sense of rhythm, and vocal technique, while also fostering emotional, intellectual, and social competences (Cuadrado & Rusinek, 2016). Beyond formal education, extracurricular music activities, particularly choir participation, provide broader opportunities for creative self-expression and social engagement (Platpere, 2020).

Choral singing for children and adolescents serves as a comprehensive educational medium that fosters the development of vocal, musical, cognitive, and social skills, including posture, breathing technique, clear diction, melodic and harmonic hearing, emotional expressiveness, and creative thinking (Rucsanda, 2021; Vītols, 2016; Batņa, 2020). Special attention must be given to boys' choirs, considering the physiological characteristics of voice transition and the importance of age-appropriate pedagogical

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[1] Periodika.lv. (n.d.). Rīgā un visā Latvijā – pasaules zēnu balsis. Retrieved May 20, 2025, from https://periodika.lv/periodika2-viewer/?lang=fr#panel:pa|issue:418148|article:DIVL3321|query:koru%20attīstībai%20Zēnu%20zēnu

[2] Metodiski ieteikumi skolotājiem mācību satura īstenošanai mūzikā 1.–9. klasei. (n.d.). Kompetenču pieeja mācību saturā. Retrieved May 26, 2025, from https://mape.gov.lv/api/files/8FE15403-DD41-43B8-BB32-EC6F022E48F0/download

approaches (Asztalos, 2022). In both school and boys' choir settings, systematic warm-up routines – encompassing relaxation, breathing, articulation, and vocal exercises – play a central role (Batņa, 2020).

Such structured approaches improve vocal quality, refine musical hearing, enhance musical thinking, and cultivate a positive attitude toward singing as a collective and artistic practice (Cuadrado & Rusinek, 2016; Wicks, 2014). The development of singing skills in schools and choirs is closely connected to students' emotional well-being and personal growth (Clift et al., 2010; Welch, 2011; Rickard et al., 2013; Saarikallio, 2019).

Existing studies highlight the positive influence of choir singing on emotional well-being, social relationships, and a sense of belonging, although the majority of such studies have been conducted with adults or seniors (Clift & Hancox, 2010; Livesey et al., 2012; Gick, 2011; Pearce et al., 2016). While regular singing may enhance subjective well-being and life satisfaction, research on children and adolescents in this regard remains limited, particularly concerning the relationship between singing skills, emotional well-being, and life satisfaction.

The concept of subjective well-being was introduced by Ed Diener (Diener, 1984), emphasizing individuals' evaluations of their own lives. Unlike the more ambiguous concept of "happiness," subjective well-being offers a more precise psychological framework encompassing both the balance of positive and negative emotions (the affective dimension) and life satisfaction (the cognitive dimension) (Proctor, 2014; Das et al., 2020). This approach enables a deeper understanding of how individuals experience and evaluate their lives, highlighting the importance of emotional well-being alongside rational satisfaction (Radočaj-Jerković, 2022). It is important to note that life satisfaction and subjective well-being are not synonymous. Subjective well-being is a broader construct that includes both cognitive life evaluations and emotional experiences (Diener et al., 1985; Diener et al., 1999; Diener et al., 2018).

Life satisfaction is regarded as the cognitive component of subjective well-being – an individual's overall evaluation of their life (Diener et al.1999) – while subjective well-being also encompasses affective aspects, namely the balance of positive and negative emotions (Diener et al., 2018). OECD guidelines similarly emphasize that subjective well-being consists of three components: life evaluation (including life satisfaction), affective experience, and eudaimonic well-being, or a sense of meaning (OECD, 2013[3]).

In the context of school choirs, singing represents a powerful means not only for the development of musical skills but also for promoting students' emotional, psychological, and social well-being, provided that it is implemented in a positive, supportive, and structured environment (Davies et al., 2023). Collective music-making strengthens communication, emotional development, and the sense of belonging to a group, thus forming the basis for a positive school environment and supporting students' emotional health (Rucsanda, 2021; Platpere, 2020). For these reasons, it is important to study both

[3] Organisation for Economic Co-operation and Development. **(2013).** OECD guidelines on measuring subjective well-being. OECD Publishing. https://doi.org/10.1787/9789264191655-en

the acquisition of singing skills and students' subjective well-being, as this allows for an evaluation of the impact of music education on students' emotional well-being and quality of life. The findings of such research may provide practical recommendations for educators and choir conductors, helping to create inclusive, emotionally safe, and creatively stimulating environments in which students can experience the joy of music-making, emotional fulfillment, and harmonious collaboration (Asztalos, 2022; Batņa, 2020).

3. METHODOLOGY AND INSTRUMENTS

3.1. Participants

Although the initial plan was to include 60 respondents – 30 boys actively participating in boys' choirs (attending more than 60% of rehearsals during the past six months) and 30 boys not involved in choir activities (the control group) – the actual number of participants varied across different parts of the study. These differences were primarily related to practical constraints of data collection, participant availability, and the voluntary nature of involvement.

In total, **39 participants completed the individual singing ability test**. Meanwhile, **20 choir members and 27 participants from the control group** took part in the online assessments, reflecting differences in motivation and interest. Such variations are typical for school-based research, where data collection occurs within real educational contexts and depends on students' and teachers' schedules, workload, and willingness to participate.

Openly reporting these differences ensures methodological transparency and allows for a more accurate interpretation of the results, while maintaining the internal coherence and quality of the study.

To ensure that respondents in the control group were not participating in other choirs, ensembles, or collective music-making activities, their extracurricular musical involvement was assessed through an online questionnaire, which recorded type, frequency, and duration of such activities. This procedure ensured that the control group accurately reflected students not regularly engaged in musical activities, allowing for valid comparisons with choir participants.

All participants were students in general education schools (ages 8–13; grades 2–7), none of whom received specialized music training as part of their general education. Although a sample of 60 may appear modest, this size was sufficient to provide statistical power for examining correlations between singing skills and life satisfaction, while maintaining the reliability of the findings. Furthermore, the formation of two balanced groups – with equivalent age ranges and socio-demographic profiles – enabled not only correlational analysis but also comparative statistical testing between groups. To further refine comparability, respondents were subdivided into two age groups: 8–10 years (grades 2–4), prior to voice change, and 11–13 years (grades 5–7), during the onset of voice transition. This subdivision allowed for examination of both developmental differences in vocal abilities and potential variations in emotional well-being and self-esteem across age stages.

3.2. Measures

Data collection employed the LongGold adapted online test battery, including Ed Diener's Satisfaction with Life Scale (SWLS), adjusted for children (Diener, 1985; Gadermann et al., 2009), to measure life satisfaction. This five-item self-report scale uses a 5-point Likert response format (1 = strongly disagree to 5 = strongly agree), yielding total scores ranging from 5 to 25, with higher scores reflecting greater life satisfaction.

Singing skills were assessed with the Singing Ability Assessment (SAA) test (Silas et al., 2023), designed to quantitatively evaluate vocal ability and melodic memory. The Singing Ability Assessment was culturally adapted with Latvian folk songs, ensuring ecological validity. The test was comprised of three components: sustained note production, rhythmic melody imitation, and melodic (non-rhythmic) reproduction. For cultural adaptation to the Latvian context, original melodic fragments were replaced with 20 Latvian folk song excerpts varying in rhythmic and melodic complexity. This ensured cultural relevance and age-appropriateness while preserving quantitative comparability.

3.2.1. Testing Procedure and Content Validity of the Singing Test

The online testing procedure included the use of computers with high-quality headphones and microphones in quiet environments. Each participant received a unique ID code ensuring anonymity. The testing sequence began with equipment calibration (microphone, volume, noise reduction) and a practice trial, followed by the main test sections. This setup enabled evaluation not only of performance accuracy but also of memory capacity, attention, and melodic perception.

The validation of the Singing Ability Assessment test emphasized whether the tasks and indicators reliably measured singing skills (including melody and rhythm components). Content validity was ensured by selecting Latvian folk song fragments with distinct rhythmic and melodic features, aligning with the music education curriculum.

3.2.2. Validation Analyses

In this study, an **exploratory factor analysis (EFA)** was conducted to reduce the dimensionality of the dataset by identifying underlying factors representing related musical structure variables. The sample consisted of N = [insert sample size] participants and included both rhythmic and melodic stimuli. Sampling adequacy was confirmed with a **Kaiser–Meyer–Olkin (KMO)** measure of **.600** and **Bartlett's test of sphericity** was significant ($\chi^2(153)$ **= 17,624,** $p < .001$), indicating that the data were suitable for factor analysis (see *Table 1* and *Table 2*).

Assumption Checks

Table 1

KMO Measure of Sampling Adequacy

	MSA
Overall	0.600
i.entropy	0.252
mean_information_content	0.680
tonalness	0.540
tonal.clarity	0.495
tonal.spike	0.474
step.cont.glob.dir	0.535
step.cont.glob.var	0.833
step.cont.loc.var	0.372
mean_int_size	0.667
int_range	0.830
dir_change	0.795
mean_dir_change	0.317
int_variety	0.424
pitch_variety	0.714
mean_run_length	0.717
d.entropy	0.521
d.eq.trans	0.559
mean_duration	0.905

Table 2

Bartlett's Test of Sphericity

χ^2	df	p
17624	153	<.001

Factor extraction was performed using the Principal Axis Factoring method. Based on eigenvalues greater than 1, scree plot inspection, and parallel analysis, a three-factor solution was retained, explaining **47.6%** of the total variance (**see Table 3**). The scree plot further supported a three-factor structure (**see Figure 1**).

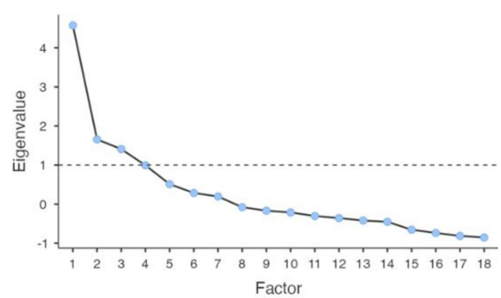
Factor extraction and variance

Table 3

Summary

Factor	SS Loadings	% of Variance	Cumulative %
1	3.91	21.7	21.7
2	2.74	15.2	37.0
3	1.92	10.7	47.6

Figure 1



To clarify the factor structure, an oblique (Oblimin) rotation was applied. Factor loadings below .30 were excluded from interpretation. Communalities ranged from .28 to .76 (**see Table 4**).

Table 4. ***Pattern matrix.***

Factor Loadings

	Factor			
	1	2	3	Uniqueness
dir_change	0.945			0.136
mean_run_length	0.929			0.171
pitch_variety	-0.784	0.304		0.170
mean_information_content	-0.696	0.321		0.299
i.entropy	0.462			0.796
mean_dir_change	0.332			0.840
step.cont.glob.dir				0.964
int_range		0.812		0.307
mean_int_size		0.805		0.161
step.cont.loc.var	0.440	0.720		0.393
step.cont.glob.var		0.574		0.489
int_variety	-0.312	0.342		0.649
tonalness				0.912
d.eq.trans			-0.797	0.369
d.entropy			0.779	0.383
mean_duration	-0.316		0.538	0.534
tonal.spike			0.318	0.897
tonal.clarity				0.957

Note. 'Principal axis factoring' extraction method was used in combination with a 'oblimin' rotation

The extracted factors showed small to moderate inter-correlations, supporting the use of an oblique rotation (see Table 5)

Table 5. ***Factor correlations.***

Inter-Factor Correlations

	1	2	3
1	—	-0.264	-0.0834
2		—	0.0176
3			—

Factor 1 was labeled *Rhythmic Complexity*, as it included items related to rhythmic entropy, duration variability, and interval direction change.

Factor 2 was labeled *Melodic–Tonal Clarity*, consisting of variables associated with tonalness, tonal clarity, and tonal stability.

Factor 3 was labeled *Information Content Variability*, reflecting measures of informational unpredictability (mean information content and entropy).

3.2.3. Reliability Analysis

Test reliability was examined using Cronbach's alpha (α). Cronbach's α and McDonald's Omega (ω) are reported with 95% confidence intervals (CI), which indicate the range within which the true reliability values are likely to fall. This provides a measure of the precision and stability of the reliability estimates (see Table 6).

When analyzing all ten parameters together (rhythm parameters: *mean_int_size, int_range, dir_change, mean_dir_change, int_variety*; melody parameters: *pitch_variety, mean_run_length, d.entropy, d.eq.trans, mean_duration*), Cronbach's α was only 0.24, indicating weak internal consistency and confirming that rhythm and melody indicators should not be combined into a single scale. For rhythm parameters, Cronbach's α initially was 0.25, but after removing the problematic indicator *dir_change*, it improved to 0.57. When the remaining indicators were standardized (converted to z-scores), Cronbach's α increased to 0.739, and McDonald's ω reached 0.766, indicating good reliability and a stable assessment of rhythmic ability.

In contrast, melody parameters did not form a coherent scale. Even after excluding individual indicators, Cronbach's α remained negative. Thus, within this test, the melody should be interpreted as a set of separate indicators that contribute to understanding singing ability but do not constitute a unified construct.

Table 6. ***Cronbach's alpha, McDonald's omega, p-values, and 95% confidence intervals for different parameter combinations.***

Scale	Cronbach's α	95% CI	McDonald's ω	p-value	Interpretation
All 10 parameters	0.24	[0.20; 0.28]	0.31	<0.001	Very weak consistency: parameters do not form a unified scale
Rhythm parameters (all)	0.25	[0.20; 0.29]	1.05*	<0.001	Weak reliability; inconsistency driven by problematic influence of dir_change
Rhythm parameters (without *dir_change*)	0.57	[0.55; 0.59]	1.22*	<0.001	Moderate reliability; stable construct after exclusion of dir_change
Rhythm parameters (standardized)	0.74	–	0.77	<0.001	Good reliability: standardized measures provide a coherent and robust scale
Melody parameters	-1.73	[-2.01; -1.48]	–	1.000	Negative reliability: items fail to cohere and capture contradictory tendencies

* McDonald's ω values greater than 1 are not practically interpretable and indicate limitations of the one-factor model.

Overall, the validation process confirms that the test is appropriate as a two-dimensional instrument that reliably evaluates singing ability by separately analyzing rhythmic and melodic components. The reliability analyses demonstrate that rhythm and melody cannot be treated as a single unified construct of singing ability. When all ten parameters were combined, Cronbach's α was only 0.24, confirming very weak internal consistency. In contrast, rhythm parameters showed a clear improvement: after excluding the problematic indicator *dir_change* and standardizing the remaining items, reliability reached acceptable levels (Cronbach's $\alpha = 0.74$; McDonald's $\omega = 0.77$), supporting rhythm as a coherent and stable construct. Melody parameters, however, consistently failed to form a reliable scale, with negative α values even after exclusions, indicating that melody should be interpreted through separate indicators rather than as a single dimension. These findings validate the test as a two-dimensional instrument, where rhythm can be analyzed as a unified ability, while melody must be assessed through distinct measures. This has important implications for future research, suggesting that collapsing rhythm and melody into a single "singing skill index" would obscure meaningful differences and that a differentiated approach better captures the multifaceted nature of singing ability.

3.3. Online Test Battery

In addition to the Singing Ability Assessment, the study employed several established tests of musical perception and skills. The **Mistuning Perception Test (MPT)** (Larrouy et al., 2019) evaluates the ability to detect whether a singer performs with accurate intonation. In each trial, participants hear pairs of short vocal excerpts – one sung in tune and one containing a controlled degree of mistuning – and must decide which version is out of tune. This test captures fine-grained auditory discrimination abilities and is particularly sensitive to individual differences in pitch accuracy perception.

The **Beat Perception Test (BAT)** (Harrison & Müllensiefen, 2018) assesses rhythmic perception skills, including pulse detection and sensitivity to metrical accents. During the task, participants listen to instrumental excerpts in which the underlying beat structure remains constant while specific rhythmic events or accent shifts are manipulated. They are asked to judge whether the beat feels aligned or displaced. This measure reflects core temporal processing skills that support rhythmic entrainment, marching, dancing, and ensemble coordination.

The **Melody Discrimination Test (MDT)** (Harrison et al., 2017) measures the ability to identify melodic changes across different tonalities. Each item consists of two short melodic sequences presented in succession. In some trials, the second melody contains a subtle modification – typically an altered pitch or interval. Participants must indicate whether the melodies are the same or different. The test captures melodic pattern recognition, short-term musical memory, and the ability to track sequential pitch structures, all of which are central to musical learning and performance.

Together, these perception-based measures offer a detailed profile of participants' auditory abilities, ranging from fine pitch discrimination and rhythmic timing to melodic memory. Their inclusion allows for a comprehensive assessment of the cognitive components that underlie broader musical development.

3.4. Questionnaires

Alongside quantitative tests, several self-report questionnaires were used to explore musical habits, environment, and beliefs. The **Concurrent Musical Activities Questionnaire (CMA)** collects information about respondents participation in everyday musical activities, such as choir, orchestra, or individual lessons. *For example, respondent indicated whether they had "played in an orchestra" or "received individual lessons on an instrument or voice" during the last three months.*

The **Musical Home Environment Questionnaire (MHE)** evaluates the musical environment in the family, parental involvement, and support for the respondents musical development and education. *Typical items ask whether parents sing in a choir or play an instrument, and how often they encourage the repondent to practise music (e.g., "Encourage me to practice music").*

The **Theory of Musicality Questionnaire (TOM)** assesses respondents beliefs about the development of musical abilities – whether they are perceived as innate or cultivated through regular long-term practice. *For instance, respondent rate statements such as "You have a certain level of musical ability and you cannot change it very much" and "You will always get better at music if you study and work hard."*

The **Goldsmiths Musical Sophistication Index (GMSI)** (Müllensiefen, 2014) provides a comprehensive overview of individual musical skills and engagement, covering listening, analysis, technical, and everyday musical abilities. *Example items include "I spend a lot of my free time doing music-related activities" from the Active Engagement scale, and "I can tell when people sing or play out of tune" from the Perceptual Abilities scale.*

This combination of diverse tests and questionnaires provided the opportunity to comprehensively evaluate students' life satisfaction, singing skills, musical perception, and additional factors such as the home musical environment and everyday involvement in music. Such an approach ensures the collection of precise, comparable, and reliable data, as well as insights into potential relationships between life satisfaction and musical skills, thereby laying the foundation for further analysis of the impact of subjective well-being on the development of singing ability in children and adolescents.

3.5. Testing procedure

The study was conducted in general education schools, within environments familiar to the students, to ensure maximum naturalness and participant comfort. Testing sessions for the two groups (choir participants and the control group) were carried out separately at times coordinated with school administration and parents. All participants and their legal guardians received both oral and written information about the study procedure and data confidentiality, and formal parental consent was obtained.

Testing took place in acoustically isolated rooms using a computer with headphones and a microphone to ensure appropriate sound quality. Each participant was assigned a unique identification code to maintain anonymity. Participants then completed the tasks from the adapted LongGold Latvia test battery. Afterwards, choir participants individually completed the newly developed Singing Ability Assessment test, which evaluates singing ability and musical memory.

The total duration of each testing session was approximately 60–90 minutes, which, for some students, risked causing fatigue – particularly during the final sections of the tasks. To minimize this risk, students were allowed to complete the tasks at their own pace. Upon completion, the data were automatically transmitted to the LongGold database for further processing and statistical analysis. In addition, students completed a short survey about their testing experience, indicating whether they enjoyed the process and how they perceived the test items and tasks. This information helps evaluate not only the methodological quality of the tests but also the participants' motivation and attitude, which are crucial for ensuring the reliability of the results.

RESULTS

Descriptive statistics for all variables included in the analysis – life satisfaction (SWL.general), rhythmic ability (BAT.ability), melodic ability (MDT.ability), and the self-reported musical skills assessed by the GMS scales – are summarised in Table 7 (see Table 7). On average, participants reported moderately high life satisfaction (M = 3.58, SD = 0.96). Rhythmic and melodic abilities showed negative mean values (BAT: M = –1.64; MDT: M = –1.56), reflecting standardised scores relative to international norms. Self-reported singing abilities (M = 3.80, SD = 0.83), musical training (M = 3.01, SD = 1.19), and perceptual abilities (M = 4.09, SD = 0.71) demonstrated meaningful variability, suggesting the presence of different levels of musical background and experience among participants.

Table 7. ***Descriptives analyze.***

Descriptives

	SWL.general	BAT.ability	MDT.ability	GMS.singing_abilities	GMS.musical_training	GMS.perceptual_abilities
Mean	3.58	-1.64	-1.56	3.80	3.01	4.09
Median	3.60	-1.60	-1.95	3.86	2.93	4.06
Standard deviation	0.957	1.48	1.14	0.829	1.19	0.706
Minimum	1.40	-4.00	-3.65	1.71	1.00	2.67
Maximum	5.00	1.88	0.826	5.57	5.71	5.44

To examine the relationships between life satisfaction and musical abilities, Pearson correlations were calculated for all variables. All correlations – including non-significant ones – are reported and interpreted, and the full correlation matrix appears in Table 8 (see Table 8).

Table 8. ***Correlation Matrix***

		SWL.general	BAT.ability	MDT.ability	GMS.singing_abilities	GMS.musical_training	GMS.perceptual_abilities
SWL.general	Pearson's r	—					
	df	—					
	p-value	—					
BAT.ability	Pearson's r	-0.097	—				
	df	43	—				
	p-value	0.525	—				
MDT.ability	Pearson's r	0.044	0.358*	—			
	df	43	43	—			
	p-value	0.773	0.016	—			
GMS.singing_abilities	Pearson's r	0.115	0.306*	0.271	—		
	df	44	43	43	—		
	p-value	0.446	0.041	0.072	—		
GMS.musical_training	Pearson's r	0.137	0.336*	0.450**	0.314*	—	
	df	44	43	43	44	—	
	p-value	0.365	0.024	0.002	0.033	—	
GMS.perceptual_abilities	Pearson's r	-0.198	0.447**	0.310*	0.469**	0.258	—
	df	44	43	43	44	44	—
	p-value	0.187	0.002	0.038	0.001	0.083	—

Note. * p < .05, ** p < .01, *** p < .001

Life satisfaction did **not** correlate significantly with rhythmic (r = –.097, p = .525) or melodic ability (r = .044, p = .773). These results indicate that children's objective rhythmic and melodic discrimination skills were not associated with their reported life satisfaction. Similarly, life satisfaction was not significantly related to self-reported singing ability (r = .115, p = .446*), musical training (r = .137, p = .365*), or perceptual musical skills (r = –.198, p = .187*). Although the directions of the associations suggested small positive tendencies for singing ability and training, these effects were minor and statistically non-significant.

In contrast, several **significant correlations** emerged among the musical ability measures themselves. Rhythmic and melodic abilities were positively related (r = .358, p = .016*). Rhythmic ability also correlated with self-reported singing ability (r = .306, p = .041*), musical training (r = .336, p = .024*), and perceptual abilities (r = .447, p = .002*). Melodic ability showed significant relationships with musical training (r = .450, p = .002*) and perceptual skills (r = .310, p = .038*). Furthermore, the GMS scales were positively interrelated: singing abilities correlated with musical training (r = .314, p = .033*) and perceptual abilities (r = .469, p = .001*). These internal associations confirm that the musical measures used in the study function coherently and capture meaningful differences in participants' musical experience and competencies.

To ensure full compliance with ethical standards, the study received prior approval from the Research Ethics Committee of Rīga Stradiņš University (Decision No. 2-PĒK-4/195/2023), thereby affirming adherence to internationally recognized research ethics principles and safeguarding the rights, dignity, and interests of all participants.

The results obtained can contribute meaningfully to the fields of pedagogy, psychology, and general education as well as cultural education. Although the present study did not identify direct statistical associations between musical abilities and life satisfaction, the findings – together with the broader body of research – offer several important implications for practice and future development.

In school choir pedagogy, the results support the view that collective music-making remains an important educational space. Even though musical aptitude itself was not linked to well-being in this sample, extensive previous research indicates that choir participation promotes emotional growth, social cohesion, and meaningful peer connections. Therefore, the present findings may be used as part of a broader scientific justification for strengthening, preserving, and developing traditions of collective singing across regions.

In the context of psychology, these results can inform the design of support programs where music and artistic self-expression are considered valuable resources for promoting emotional balance, self-esteem, and social connection in children and adolescents. While our quantitative data did not reveal direct correlations, the theoretical pathways identified in the literature – including social integration, self-esteem, and stress regulation – remain relevant for psychological practice.

In educational policy, the data contribute to the growing evidence base highlighting the broader significance of arts and music education. Combined with existing empirical research, the present findings can be used to support arguments for sustained funding of choral education, cultural initiatives, and music-based youth programs, emphasising their potential role in fostering social integration, cultural identity, and community well-being.

DISCUSSION

The results of this study suggest that the direct relationship between singing skills and children's well-being is less straightforward than often assumed. In our data, neither rhythmic nor melodic ability showed a significant correlation with life satisfaction, indicating that singing skills may not function as a direct predictor of subjective well-being. Nevertheless, the broader literature points to the possibility that singing-related benefits are mediated by psychosocial mechanisms rather than emerging from musical ability itself. In this sense, singing skills may contribute indirectly to children's emotional balance, self-esteem, and general well-being through the contexts and experiences that surround musical activity, rather than through technical competence alone.

For young people, the most plausible pathway from choir participation to well-being appears to be social belonging rather than stress reduction. Although our results did not show a significant link between musical ability and life satisfaction, the theoretical framework and previous research consistently highlight choirs as unique communities of support. Collective musical engagement has been found to foster rapid social bonding, strengthen peer relationships, and activate physiological systems associated with social connection (Pearce et al., 2015; Weinstein et al., 2016). These mechanisms may explain why choir participation can enhance well-being even when individual musical aptitude does not directly correlate with life satisfaction.

The findings of this study therefore shed light on the potential mechanisms linking singing to well-being and suggest that these associations are likely mediated by several psychosocial factors rather than being linear or unidimensional. Recent literature highlights three central components – social integration, self-esteem, and stress regulation – that together provide a coherent explanatory model.

The first component, social integration, is especially relevant for children and adolescents. Group singing serves as a powerful social tool that accelerates the formation of interpersonal bonds and enhances feelings of belonging. Empirical work shows that collective music-making facilitates faster social cohesion and is associated with neurochemical processes that promote affiliation (Pearce et al., 2015; Weinstein et al., 2016). This aligns with the idea that social belonging may be a key mediator between singing activities and subjective well-being.

A second potential mediator is self-esteem. Participation in choirs, including rehearsals and performances, can promote feelings of achievement and competence, which are well-established predictors of psychological well-being. Singers themselves often report improvements in relaxation, confidence, and social connectedness as key benefits of participation (Clift & Hancox, 2010). Although these relationships did not manifest strongly in our quantitative correlations, they remain theoretically plausible pathways through which choir participation could support well-being.

A third component concerns stress regulation. Physiological studies indicate that singing can have a calming effect in low-stress contexts, reducing cortisol and cortisone levels, while higher-stress performance situations may evoke different hormonal responses (Fancourt et al., 2015). This suggests that the link between singing and stress regulation is context-dependent and may not be captured through cross-sectional correlations such as those used in the present study.

Recent scholarship further strengthens the argument that group singing supports well-being across multiple dimensions. Research with youth choirs highlights that the experience of well-being depends strongly on the social context of participation (Blagojević, Habe, & Bajec, 2025). Empirical work with children shows that group singing can enhance positive affect and perceived social belonging (Davies, Bentham, & Duah, 2023), and early childhood research indicates that singing contributes to health and developmental well-being (Welch & Baxter, 2025). More broadly, music education has been linked to psychological well-being via self-efficacy and self-esteem, underscoring the importance of perceived competence in music learning (Jiang, 2024). Physiological studies of group chanting similarly show reductions in stress and increases in social connectedness (Perry, Polito, & Thompson, 2024).

Taken together, these findings point to a mediation model in which singing influences subjective well-being **indirectly** – through mechanisms of social integration, self-esteem, and stress regulation – rather than through musical ability itself. This model helps explain why the present study did not find direct correlations between musical skills and life satisfaction, while substantial evidence from broader literature continues to support the psychosocial value of group singing. Future research should empirically test these mediating relationships using larger samples, longitudinal designs, and multi-method assessments of both musical engagement and well-being.

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DZIEDĀŠANAS PRASMJU ATTĪSTĪBAS SAIKNE AR DZĪVES APMIERINĀTĪBU: PĒTĪJUMS ZĒNU KOROS

Reinis Maurītis, Valdis Bernhofs

KOPSAVILKUMS

Šajā pētījumā analizēta savstarpējā mijsakarība starp dziedāšanas prasmju attīstību un dzīves apmierinātību bērnu un pusaudžu vecumā, īpašu uzmanību pievēršot zēnu koru kontekstam. Dziedāšana un kolektīvā muzicēšana ir daudzdimensionāls process, kas ietver vokālās, muzikālās, emocionālās, kognitīvās un sociālās prasmes. Lai gan kolektīvās muzicēšanas - kordziedāšanas - ietekme uz emocionālo labbūtību visbiežāk pētīta pieaugušo vidē, bērnu un pusaudžu koros - īpaši zēnu koros - šī joma līdz šim aplūkota ļoti maz. Latvijas skolu koru, šajā gadījumā zēnu koru, tradīcija nodrošina piemērotu vidi, kurā izzināt muzikālās attīstības, īpaši dziedāšanas prasmju, un apmierinātības ar dzīvi mijiedarbību reālos pedagoģiskos apstākļos, ņemot vērā gan muzikālos, gan sociāli emocionālos aspektus.

Pētījumā izmantota tiešsaistes testēšanas platforma *LongGold Latvia*, kas apvieno dzīves apmierinātības mērījumu ar dažādiem muzikālo prasmju testiem, tostarp ritma un melodijas uztveri, muzikālās vides raksturojumu, mūzikas klausīšanos un citus ar muzikālo attīstību saistītus rādītājus. Dziedāšanas prasmju novērtēšanai tika izmantots jaunizveidots un Latvijas kultūrvidei adaptēts *Singing Ability Assessment* tests, izmantojot latviešu tautasdziesmu melodijas fragmentus. Šāda pieeja nodrošināja iespēju atsevišķi analizēt ritma un melodijas komponentus, kas atbilstoši validācijas rezultātiem veido divas atšķirīgas prasmes, nevis vienotu dziedāšanas skalu.

Pētījumā piedalījās respondenti vecumā no 8 līdz 13 gadiem, kuri tika sadalīti divās grupās: respondenti, kas regulāri apmeklē un dzied skolas korī, un respondenti bez kordziedāšanas pieredzes. Pirmie iegūtie rezultāti liecina, ka respondenti, kuri regulāri apmeklē un dzied korī uzrāda augstāku ritma reproducēšanas prasmi, savukārt melodiskie rādītāji neveidoja iekšēji konsekventu skalu un tādēļ analizējami kā atsevišķi parametri. Dzīves apmierinātības līmenī būtiskas atšķirības starp abām grupām netika konstatētas, un korelācijas starp muzikālajām spējām un dzīves apmierinātību izrādījās nebūtiskas. Tas norāda, ka dziedāšanas tehniskās prasmes pašas par sevi nav tiešs subjektīvās labbūtības rādītājs.

Tomēr teorētiskā un empīriskā literatūra atklāj, ka kolektīvās muzicēšanas pozitīvā ietekme uz labbūtību var izpausties netieši – caur sociālo piederību, pašvērtējumu un emocionālās regulācijas mehānismiem. Koris funkcionē kā īpaša sociālā vide, kas veicina sadarbību, komunikāciju, grupas identitāti un piederības sajūtu, kas bērnu un pusaudžu vecumā ir īpaši nozīmīga emocionālās un sociālās attīstības dimensija. Šie aspekti skaidro, kādēļ ieguvumi no kordziedāšanas var parādīties arī tad, ja tie nav tieši saistīti ar muzikālo prasmju līmeni.

Pētījums sniedz nozīmīgu ieguldījumu dziedāšanas prasmju novērtēšanas metodoloģijā, apliecinot, ka ritms un melodija jāvērtē kā divas atsevišķas prasmes. Vienlaikus pētījums akcentē kolektīvās muzicēšanas nozīmi bērnu un pusaudžu emocionālajā, sociālajā un kognitīvajā attīstībā un iezīmē nepieciešamību turpmākos pētījumos padziļināti analizēt netiešos labbūtības veidošanās mehānismus.

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THE IMPACT OF AUDIO-VISUAL STIMULATION ON MUSIC IMPROVISATION: AN EEG HYPERSCANNING CASE STUDY

Jachin Edward Pousson, Mahrad Ghodousi

This case study uses the EEG Hyperscanning method to investigate the impact of an Audio Visual Stimulation (AVS) program designed to induce a creative mental state on the brain activity and music improvisation behavior of one subject pair. Over the course of 2 sessions, 12 repetitions of 2-minute musical improvisation tasks were performed by the subject pair. The 11-minute AVS program called "Creative Pop" precluded the improvisation tasks only in the second session and was presented to each subject using a consumer device called a "Vizr" which generates strobing light patterns choreographed to music. EEG Hyperscanning data synchronized sample-to-sample at a resolution of 500Hz was recorded from 32 electrodes per subject before, during and after AVS stimulation as well as during improvisation tasks. Lempel-Ziv (LZ) complexity and Granger Causality (GC) connectivity were used to measure Brain-Signal Variability (BSV) and Intra/Inter-Brain Synchronization (IBS) respectively. Both BSV and Inter-Brain Synchronization were found to increase during the final minute relative to the full 11-minute duration of the AVS and further increased 30 seconds post-AVS in both subjects. Additionally, an increase in Inter-Brain Synchronization and a decrease in Intra-Brain Synchronization was recorded during the improvisation tasks in the second session post-AVS.

Keywords: Electroencephalography (EEG) Hyperscanning; Audio-Visual Stimulation (AVS); Brain Signal Variability (BSV), Lempel-Ziv (LZ) complexity; Intra/Inter Brain Synchronization (IBS); Granger Causality (GC) connectivity; Music Improvisation.

INTRODUCTION

Approach

This project used an EEG Hyperscanning method to study the effects of a strobing AVS program on musical improvisation. Systematic musicology provides an umbrella under which these areas can be connected and approached in a scientific way. Musical improvisation has been an enduring subject of interest not only in the field of systematic musicology, but research using neuroimaging techniques are currently very scarce. This is mainly due to challenges inherent to the technology, and a lack of interdisciplinary collaboration. This case study provided a unique opportunity to take a snapshot of inter-brain dynamics during musical improvisation before and after exposure to stimulation designed to induce a creative mental state. Analysis of the EEG data recorded during this study was performed by JVLMA's[1] research collaboration partners at the Department of Biophysics, Vilnius University.

1 Jāzeps Vītols Latvian Academy of Music (Jāzepa Vītola Latvijas Mūzikas akadēmija).

Audio Visual Stimulation

Rhythmic light and sound in the format of AVS programs have long been used by psychologists and neuroscientists to modulate and study brain activity (17–20). The practice of using AVS to induce relaxation or hypnosis saw a rise in interest around seven decades ago (Morse 1993, 111–126), and increasingly since the turn of the century, devices made to deliver light and sound pulses at specific frequencies have been found effective to entrain the EEG into desired states in the context of therapy for pain or anxiety relief (Huang and Charyton 2008, 38–49). Despite being found to be an effective therapeutic tool, findings concerning the specific entrainment frequencies to which the EEG signal responds are inconsistent. Individuals clearly have different and transient responses to AVS (Teplan et al. 2011, 17–24).

Typical AVS programs use strobing lights at specific frequencies paired with music or sound embedded with reinforcing aural pulsations which sometimes modulate in frequency over the program duration. The AVS program used in this case study is not typical – it features a 3x3 grid of LED lights capable of delivering a highly complex and geometric patterns of photic stimulation. This approach to AVS design is aimed not at entraining or modulating to single frequencies, but rather at engaging the visual cortex with constantly evolving patterns. Exposure to this type of AVS is not expected to entrain, but rather entertain – to increase the frequency and level of transience to different states rather than to stabilize a specific state. The creators of the Vizr device propose that this approach may have an impact on BSV, which has been linked to a creative mental state supporting improvisation (Dolan et al., 2018, 18–19).

Music Improvisation

Evidence from EEG hyperscanning studies have found an increase in certain measures of IBS during interpersonal coordination (Chen et al, 2021, 1–2), as well as during music improvisation on the guitar (Müller et al. 2013, 1–2). IBS is predicted to increase during music improvisation, but the relationship between IBS and BSV has not been well explored. This case study aims to investigate the possible impact of AVS on BSV and IBS in the EEG signal, using behavioral data from music improvisation tasks performed by a subject pair to shed light on its effects on co-creative interpersonal coordination.

The coordination of biological or behavioral processes to signals is has been termed interactional synchronization. Signal complexity and intentionality facilitate this synchronization, which facilitates prediction, communication and affiliation (9–11). Synchronization in musical interaction typically requires rhythmic entrainment to a repeating pattern over time, however it does not require that the rhythm contain a constant tempo or time signature. Musical interaction has thus been used as a framework for measuring interactional synchronization (Volpe et al, 2016, 1–8). This enables observing the brain's response to changes in task focus, coordinated behavior or the environment in a more ecologically valid manner. Indeed, systematic musicologists have called for increased ecological validity, and a more embodied approach in EEG studies (Leman, 2008, 104, Leman and Maes 2014, 236–237) because EEG data alone 'in a vacuum' is difficult to relate to processes experienced in everyday life.

The majority of EEG music studies have investigated the listener responses, while relatively few have examined the processes involved in music performance, let alone musical improvisation. This gap is partly due to the EEG signal's well-documented susceptibility to noise from body movement – an inherent requirement of instrumental performance – as well as environmental interference (Rakotomamonjy et al. 2005, 45–46). In addition, music performance and improvisation are highly complex human behaviors involving multiple variables that make experiments difficult to control (Pousson et al. 2021, 1–2). This case study takes on the technical challenges of recording EEG hyperscanning data from a subject pair during AVS stimulation and music improvisation, and aims to connect findings to others in this relatively new research space.

Brain Signal Variability metric

Lempel-Ziv (LZ) complexity was chosen to measure BSV, in order to connect to and build upon findings in past studies. LZ complexity has been a preferred method for studying brain entropy and signal complexity within a theoretical framework called the "Entropic Brain Hypothesis" (EBH) proposed by the research led by Carhart-Harris (Carhart-Harris et al. 2014, 1–3). The EBH proposes that human cognition may be distinguished by two states:1) "primary" during which the mind regresses under specific conditions becoming more open to suggestion and emotion, characterized by increased levels of signal complexity, and 2) "secondary" during which more regular and stable cognitive processes and self-awareness are in place, characterized by reduced levels of signal complexity.

LZ complexity is an algorithm initially introduced to measure the complexity of binary sequences (Lempel and Ziv 1976, 75–81), but has been extended to various types of data including the EEG signal for medical and research applications (Radhakrishnan and Gangadhar 1998, 89–94; Zhang et al. 2001, 1424–1433; von Wegner et al. 2023, 296–311). Increased LZ complexity in the EEG signal has been correlated with ego dissolution and vivid imagination (Schartner et al. 2017, 9), both important conditions for the mental state of flow (62–66) that play a role in the creative process of music improvisation (Sawyer 2015, 29–52). In this case study LZ complexity is calculated in the mathematics software MATLAB [2], based on Lempel and Ziv 1976 (see EEG data analysis pipeline for details).

2 https://www.mathworks.com/matlabcentral/fileexchange/38211-calc_lz_complexity

Intra and Inter Brain Synchronization metric

Granger Causality (GC) connectivity was chosen to measure both Intra and Inter Brain Synchronization, within and between subjects respectively. GC connectivity provides information on the direction of the flow of information, illustrating interactions between brain regions (Tafreshi et al. 2019, 555–566; Zervakis et al. 2011, 302–314; Haufe et al. 2011, 1–2; Kong et al. 2015, 19181–19198).

GC is a statistical test for determining if one time series can be used to predict another, where if a signal *A* causes a signal *B* then past values of *A* should help predict *B*, but past values of *B* alone do not provide sufficient information to predict future values of signal *B* (Granger 1969, 424–438). The use of GC in this case study builds upon previous research concerning Intra-brain Synchronization during expressive music performance (Ghodousi et al. 2022, 1–12). MATLAB was used to calculate both Intra and Inter-Brain Synchronization in subject pairs (see EEG data analysis pipeline for details).

MAIN AIMS AND TASKS:

Main Objectives

1. Determine and characterize the impact of AVS using the Vizr device on BSV and IBS in context of music improvisation tasks.
2. Evaluate findings and recommend steps for further investigation.

Main Tasks

1. Identify, record and compare BSV and IBS measures before, during, and after AVS.
2. Identify, record and compare BSV and IBS measures during music improvisation before and after AVS.
3. Record and compare audio during music improvisation before and after AVS.

Expectations

1. BSV measures was expected to be increased post-stimulation, while Intra-Brain Synchronization is expected to decrease.
2. Inter-Brain Synchronization measures was expected to be increased during music improvisation tasks post-stimulation.
3. Audio recorded of the improvisation tasks is behavioral data expected to implicate links between BSV and IBS.

MATERIALS

The Vizr device and stimulation program

The Vizr instruction manual and website[3] state that it is a consumer device for adult use, and is not classified as a medical device. Vizr's creators state that it is designed to provide a sensory experience, entertainment, and to contribute to positive emotional and mental well-being. There are also clear warnings to users regarding epileptic and other types of photosensitive seizures that can be triggered by flickering light, and a light sensitivity test for users who may be unsure.

The device itself (Fig.1) is a plastic rectangular box called a "Light Box", 115x89x30 mm, weighing 109 grams. On one flat surface is an array of 9 white LED lights arranged in a 3x3 grid. The Light Box snaps magnetically onto a plastic bar mounted on a head strap, positioning the Light Box 8-10 cm directly in front of a user's eyes. The Light Box connects to a mobile application called "Neurovizr" which controls the Light Box and runs AVS programs via Bluetooth on mobile devices. The Light Box can alternatively be mounted onto stands and positioned at the same distance from a user's eyes, if other headgear such as EEG electrodes in our case are being used.

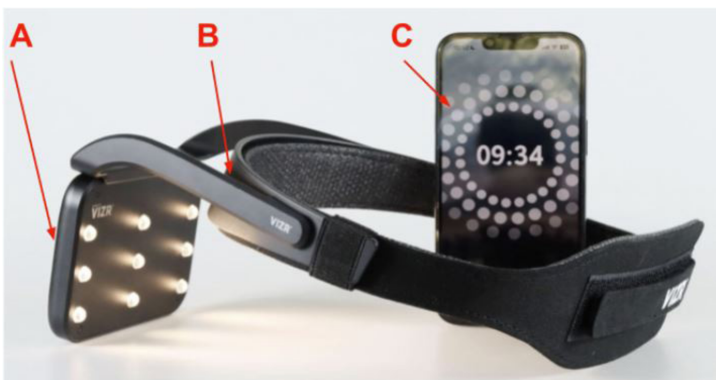


Figure 1: Image of the Vizr device (A), headgear (B) and Neurovizr mobile application (C).

The AVS programs consist of audio choreographed with strobing light patterns designed to be experienced by users with eyes closed. Within the Neurovizr app there are various categories of stimulation programs aimed to induce mental states for activities such as athletic training, meditation or better sleep. This case study used a stimulation program recommended by the Vizr creators called "Creative Pop", which aims to boost a creative state of mind. This program consists of 11 minutes of AVS followed by 30 seconds of nature sounds (bird calls and running water) without photic stimulation. The visual component of the program presents a flicker which modulates in frequency from 5-20 Hz, while patterns of movement and intensity within the 3x3 grid change at intervals between 5 to 120 seconds. The audio component of the program consisted of

3 https://neurovizr.com/

instrumental loops (plucked strings, percussion, and a synth pad) made with samples or a synthesizer layered on top of each other. The loops are of different lengths and evolve over the course of the program. There is also the constant presence of a monaural pulse at a frequency of 16-20 Hz synchronized with the photic stimulation.

Subjects

In this pilot study, one male jazz drummer and one female tenor saxophonist – both academic music students with over 5 years playing experience in good physical and mental health – volunteered to participate. They were fully briefed on the study procedure and objectives, and introduced to the Vizr device in person a week before the second recording session to familiarize themselves with its functions and experience of use.

METHODS

EEG and audio signal recording

The EEG hyperscanning method was used to record 32 channels of EEG data per subject at a resolution of 500Hz using a pair of Enobio 32 NECBOX EEG systems with Dry electrodes and CMS/ DRL grounding provided with an ear clip. EEG data was recorded using two instances of Neuroelectrics Instrument Controller (NIC) software synchronized via the LSL layer. Markers were added to the EEG data manually at the start and end of each trial, thus the hyperscanning data was manually synchronized sample to sample by timestamp. Audio was recorded using a stereo pair of microphones and a Digital Audio Workstation (DAW).

Experiment protocol

One pair of subjects attended two recording sessions taking place on different days. Subject 1 was a drummer, while subject 2 was a saxophonist. A reduced drum kit consisting of a snare drum, floor tom and a ride cymbal were set up next to a chair for the saxophonist in an acoustically treated laboratory space.

Two improvisation task types were performed at each session with different focuses. The first task type was <u>informal</u> – subjects were asked to play as if just for fun, without any pressure to technically impress. The second task type was <u>formal</u> – subjects were instructed to play as if recording for an audition or competition. There was no pre-determined musical material but subjects were allowed to communicate and plan before starting each task. Both tasks had a duration of 2 minutes, and were repeated 3 times each per session, resulting in a total of 12 trials per subject.

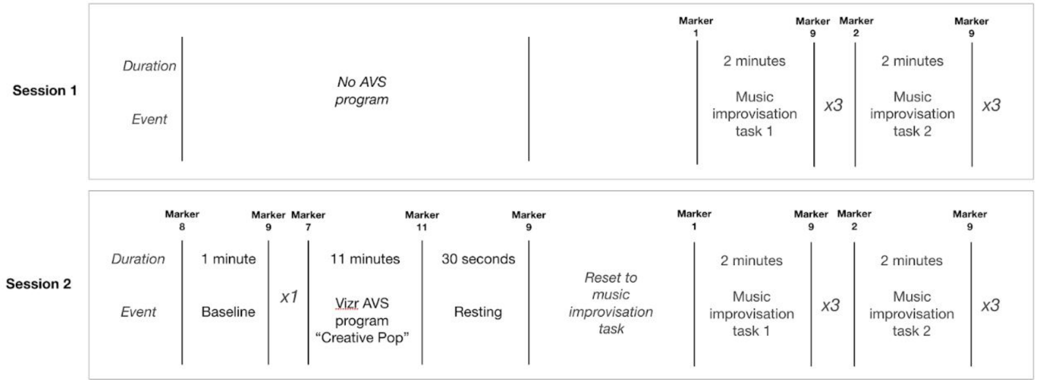


Figure 2: Recording protocol of session 1 (above) and session 2 (below), where identical music improvisation tasks are performed in both sessions, precluded with AVS stimulation in session 2.

No AVS stimulation was used in the first session. At the second session, subjects were exposed to an AVS program before undertaking the improvisation tasks (Fig.2). Two Vizr devices were synchronized via Bluetooth on one mobile device to play the AVS program "Creative Pop", and mounted on stands positioned 8–10 cm from the subjects' faces in darkened lighting conditions. The audio was played at a comfortable level through audio speakers. These adjustments eliminated the need for subjects to wear the Vizr headgear and audio earphones, in order to accommodate for the electrode caps worn on their heads.

EEG DATA ANALYSIS PIPELINE

This pipeline processes EEG data in several steps to clean and prepare it for further analysis. The steps include:

1. **Dataset Loading and Preparation**:
   - EEG data is loaded into EEGLAB from the specified location file (Enobio32.locs).
   - The datasets are synchronized based on the first event latencies to ensure temporal alignment across the two datasets (EEG1 and EEG2).
2. **Synchronization**:
   - The datasets are adjusted so that their first events start at the same point by removing extra samples and aligning their event latencies.
   - If one dataset is longer than the other, it is trimmed to ensure both have the same length.
3. **Dataset Concatenation**:
   - EEG1 and EEG2 datasets are concatenated along the channel dimension to create a combined dataset (newEEG), resulting in a dataset with 64 channels.

4. **Cleaning and Artifact Removal:**
   - The combined dataset is cleaned using the pop_clean_rawdata function with specified criteria for filtering and noise reduction.
   - High-pass filtering is applied to remove slow drifts, and burst artifacts are processed with specific thresholds.
5. **Independent Component Analysis (ICA):**
   - ICA is performed separately on EEG1Cleaned and EEG2Cleaned datasets to identify and remove artifacts (e.g., eye blinks, muscle movements).
   - Components are labeled using the ICLabel toolbox, and components with high artifact probability are removed.
6. **Segmentation:**
   - The cleaned datasets (EEG1Cleaned and EEG2Cleaned) are segmented based on specific event pairs (e.g., 8–>9, 7–>10) and maximum durations.
   - For each event pair, valid segments are extracted, stored in a structure (cut_EEG_struct1 and cut_EEG_struct2), and logged for trial counts.
7. **Saving Results:**
   - The segmented data (cut_EEG_struct1 and cut_EEG_struct2) and their corresponding logs are saved in .mat files for further analysis.

8. **Logging:**
   - Detailed logs are maintained for each step, including filtering, ICA, artifact rejection, and event-based segmentation. These logs track trial counts and invalid segments.

EXPLANATION OF THE LZ COMPLEXITY ANALYSIS PIPELINE

This pipeline calculates and visualizes the *Lempel-Ziv (LZ) complexity* of EEG data for specified events and subjects. LZ complexity is a measure of sequence randomness and structural complexity, normalized for each channel and trial.

PIPELINE DESCRIPTION

1. **Initialization:**
   - Parameters like the number of EEG channels (num_channels = 32), the events to process, and the subject-specific EEG data structures (cut_EEG_struct1, cut_EEG_struct2) are initialized.
   - An output folder (D:\VIZR\LZ) is defined for saving results.
   - Channel names are loaded from StandardChannels.mat to label the axes in the plots.

2. **Event and Subject Iteration:**
   - The pipeline loops through the specified events (Event1_9, Event2_9, etc.) and processes data for each subject separately.
3. **Trial-wise LZ Complexity Calculation:**
   - For each trial in the specified event:
     - **Common Average Referencing (CAR)**: The mean signal across all channels is subtracted from each channel to reduce noise.
     - **Binary Conversion**: Each channel's data is converted into a binary sequence by z-scoring and thresholding around zero (binary_sequence = zscored_data > 0).
     - **LZ Complexity Calculation**: The binary sequence is analyzed using the calculateLZComplexity function to compute normalized LZ complexity for each channel.
   - The results are stored in lz_complexity_per_channel_trial (a matrix of size num_channels x num_trials).
4. **Channel-Wise and Overall Average:**
   - **Channel-Wise Average**: The average LZ complexity is computed across trials for each channel (avg_lz_complexity_channels).
   - **Overall Average**: The mean of all channel-wise averages is calculated (overall_mean_lz_complexity).

<u>In all plotted data, Subject 1 is the drummer and Subject 2 is the saxophonist.</u>

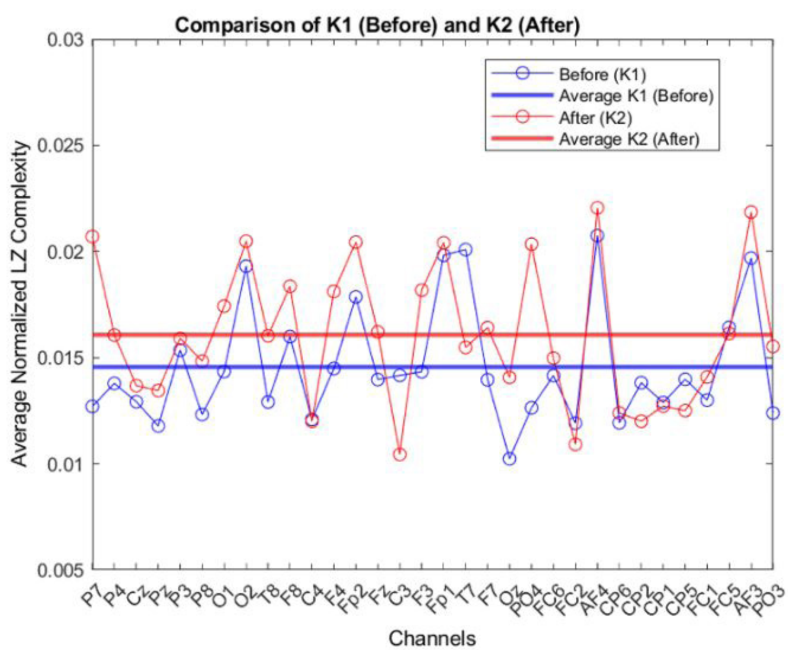


Figure 3: Example of average normalized LZ complexity data plotted per electrode (thin line) and the mean of all electrodes (thick line) during music improvisation tasks before (blue) and after (red) AVS.

EXPLANATION OF THE GRANGER CAUSALITY ANALYSIS PIPELINE

This pipeline computes *Granger causality (GC)* for EEG data across specified events, focusing on connectivity between two subjects during hyperscanning experiments. The output is an averaged Granger causality matrix for each event, saved for further analysis. Granger causality is a statistical method to determine whether one time series can predict another. In the context of EEG:

- **GC measures directed connectivity**: It indicates whether activity in one EEG channel can predict activity in another.
- **Applications**: Granger causality is widely used in neuroscience to analyze functional connectivity and understand how different brain regions interact.

PIPELINE DESCRIPTION

1. **Initialisation:**
   - Parameters such as the sampling rate (fs = 500 Hz) and window length (3 seconds) are defined.
   - The event pairs to analyse are selected (e.g., Event1_9, Event2_9), and the output folder is set to save results.
2. **Event and Trial Selection:**
   - The pipeline checks whether the specified event exists in both subjects' EEG datasets (cut_EEG_struct1 and cut_EEG_struct2).
   - If trials are available, the analysis proceeds.
3. **Trial-Wise Analysis:**
   - For each trial:
     - EEG data from both subjects (32 channels each) is loaded.
     - Common Average Referencing (CAR) is applied to reduce noise.
     - Trials from both subjects are aligned by their shortest length.
     - The trial is divided into **3-second windows** for localized Granger causality analysis.
4. **Window-Wise Granger Causality Calculation:**
   - For each window:
     - EEG data from both subjects is concatenated into a 64-channel dataset.
     - Granger causality is calculated for each pair of channels (i,ji, ji,j) using a predefined function granger_cause.
     - **Significant Causality**: If the Granger causality statistic (FFF) exceeds a critical value (cvc_vcv), the causality is considered significant, and a connection is marked in the connectivity matrix.

5. **Averaging Across Windows and Trials:**
   - For each trial:
     - Granger causality matrices are averaged across all windows.
   - For each event:
     - The trial-averaged Granger causality matrices are accumulated and averaged across all trials.
6. **Saving Results:**
   - The final Granger causality matrix for each event is saved as a .mat file in the specified output folder.
   - **Illustration methods: Circular plot and heatmap**

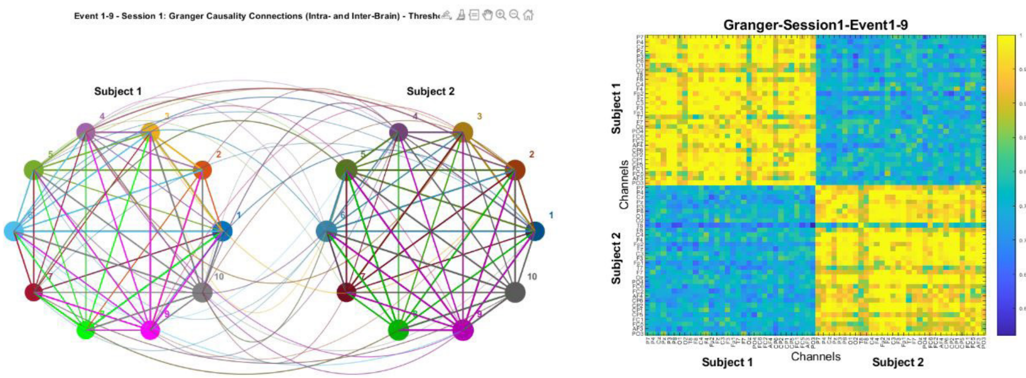


Figure 4: Example of circular plot (left) and heatmap (right) for illustrating GC connectivity. In the circular plot Node Radius and line thicknesses are equal to the strength of the outgoing connection. Outgoing connection from each node has the same color of the node. In the heat map Intra-Brain Synchronization are shown within each subject (32 x 32 electrodes) on the top left (subject 1) and bottom right (subject 2), while Inter-Brain Synchronization between subjects is shown on the top right (subject 1 – subject 2) and the bottom left (subject 2 – subject 1).

DATA ANALYSIS RESULTS

The EEG data analysis was performed with the aim to investigate the impact of AVS using the Vizr device on Brain Signal Variability (BSV) as well as Inter and Intra-brain Synchronization (IBS). Lempel-Ziv (LZ) complexity and Granger Causality were used to calculate BSV and IBS respectively.

LZ COMPLEXITY RESULTS CONCERNING BSV

The average LZ complexity result was first divided by the duration of each recorded condition, where the AVS program duration was 11 minutes long, the baseline before stimulation was 1 minute, and the resting state after stimulation was 30 seconds.

The two upper plots in Figure 5 show average normalized LZ complexity per electrode before (blue), during (green) and after (red) AVS using the Vizr device, in subjects 1 and 2. Average LZ complexity decreased in both subjects during, but also both increased after stimulation. Average LZ complexity after stimulation as compared with before stimulation increased in subject 1 but decreased in subject 2.

The two lower plots in Figure 5 show LZ complexity during only the <u>final minute</u> of AVS, instead of all 11 minutes. It was found that LZ complexity in both subjects was higher towards the end of the stimulation than during the whole 11 minutes, which could imply a steady increase over time.

Subject 1 **Subject 2**

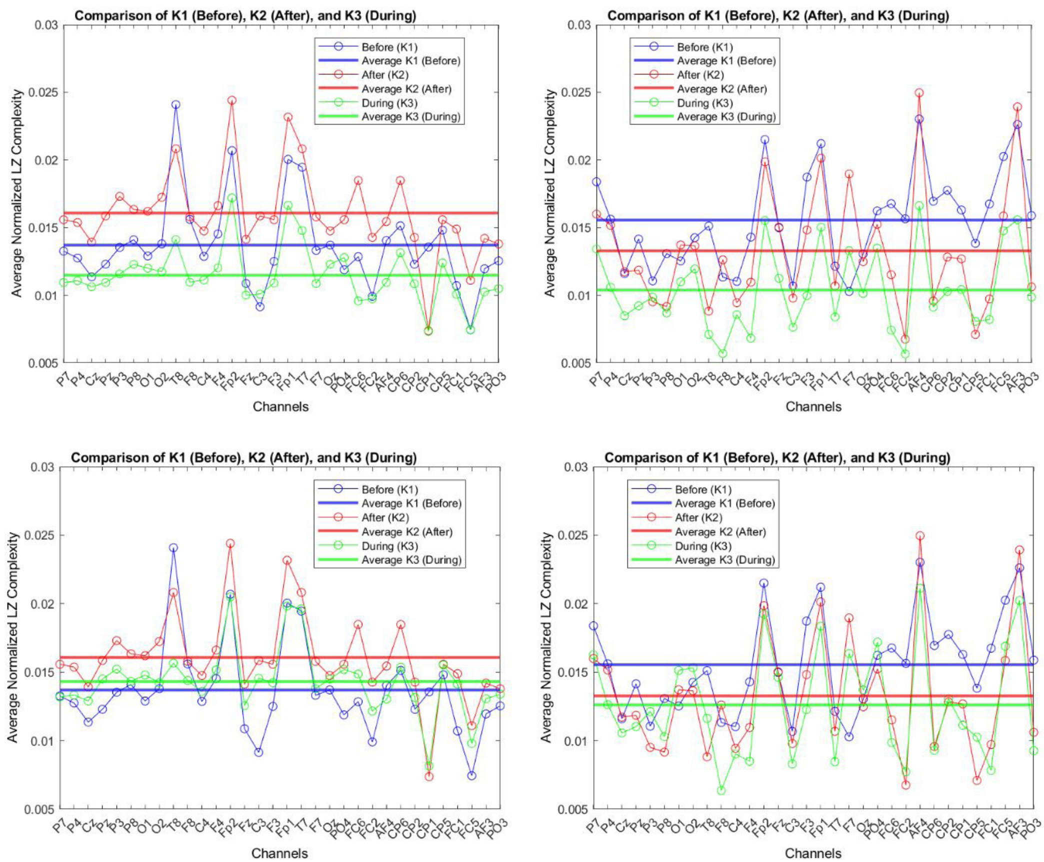


Figure 5: Average, normalized LZ complexity per electrode and across all electrodes, before (blue), during (green) and after (red) AVS using the Vizr device. The two upper plots show LZ complexity during stimulation averaged over 11 minutes, while the two lower plots show LZ complexity during the final minute of stimulation.

Next, LZ complexity was compared during music improvisation tasks 1 (informal) and 2 (formal) between the first session (before AVS) plotted in blue and the second session (after AVS) in Figure 6.

Subject 1 **Subject 2**

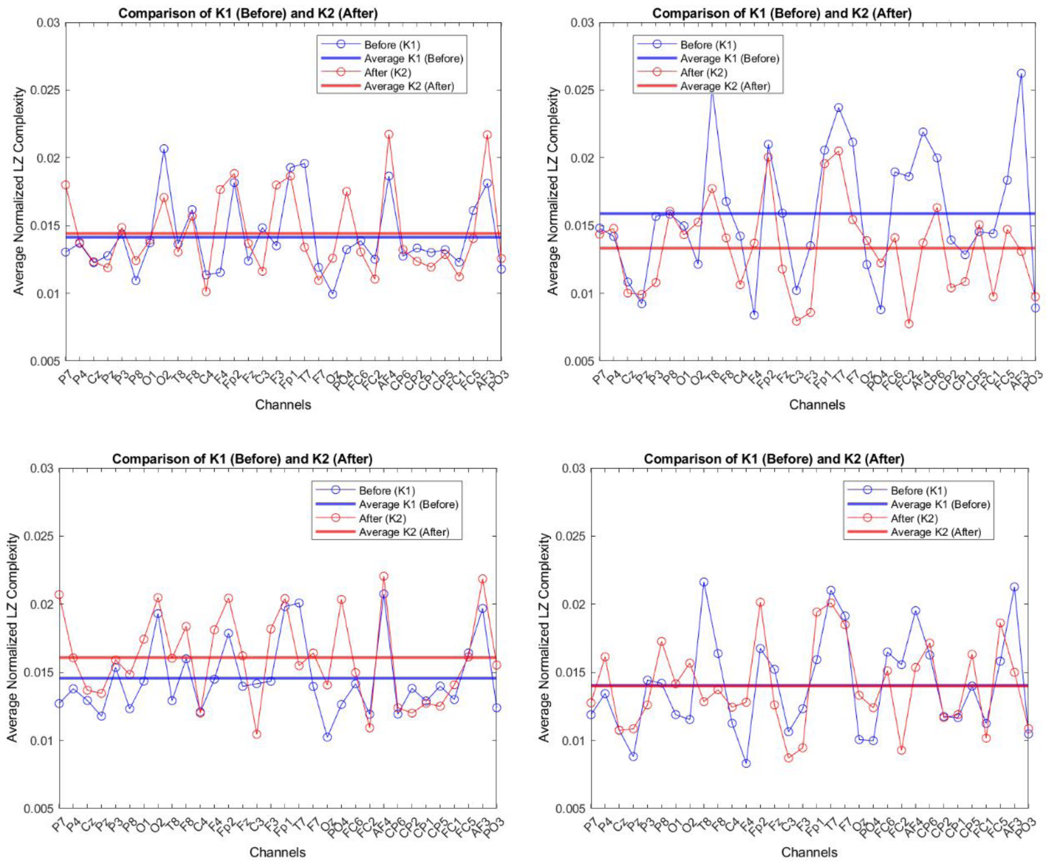


Figure 6: Average, normalized LZ complexity per electrode and across all electrodes during improvisation tasks 1 (top row) and 2 (bottom row), before (blue) and after (red) AVS.

During task 1 LZ complexity in subject 1 showed almost no change post AVS, whereas subject 2 showed a decrease, modulating closer to levels recorded in subject 1. During task 2 LZ complexity in subject 1 increased post AVS, whereas subject 2 showed almost no change. The modulation of LZ complexity in response to the AVS program clearly varied between subjects, but some commonalities could be observed. Levels of LZ complexity in both subjects increased in task 2 compared with task 1 post AVS. Odd-numbered electrodes are positioned on the left hemisphere while even-numbered are positioned on the right. LZ complexity in both subjects were more increased in the right hemisphere compared to in the left in both tasks post AVS.

GRANGER CAUSALITY RESULTS CONCERNING IBS

For clarity of presentation and to connect findings with previous research (Ghodousi et al. 2022, 1–12), data from 32 electrodes was grouped into 10 Regions of Interest (ROI) distributed over the scalp in Figure 7.

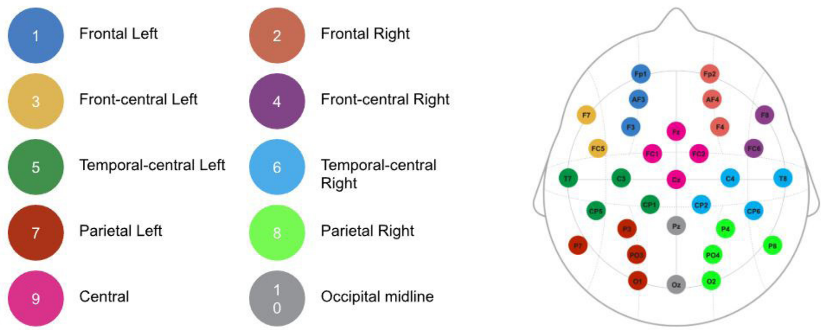


Figure 7: 32 electrode montage grouped into 10 Regions of Interest (ROI) for Granger Causality connectivity analysis.

Granger Causality connectivity was calculated before, during and after AVS using the Vizr device (Fig.8). Intra-brain connectivity was plotted as connections within each circle of nodes and remained largely unchanged across conditions. Inter-brain connectivity was plotted as connections between the two circles of nodes, where the most significant changes could be observed.

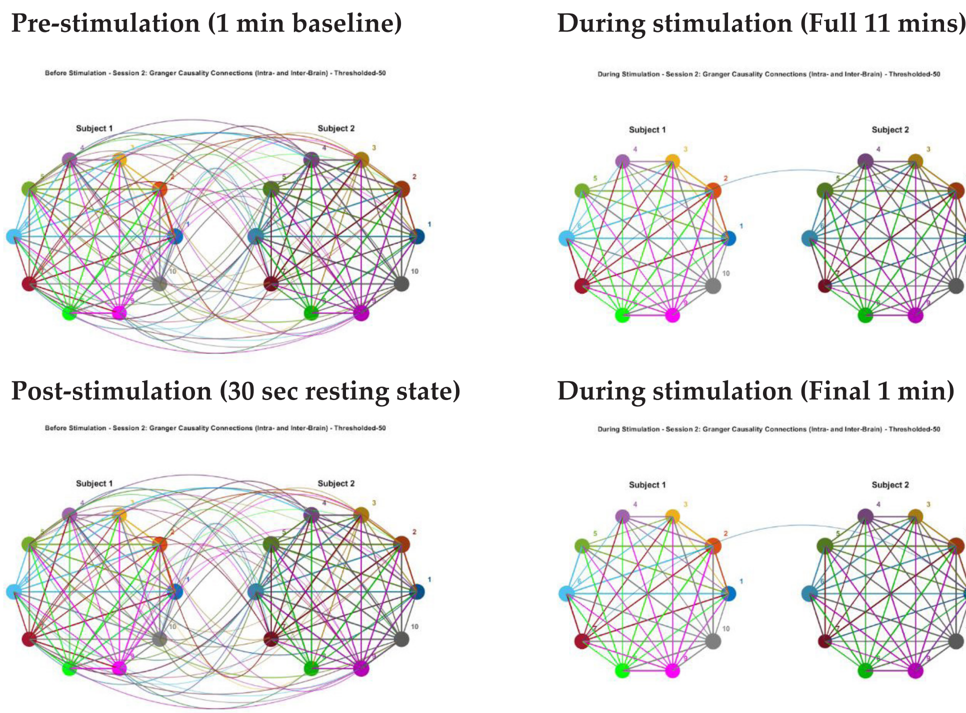
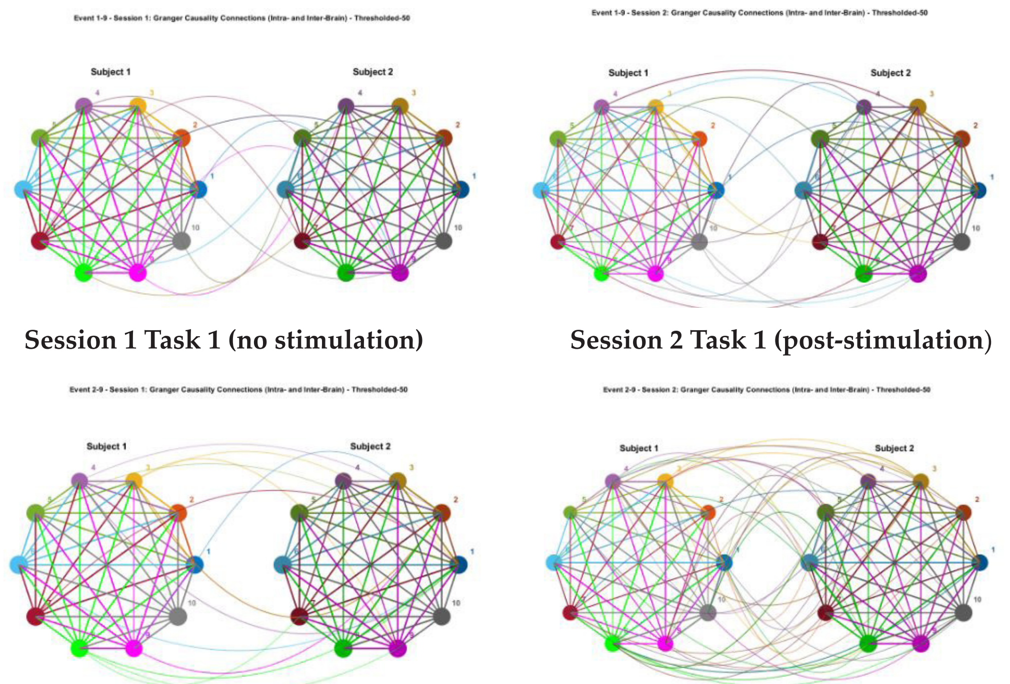


Figure 8: Intra (within node circles) and Inter (between node circles) brain connectivity before, during and after AVS.

The number and strength of inter-brain connections were significantly increased during the resting state post-stimulation. The final minute of the AVS program also showed more inter-brain connections than during pre-stimulation or during the full 11 minutes of stimulation. Granger Causality connectivity was also compared during improvisation tasks between session 1 (no stimulation), and session 2 (post-stimulation) in Fig. 9.



Session 1 Task 1 (no stimulation) **Session 2 Task 1 (post-stimulation)**

Session 1 Task 2 (no stimulation) **Session 2 Task 2 (post-stimulation)**

Figure 9: Intra (within node circles) and Inter (between node circles) brain connectivity during music improvisation tasks 1 and 2 compared between session 1 with no AVS, and session 2, after AVS.

In both sessions inter-brain connectivity increased during task 2 (formal playing) as compared with task 1 (informal playing). Further, inter-brain connectivity was increased in session 2 (post-stimulation) as compared with session 1 (no stimulation).

Out of all the conditions measured, inter-brain connectivity was found to be the highest during the resting state post-stimulation. This was an unexpected result, since during the resting state, the subjects sat still with eyes closed in the darkened lab, not interacting in any way. Notably, during this 30 second resting period, the Vizr program was playing nature sounds (bird song and running water) designed to ease a user out of the stimulation program.

Another observation was made regarding subject 1. Intra-brain Synchronization was found to be reduced in session 2, post-stimulation during tasks 1 and 2. At the same time, subject 1's LZ complexity was increased, implying an inverse relationship between BSV and Intra-Brain Synchronization (Fig. 10).

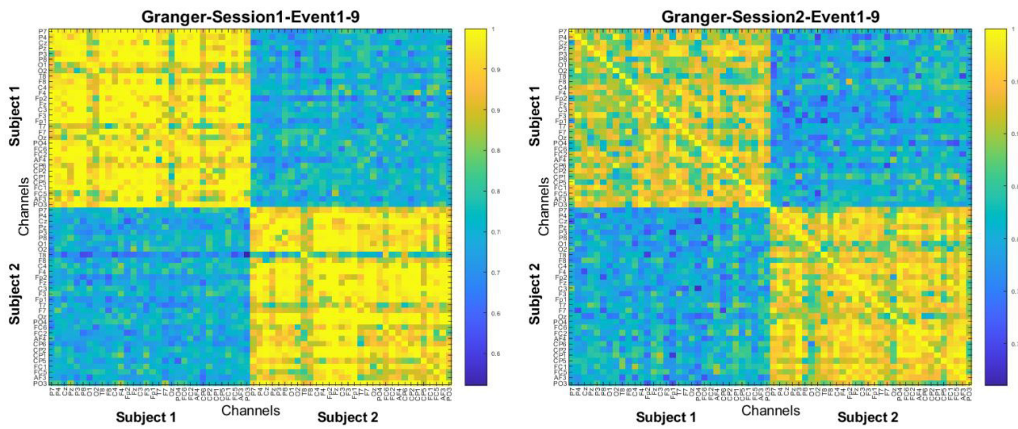


Figure 10: Intra (top left and bottom right regions) and Inter (bottom left and top right regions) brain connectivity plotted as a heat map electrode by electrode in subjects during task 1 compared between session 1 (left) with no AVS, and session 2 (right), after AVS.

MUSIC DATA

Alongside EEG data, the audio of the music that the subjects played during the improvisation tasks was recorded. Each of the tasks had a duration of 2 minutes, and were repeated 3 times each. The 2 music improvisation tasks had different goals.

For task 1, the subjects were invited to play informally, as if in a familiar rehearsal or studio space. The subjects were already familiar with each other's playing styles from experience working together in various other academic and jazz projects and recordings, and as such they were comfortable improvising together in this capacity.

For task 2, the subjects were instructed to play formally, with aims to impress, as if recording for publishing, or submitting to an audition or competition. The distinction between the two tasks was made in order to observe if BSV or IBS measures may be affected by the goal of the music interaction. Below is an image of the recorded audio waveforms, labeled according to the tasks and sessions (Fig.11).

Audio signal during task 1 (informal) compared between session 1 (upper waveforms) and session 2 (lower waveforms)

Audio signal during task 2 (formal) compared between session 1 (upper waveforms) and session 2 (lower waveforms)

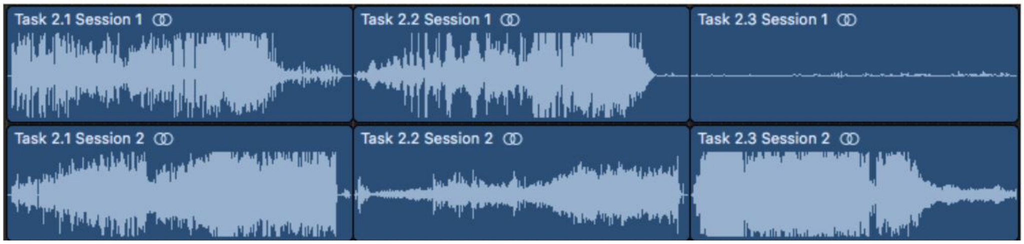


Figure 11: Comparison of audio signal waveforms between improvisation tasks 1 (informal) and 2 (formal), and between sessions 1 (no AVS) and 2 (post AVS).

As generally expected, the amplitudes of the waveforms increased from task 1 to task 2, except in the third instance of task 2 in session 1, where the musicians opted to play at a quiet dynamic, which can be more technically challenging and impressive than at a loud or medium dynamic. When comparing session 1 (before AVS) and session 2 (after AVS), there was more overall amplitude in session 2.

When listening to the music itself, it became clear that the rhythms shared by both subjects in session 1 shared a common pulse more than in session 2, where rhythms were treated more like overlapping and contrasting textures. Rhythmic density was generally higher in the second session as compared with the first. Furthermore, the frequency of new ideas introduced in the improvisations was higher in the first session, whereas in the second session, new ideas were more interconnected or overlapped with previously played material.

In session 1 the saxophonist's playing featured more clarity in the role of a solo melodic voice, outlining and accenting on the drummer's ideas. In session 2, the saxophonist's playing featured more rapid runs of repeated notes, looped variations of various ideas, and timbral effects. In session 1, the drummer's playing locked more frequently into grooves, or looped rhythmic ideas, whereas in the second session the drummer's playing featured more ambiguity, gestural accents and textural complexity.

DISCUSSION

Regarding the findings concerning BSV using the LZ complexity metric, it was found that while LZ complexity decreased during the majority of the duration of the AVS program itself, it was increased during the final minute as well as after stimulation in both subjects. This could imply a steady increase over time. Their average levels of LZ complexity compared to pre-stimulation were different, however a difference in LZ complexity pre-stimulation is to be expected between subjects.

Research (Dolan et al. 2018, 18–19) found that LZ complexity increased in improvisation music tasks as compared with prepared music tasks, and discussed how this increase may potentially facilitate the mental state of flow characterized by Csikzentmihaly (Csikzentmihaly 1990, 48–67) and how conditions for flow may potentially be linked to increased BSV in primary states characterized by the EBH proposed by Carhart-Harris (Carhart-Harris et al. 2014, 20). In our study, no prepared music condition was involved, however LZ complexity was found to increase in both subjects in task 2 as compared to task 1 post AVS. Recall that in task 2, the subjects were instructed to perform formally - as if for an audition or competition. This finding aligns with conditions for group flow in jazz ensembles where it is less likely to occur in rehearsals when there is no pressure, as opposed to in front of an audience where there is a risk of failure (Sawyer 2015, 43).

Additionally, found the LZ complexity increase localized mainly in the right hemisphere during improvisation music tasks as compared with prepared music tasks (Dolan et al. 2018, 16). A similar trend was found in our results, where LZ complexity in the right hemisphere was increased higher than in the left in both tasks in the second session post AVS, with relatively higher LZ complexity recorded during the second task as compared with the first.

Notably, while subject 1's LZ complexity increased post-stimulation as compared with pre-stimulation, the opposite was observed in subject 2. Consider that subject 1 is a jazz drummer, and the role of the jazz drummer in free improvisation is not necessarily to keep a pulse, but to provide a constantly changing stream of rhythmic ideas while also accenting the rhythms of other players. Consider also then that subject 2 is a saxophonist, and the focus of this role is similar to spoken language – where notes and rhythms become deliberate like words and phrases – but can culminate into arpeggiated runs, timbral effects or textures, and expressive outbursts. Since the saxophonist's role is typically a melodic voice, the more ambiguous and textural rhythms featuring in the drummer's playing in session 2 may have prompted them into less familiar territory. In other words, possibly the drummer was able to let go of the notion of formulating a clear groove more easily, which in turn limited opportunities for the saxophonist to play clear words and phrases, and thus may have demanded a higher cognitive load, triggering a decrease in BSV. Another interpretation could be that the saxophonist's BSV adjusted to the situation presented by the interaction with drummer, decreasing to adapt to the other person's level, in line with evidence that mental states supporting improvisation are communicable (Dolan et al. 2018, 1–3), contributing to a higher sense of shared experience.

Regarding the findings concerning IBS using Granger Causality connectivity, it was found that there were increased Inter-Brain connections during the last minute of AVS, as compared with before stimulation and during the full duration of the stimulation. Subjects were not interacting with each other, but were experiencing the same AVS program sitting side by side in the darkened lab. It is plausible that simply experiencing the same stimuli together with a familiar person, such as in watching an intense movie together, contributed to an increase of IBS over time. The AVS program was long, complex and evolving as opposed to typical stimuli aimed at entraining specific frequencies. This makes it problematic to compare directly with AVS studies using simpler stimuli at shorter durations with single subjects. For example, a study on the direct effects of long-term exposure to 20 minute AVS programs recorded a steady increase in Intra-Brain Synchronization using coherence measures over 25 sessions. Contrarily, we found a decrease in Intra-Brain Synchronization, but an increase in Inter-Brain Synchronization post AVS using GC connectivity measures. The variables of single subject versus subject pair and simple stimuli versus complex stimuli may be the reason behind these different findings, or it may be that coherence and connectivity measures are not mutually comparable in this respect. Case in point, the team of scholars implemented 6 connectivity metrics programmed into a neurofeedback system for indicating Inter-Brain Synchronization in subject pairs during social interaction, but did not discuss the efficacy or implications of using one metric over another (Chen et al. 2021, 9–10). A more comprehensive comparison of IBS metrics and the implications of their differences is needed to bring clarity to context.

Regarding the unexpected and significant increase in Granger Causality connectivity during the resting state, it is possible that the musical training of the subjects involved, as well as their closeness and familiarity with nature sounds living in Latvia may have been the cause of this surprising result. The melodic and rhythmic patterns of bird calls are particularly ear-catching to people with a highly developed sense of musical perception, and have been explored extensively as musical material, particularly in the composition work of Olivier Messiaen (1908–1992) as well as in the jazz saxophone playing of Charlie Parker (1920–1955). Thus, we may not rule out the possibility these bird calls and the sound of flowing water may have sounded more salient and interesting to the academically trained ear after the long, hypnotic and repetitive audio component of the AVS.

Regarding the findings concerning IBS using Granger Causality connectivity during the improvisation sessions, IBS was observed to increase from task 1 (informal playing) to task 2 (formal playing). This confirmed our expectations that when pressure to impress is added, a higher level of IBS can be observed. A further increase in IBS was observed from both tasks in session 1 (no AVS) to session 2 (after AVS). This confirmed our expectations that IBS may be positively impacted by the AVS program using the Vizr device, however the existing familiarity between the subjects as music colleagues may have been a factor in this result. Additionally, the subjects had been given the Vizr devices to try at home 2 weeks before the second session in order to familiarize themselves with the experience. Their individual experiences may have had priming effects, which may also have been a factor in this result.

SUMMARY AND RECOMMENDATIONS

Photic stimulation using controlled flicker frequencies have been used by psychologists to modulate mental states for decades, and it stands to reason that the AVS programs such as those provided by the Vizr device have a definite impact on the human mind, and in turn may impact performance and creativity. The use of 2 Vizr devices in parallel to deliver synchronized AVS to a pair of subjects, as well as the use of co-creative music improvisation tasks as a framework of understanding the impact of that stimulation is a unique experimental situation that the EEG Hyperscanning method has potential to shed light upon. In future steps, a precise technical description of the methods used to create the AVS program chosen in this study and the rationale behind its expected facilitation of a creative mental state would be useful for discussing it in comparison with typical AVS designed for EEG research.

This pilot study was limited to data gathered from 2 subjects, playing different instruments with different roles in frames of music improvisation, in 2 different sessions. Prior to the second session, neither of the subjects had prior experience with the Vizr device. Further limitations were that we had no access to the tools and methodology used to design the photic stimulation, nor control over the audio component of the stimulation program, introducing the risk of cultural bias. Increased datasets and better controlled studies are recommended for continuing this research.

Role-specificity is likely to explain why the AVS had some similar and some different effects on the BSV of the two subjects. The only commonality between BSV and IBS findings was that they both increased during the final minute of the AVS program relative to the full duration of the stimulation. No relationship between IBS and BSV measures could be observed during the improvisation tasks themselves, implying that BSV in one or both subjects may have adapted to the situation, but an decrease in Intra-Brain and increase in Inter-Brain Synchronization post-stimulation could clearly be observed. Looking to the future, an increased number of subject pairs is required to be able to apply statistical analysis to the results. Further, more control over the roles of the instrumentalists involved as well as familiarity between subjects is recommended to continue this investigation. Additionally, it is recommended to control and shorten the time allowed to reset to the improvisation tasks in the second session (see Fig. 2), in order to determine whether the increased IBS recorded during the resting state would perpetuate more directly into the improvisation tasks. Finally, it may be useful to perform analysis on the EEG power spectrum which is typically reported and compared to others in the research field.

The investigation of the impact of AVS programs on co-creative processes such as music improvisation has the potential to bridge many fields, inviting them to intersect under the umbrella of Systematic Musicology. Findings from the case study showed: 1) mutual adaptation of BSV, 2) decreased Intra and increased Inter-Brain Synchronization and 3) increased complexity of behavioral data during music improvisation post AVS. This could imply that group-based AVS or group neurofeedback programs may have powerful pro-social effects which may positively influence the quality and outcomes of post-stimulation interactions. These may not be limited to music, but may extend to other types of co-creative tasks requiring goal-directed interpersonal coordination and group flow such as in sport, dance, science, business, or security teams.

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AUDIOVIZUĀLĀS STIMULĀCIJAS IETEKME UZ MUZIKĀLO IMPROVIZĀCIJU: EEG HIPERSKENĒŠANAS GADĪJUMA IZPĒTE

Džeikins Edvards Pūsons, Mahrāds Godūsi

KOPSAVILKUMS

Muzikālā improvizācija ilgstoši bijusi intereses objekts arī sistemātiskās muzikoloģijas jomā, tomēr pētījumi, kuros izmantotas neiroattēlveidošanas metodes, joprojām ir nepietiekami. Šajā gadījuma izpētē tika izmantota eletroencefalogrāfijas (EEG) hiperskenēšanas metode, lai pētītu periodiski mirgojošu audiovizuālo stimulāciju (AVS) programmas ietekmi uz muzikālo improvizāciju vienā indivīdu pārī.

11 minūšu ilgā AVS programma tika izmantota tikai pirms improvizācijas uzdevumiem otrajā sesijā un tika demonstrēta katram dalībniekam, izmantojot patēriņa ierīci *Vizr*, kas ģenerē periodiski mirguļojošus gaismas rakstus, sinhronizētus ar mūziku. To izmantošanas mērķis bija inducēt radošu mentālo stāvokli.

Ritmiskas gaismas un skaņas stimulācijas AVS formātā jau ilgstoši tiek izmantotas psiholoģijā un neirozinātnē smadzeņu aktivitātes modulēšanai un izpētei (Teplan et al. 2003). Lai gan AVS ir atzīta par efektīvu terapeitisku līdzekli, pētījumi liecina, ka indivīdu reakcijas uz AVS ir atšķirīgas un nepastāvīgas (Teplan et al. 2011).

Šajā gadījuma izpētē izmantotā AVS programma sastāvēja no 3×3 LED gaismu režģa, kas nodrošināja ģeometriskus fotiskās stimulācijas rakstus. Šāda AVS dizaina pieeja ir vērsta uz pārejamības palielināšanu starp mentālajiem stāvokļiem. Pakauša daivas redzes garozu aktivizēja pastāvīgi mainīgi paterni. Šī pieeja ir netipiska, jo lielākā daļa AVS programmu ir orientētas uz konkrēta mentālā stāvokļa ritmisku piesaisti un stabilizēšanu. Ierīces *Vizr* izstrādātāji izvirza pieņēmumu, ka šāda pieeja var ietekmēt smadzeņu signālu svārstīgumu (*Brain Signal Variablity*, BSV), kas ir saistīta ar radošu mentālo stāvokli tieši muzikālajā improvizācijā (Dolan et al.).

EEG hiperskanēšanas pētījumi ir uzrādījuši noteiktu sinhronizāciju starp dalībnieku smadzenēm sinhronizācijas (*Inter-Brain Synchronization*, IBS) rādītāju pieaugumu vairāku personu koordinētas darbības laikā (Chen et al. 2021), kā arī muzikālās improvizācijas laikā, piemēram, ģitāras improvizācijā (Müller et al. 2013). Tiek prognozēts, ka IBS pieaug arī muzikālās improvizācijas laikā, tomēr attiecības starp IBS un BSV līdz šim ir maz pētītas.

Šī gadījuma izpētes mērķis ir izpētīt EEG signālā fiksēto AVS ietekmi uz BSV un IBS muzikālās improvizācijas laikā.

EEG hiperskanēšanas dati 500 Hz izšķirtspējā tika **reģistrēti** no 32 elektrodiem, **vienlaikus no vairākiem indivīdiem. Ieraksti tika precīzi saskaņoti laikā, lai katrs datu atskaites punkts no viena indivīda atbilstu tieši tam pašam laika momentam**

arī pārējiem. Dati tika reģistrēti katram dalībniekam pirms AVS stimulācijas, tās laikā un pēc tās, kā arī improvizācijas uzdevumu laikā. BSV un IBS mērījumiem **tika izmantoti** Lempela–Zīva (Lempel – Ziv, LZ) algoritms un Grendžera cēloņsakarība (*Granger Causality*, GC), attiecīgi mērot smadzeņu signālu mainīgumu un smadzeņu sinhronizāciju **starp dalībnieku smadzenēm un viena indivīda smadzeņu ietvaros.**

Paaugstināta LZ sarežģītība EEG signālā ir saistīta ar pašpieredzes robežu izmaiņām un spilgtu iztēli (Schartner et al. 2017) – abi faktori ir būtiski plūsmas stāvokļa (*flow*) mentālajai pieredzei (Csikszentmihalyi 1990) un spēlē nozīmīgu lomu muzikālās improvizācijas radošajā procesā (Sawyer 2015). Balstoties uz līdzšinējp mūsu pētniecības grupas pieredzi (Ghodousi et al. 2022), GC tika izvēlēta IBS mērīšanai attiecīgi viena indivīda ietvaros un starp indivīdiem. GC ir statistiska metode, kas sniedz informāciju par informācijas plūsmas virzienu, ilustrējot mijiedarbību starp smadzeņu reģioniem (Tafreshi et al. 2019; Zervakis et al. 2011; Haufe et al. 2011; Kong et al. 2015). Šajā pētījumā iegūto EEG datu analīzi veica sadarbības partneri Viļņas Universitātes Biofizikas nodaļā.

Lai izpētītu AVS ietekmi uz muzikālo improvizāciju, tika salīdzināti BSV un IBS rādītāji divās sesijās. Pirmajā sesijā tika reģistrēti tikai muzikālās improvizācijas uzdevumi. Otrajā sesijā, pirms improvizācijas uzdevumiem, tika veikta AVS stimulācija. Tika izvirzīta hipotēze, ka BSV palielināsies tieši pēc AVS, savukārt IBS, salīdzinot ar pirmo sesiju, palielināsies pēc stimulācijas otrajā sesijā – improvizācijas laikā. Pētījumā brīvprātīgi piedalījās viens vīrietis – džeza bundzinieks – un viena sieviete – tenora saksofoniste; abi bija akadēmiskās mūzikas studenti ar vairāk nekā piecu gadu instrumentālās pieredzes praksi, labā fiziskās un mentālās veselības stāvoklī. Dalībnieki tika pilnībā informēti par pētījuma procedūru un mērķiem, kā arī klātienē iepazīstināti ar *Vizr* ierīci nedēļu pirms otrās ierakstu sesijas, lai nodrošinātu iepazīšanos ar tās funkcijām un lietošanas pieredzi.

Gan BSV, gan IBS, salīdzinot ar visu 11 minūšu stimulācijas periodu, abiem dalībniekiem palielinājās AVS pēdējās minūtes laikā un turpināja pieaugt vēl 30 sekundes pēc AVS. Papildus tika novērots sinhronizācijas pieaugums starp dalībniekiem un sinhronizācijas samazinājums viena dalībnieka smadzenēs improvizācijas uzdevumu laikā otrajā sesijā pēc AVS. Rezultāti norāda, ka grupās balstītas AVS vai grupu neirofīdbeka (*neurofeedback*) programmas var radīt spēcīgus sociāli veicinošus efektus, pozitīvi ietekmējot mijiedarbības kvalitāti un rezultātus pēc stimulācijas.

MAKING MUSIC WITH BRAINWAVES: BRIDGING SYSTEMATIC MUSICOLOGY AND NEUROSCIENCE WITH BRAIN-COMPUTER MUSIC INTERFACE RESEARCH

Jachin Edward Pousson, Valdis Bernhofs

This article explores the integration of systematic musicology and neuroscience through Brain–Computer Music Interfaces (BCMI), highlighting its potential to reshape how musical interaction is understood and practiced. Building on traditions from Helmholtz and Adler to contemporary neuromusicology, the study situates EEG-based research within a "third wave" of music–brain studies that emphasizes ecological validity, expressive intent, and inter-brain synchrony. At Jāzeps Vītols Latvian Academy of Music (JVLMA), EEG studies of expressive piano performance and hyperscanning during musical interaction provide novel insights into intra- and inter-brain dynamics. These findings are applied to the design of BCMI systems that function as genuine musical instruments rather than laboratory artifacts, enabling musicians to shape sound and visual environments through neural states in real time. Artistic applications, including orchestral works and electronic performance systems, demonstrate the feasibility of BCMI as both a scientific tool and an artistic medium. Beyond technical innovation, the research underscores institutional benefits: developing in-house EEG capacity strengthens interdisciplinary collaboration, attracts international partnerships, and positions music institutions at the forefront of an expanding field. The article argues that BCMI represents not only a frontier for science and art, but also a model for institutional growth and interdisciplinary research in music and neuroscience.

Keywords: EEG, BCMI, Systematic Musicology, Neuroscience

INTRODUCTION

Musicology in its broadest sense encompasses systematic, historical, and ethnographic approaches to understanding musical life. Each of these domains is concerned, albeit in different ways, with how musical meaning is created, transmitted, and experienced. Neuroscience adds yet another perspective: it provides empirical access to the brain and body processes that unfold during musical activity.

The integration of neuroscience into systematic musicology is relatively recent. Hermann von Helmholtz laid the physiological and acoustical foundations for what later became systematic musicology (Helmholtz 1877), while Guido Adler offered the first explicit definition of *Musikwissenschaft* as comprising historical and systematic branches (Adler 1885). Although the foundations of systematic musicology were laid in the 19th century, the direct application of neuroimaging and other brain-based methods to the study of music emerged much later. It was only in the late 1980s and 1990s that techniques such as electroencephalography (EEG) and other neuroimaging methods, including positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) began to be systematically employed in music research (Zatorre 2001, Peretz and Zatorre 2005). By the early 2000s, neuromusicology had consolidated as a recognized subfield, with institutions such as the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig (Koelsch 2005), McGill University in Montreal (Robert J. Zatorre, Isabelle Peretz), and Finnish/Scandinavian networks (Mari Tervaniemi, Risto Näätänen) leading the way.

Since then, systematic musicology and neuroscience have increasingly overlapped through paradigms such as embodied music cognition (Leman 2008), hyperscanning for studying social interaction (Lindenberger et al. 2009, Sänger et al. 2013), and the development of brain–computer music interfaces (Miranda & Castet 2014). Globally, the field can now be described as entering a "third wave": moving beyond proof-of-concept studies toward ecologically valid, socially embedded contexts such as group improvisation, live performance, and music therapy.

In Latvia, systematic musicology has developed rapidly, though it remains a relatively young discipline. The integration of neuroscience into Latvian music research began with early collaborations with the Department of Neuroradiology at Heidelberg University (Peter Schneider), where musicality assessment tools were developed for use in clinical research. At Jāzeps Vītols Latvian Academy of Music (JVLMA), the first in-house EEG-based music studies were launched in 2019 in cooperation with Vilnius University (Biophysics Department, Lithuania) and National Sun Yat-sen University (Neuroergonomics Lab, Taiwan). This initiative positioned JVLMA among the very few European music institutions with its own EEG capability. Since then, the EEG laboratory has enabled Latvia to participate in cutting-edge international projects, including investigations of expressive intent in piano performance (Pousson et al. 2021), EEG connectivity during music performance (Ghodousi et al. 2022, 2023), and inter-brain synchronization during musical interaction (ongoing since 2022).

The JVLMA team's research stands out for integrating systematic musicology, artistic practice, and neuroscience from the very beginning, rather than adopting neuroscientific methods only at a later stage. At JVLMA, one of the main research directions focuses on Brain–Computer Music Interfaces (BCMI) and ecologically valid performance settings, which together give Latvian research a distinctive profile in this emerging international field.

The novel contributions of the Latvian team include a clear prioritization of ecologically valid performance settings over passive listening paradigms, the incorporation of expressive intent and inter-brain synchrony into BCMI design rather than relying solely on emotion detection, and the demonstration of concrete artistic applications that extend usability beyond the laboratory.

This article reflects on the development of this approach and its implications for systematic musicology and Brain–Computer Music Interface (BCMI) research. It provides an overview of systematic musicology research employing neuroscience methodology at JVLMA since 2019. The overarching research goal has been to design BCMI systems as new kinds of musical instruments, enabling novel forms of musical communication and expressivity.

This article is written primarily for Systematic Musicology readers, and aims to provide a focused perspective on the implications of using neuroscience methodology to investigate musical phenomena. As such, some technical details necessary for neuroscience readers are not included here, but can be found in the previous articles published by our research team (Pousson et al. 2021, Ghodousi et al. 2022, Ghodousi et al. 2023, Pousson et al. 2023).

For Systematic Musicologists, a brief narrative of how our music institution became capable of recording EEG data is included, because it bears good examples of how inherent inter-disciplinary challenges were overcome. For ease of understanding, a brief explanation of key terms is provided below:

Electroencephalography (EEG): A neuroimaging technique which measures differences in electrical potential typically in the 0.5-100 microvolt (μV) range between locations across the scalp and a reference site (Berger 1929, Teplan 2002).

Embodied Music Interaction (EMI): A Systematic Musicology research paradigm holding that body movement is central to music cognition.

Brain-Computer Interface (BCI): A system combining EEG hardware and real-time analysis software, enabling a user to control a computer using their brain signals.

Brain-Computer Music Interface (BCMI): A BCI designed for musical purposes – for research, education, training or performance.

Hyperscanning (HS): A method of recording synchronized EEG signals from two or more brains simultaneously, in order to study human interaction.

Inter-Brain Synchronization (IBS): Synchronization in the EEG signal between two or more brains, which may be measured using various approaches.

These terms come together in our research work in the following way: The **EEG** method is used to record the brain activity of musicians engaged in **EMI**. This EEG data is then analyzed for evidence of **IBS** and characteristics which could be potentially classified in real-time for **BCI** applications. The **HS** method provides the prospect of **IBS**-based collaborative **BCMI** systems in the future.

This research is beneficial for both systematic musicology and neuroscience by connecting two important steps. First, to increase a fundamental understanding of neurophysiological processes underlying EMI – a complexly coordinated yet under-investigated human behavior. Second, to harness this increased understanding to develop BCMI tools that enable musical growth and potentially benefit human communication, cooperation and coordination.

BACKGROUND: THE BCMI FIELD AS AN INTERDISCIPLINARY BRIDGE

Systematic Musicology is an umbrella under which neuroscience, nusic computing, and embodied music interaction research co-exist – and the field of Brain-Computer Music Interfacing is in an excellent position to help bridge them. It has been the duty of our research efforts to take careful consideration of research paradigms inherent to the overlapping disciplines and to respectfully and creatively find appropriate solutions for working together.

Musicologist Marc Leman reflected on systematic musicology's role in scientific investigation of musical phenomena, and called for more direct multi-disciplinary collaboration between the musical arts and the sciences. He explained that embodied music cognition involves a dynamic loop of energy transfer from bioelectrical processes in the brain to biophysical energy output from the human body, into a musical instrument which converts this into acoustic energy, completing the loop upon re-entering the brain through the ears of the performers and listeners (Leman 2008, 104). In Leman's view, all parts of this dynamic loop are essential to the experience of performing music, and so removing any of them to isolate some part of the process in favor of experimental control undermines the ecological validity of the findings (Leman and Maes 2014, 236–237; Leman et al. 2017, 1). For example, the brain of a pianist lying down in an MRI scanner is certainly in a different state than if they were on the concert stage. What conclusions could then be reliably drawn from data collected in unrealistic situations? Leman encouraged a multi-disciplinary approach which could accept mixed methods to bridge these gaps. We often hear this advice of Leman's ringing true on our research path.

Our systematic musicology laboratory at JVLMA obtained our first clinical grade EEG device – an Enobio 32[1] in 2019 through a two-year collaborative project (LV-LT-TW Scientific Cooperation) together with neuroscientists from the Biophysics department at Vilnius University in Lithuania and the Neuroergonomics department at National Sun Yat-sen University in Taiwan. The project's goal was to develop a BCMI system for embodied music interaction – which clearly necessitated the alignment of musicological and neuroscientific goals. The neuroscientists recommended to begin with collecting EEG data from piano playing subjects. They would then report characteristics in the power spectrum and discuss how these may support processes underlying expressive music performance. The systematic musicology team members would then be able to use this outcome to develop BCMI software to detect different expressive states in real time. We needed to coordinate closely to plan steps to achieve these aims and overcome challenges which have hindered BCMI research pursuits in the past. The following section is a reflection of our interdisciplinary team's experience in facing these challenges.

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[1] https://www.neuroelectrics.com/products/clinical/enobio-dx

CHALLENGES OF MUSIC-NEUROSCIENCE RESEARCH

EEG music studies are currently scarce, and we soon discovered why. Three major challenges stand out currently. First, typical EEG studies require subjects to remain still so as not to introduce noise artifacts from body movements into the EEG signal, whereas typical music interaction requires body movement to play an instrument or to respond naturally. Second, there are only a few music institutions in the world with access to equipment and expertise in both musicology and neuroscience fields. Third, there are semantic gaps between how we speak about music – in terms of physical/architectural properties or in terms of perceptual/experiential properties. Overcoming these sometimes involved the painstaking explanation of fundamental concepts between the neuroscientists and musicologists, but respectful communication allowed for meaningful discussions and deeper understanding.

Regarding the first challenge, it is important to acknowledge that the EEG is currently a fragmented field of practice. Unfortunately, consumer EEG devices and the companies producing them have increasingly targeted the mental-wellbeing market with lofty claims, which has in turn obscured fundamental principles of the EEG method and its data analysis from public view. Before we were able to obtain the clinical grade EEG system we experimented with several consumer grade EEG headsets claiming BCI capability. Such devices were found unsuitable for either research or BCMI applications due to latency, unstable connections, or poorly developed proprietary software (Maskeliunas et al. 2016, 18–21). The clinical grade EEG system however, was able to record in a format and quality which the neuroscientists could accept working with. They formulated a preprocessing pipeline for our study to allow for and to filter out body movements necessary for playing the piano. In order to simulate the removal of body movement artifacts in real time at the stage of developing a BCMI system, signals from individual electrodes that were likely not originating from the brain (above 100 microvolts) were filtered out.

Regarding the second challenge – when our systematic musicology team visited our neuroscience project partners in Lithuania and Taiwan, we caught our first real glimpse into their world. Vilnius University has a reputable biophysics department and EEG lab, and National Sun Yat-sen University has a Neuroergonomics lab designing EEG hardware and building BCI game controllers. When we presented our goal to build a BCMI for EMI applications, the feedback from neuroscientists revealed that some of our assumptions about real-time EEG classification were quite naive. There are thousands of articles published about emotion detection in the EEG but currently only a handful have collected data from subjects during music performance. Furthermore, the concept of an emotion-driven BCMI was further confounded by the issue that actual felt emotions and aesthetically expressed emotions are often not the same during music performance. This distinction is rarely made in music research using the EEG method, so careful consideration was needed to guide our approach.

The neuroscientists recommended that to move towards our goal of building a BCMI system, we should begin by training to collect EEG data. Next, we would design an experiment, program a recording protocol, set up an EEG lab space at JVLMA, and record our own EEG dataset of musicians performing. Once that data set was analyzed and the results reported, we could then proceed to the next step of programming BCMI software based on those findings. After accepting this plan, we pressed forward to take the necessary first steps, gaining new skills and learning scientific standards for EEG data collection and analysis.

As for the third challenge – our research vocabulary increased as the neuroscientists on our team began to train the musicologists to collect data with our EEG device and evaluate our first EEG recordings for signal quality. We worked together to design an EEG data collection protocol that aimed to maintain maximal experimental control while accounting for human factors including the number of times a one-minute piano score could be repeated within a single recording session, the amount of rest time between recording sessions, and the configuration of the recording environment to avoid a hospital-like setting. Over the course of many discussions, mutual respect for each other's disciplines grew. The neuroscientists began to appreciate the potential for music interaction as a framework for EEG research and took on the challenge with us to choose approaches that upheld the standards of both of our fields. Taking all points into consideration, we were able to modify a music practice room in the music academy to function adequately as an EEG recording room.

THE EEG METHOD AND IMPLICATIONS FOR MUSIC RESEARCH

Electroencephalography (EEG) is an often-used method for brain music studies, chosen for its high temporal resolution and mobility in ecologically valid environments compared to other neuroimaging techniques (Czeszumski et al. 2020, 3). Consider a few facts about the EEG method: a) The EEG signal itself consists of differences in electrical potential measured in the microvolt range between specific locations on the scalp and a reference site over time (Teplan 2002, 5), and these are recorded in software on a computer, b) An EEG recording protocol is a chosen or bespoke software that controls the sequence of the experiment, and marks EEG data at the precise onset and offset of events in the sequence for later analysis, c) EEG data needs to be preprocessed before analysis to filter noise, remove artifacts, and cut it into segments known as epochs. Furthermore, analysis typically involves superimposing as many epochs as possible upon each other to find evidence of the brain's responses to specific stimuli or tasks. These facts had several implications for an experiment design involving musicians playing musical instruments summarized in the next paragraph.

Implications of the first fact were that the recording space needed to be away from the street and heavy electrical systems like elevators or kitchens as these might become unwanted sources of electrical line noise. The space also needed to be furnished to minimize electrical noise from computer equipment, lights and telecommunications.

It also needed to be arranged in such a way that participants could play a piano in a natural seated posture while wearing an electrode cap with a USB cable attached to the back of it for EEG signal acquisition. Another implication of working with signals in the microvolt range is that it takes approximately 30–45 minutes to place the electrode cap on a subject's head, apply conductive gel to all electrodes and make adjustments for a quality signal. The second fact implied that the sequence of the experiment needed to be programmed using third party software capable of communicating with our EEG recording software, defining the number of trials and their groupings into runs and sessions while taking into consideration a realistic number of trials that could be recorded per subject, per day. The third fact implied that analysis results may not be applicable to BCMI for live performance since this requires real-time EEG analysis. We needed to wait for the outcomes before we could find out if they were indeed useful for our intended purpose. In the following section, two research projects are described and outcomes discussed, in particular those with implications for BCMI applications.

EEG RESEARCH ON EMBODIED MUSIC INTERACTION: PRELIMINARY RESEARCH: CHARACTERIZING EXPRESSIVE INTENT IN THE EEG DURING PIANO PLAYING

Our first EEG research project aimed to investigate brain activity during expressive music performance. Expressive intent is a term describing how instrumentalists employ expressive cues to communicate musical intentions (Sloboda and Juslin 2010). These expressive cues may be written or only implied in a musical score but they serve to communicate certain moods or evoke certain emotional responses in context of the narrative of the piece (Juslin and Västfjäll 2008, 566), if there is one. For example, *legato* and *staccato* playing may serve to evoke contrasting emotions in a piece. On this basis we aimed to characterize brain activity related to the act of playing expressively with intent to communicate contrasting moods.

We adopted Russell's Circumplex model of affect (Russell 1980, 1164) as a basis for labelling five contrasting moods; Neutral, Distressed, Excited, Depressed and Relaxed as shown in Figure 1. The piano was chosen for its ubiquity in academic music discipline.

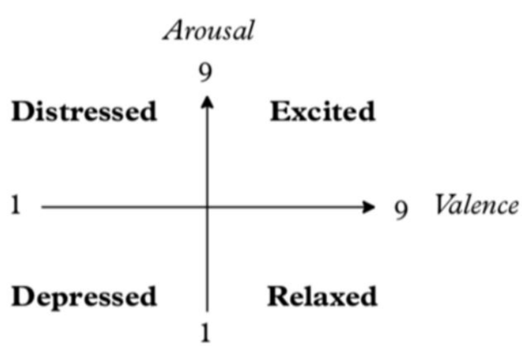

Figure 1: Two dimensional model of affect using 9-point scales on the dimensions of Arousal and Valence, based on the Circumplex model of affect (Russell 1980, 1164).

A music score with a duration of 60 seconds was composed for participants to play on the piano as shown in Figure 2. The score was designed so that it was easy to learn quickly and the music consisted of a melody with bass accompaniment in an extended pentatonic scale to avoid dominant-tonic tensions which could confound the task of playing the same score with different expressive intentions. The first 30 seconds were to be played Neutral, without expression at a strict tempo. The next 30 seconds were an exact repeat, to be played with intent to express one of the four other contrasting moods (Fig. 1). The note heads on the second page lacked rhythmic durations and included the option to repeat if time allows, providing a greater degree of freedom to interpret rhythmic phrasing, tempo, dynamic, articulation and embellishment appropriate for the intended expression.

Figure 2: Music score designed for the performance task in this study. The left page is performed without expression (Neutral) while the right page is a repeat, played expressively.

The neuroscientists determined that a dataset of 10 participants with 200 trials per participant was adequate for the scope of this project. We determined that with each trial consisting of a one-minute piano-playing task, participants could realistically complete a maximum of 50 trials in a single recording session; therefore four sessions per subject were scheduled on different days. Each session was divided into 10 runs consisting of five trials each. The sequence of a single trial is shown in Figure 3. The EEG recording protocol was programmed accordingly to mark onsets and endings of each trial per run and session. EEG data was recorded using a clinical grade 32 channel EEG system (Enobio32) at a sample rate of 500Hz. Please refer to the published article (Pousson et al. 2021, 3–5) for technical details and the analysis pipeline.

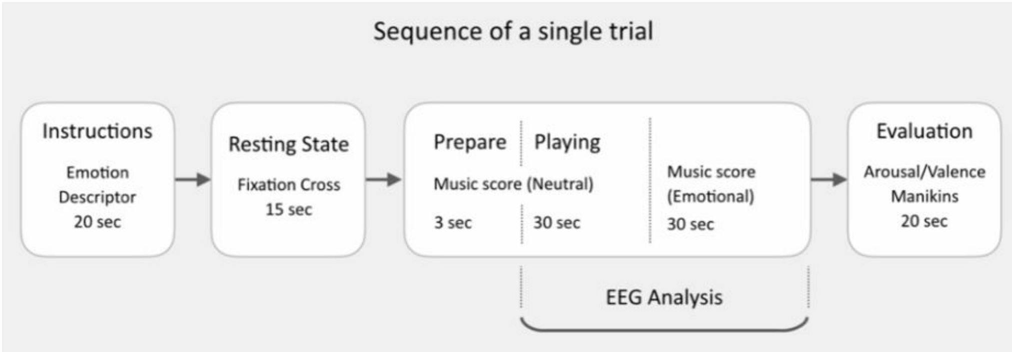

Figure 3: Sequence of a single trial of the EEG recording protocol used in this study. Subjects were guided through this sequence via instructions presented on a screen placed at eye level on top of an upright piano.

This experiment design enabled us to capture brain activity from musicians in five contrasting conditions during the act of expressive music performance. In order to connect findings to the wider neuroscience field, the biophysicists recommended a spectral power analysis across four Regions of Interest (ROI). They averaged together the spectral power data per condition from all 10 pianists, grouped the electrodes into ROIs at the front left, front right, back left and back right of the head, and plotted the results as shown in Figure 4.

Each of the four charts represents an ROI, and the plotted data shows the power spectrum per expressive condition relative to the Neutral condition averaged together from all 10 subjects over all 2000 trials. Here we were able to see small differences between contrasting conditions. In the High Arousal (HA) conditions Distressed and Excited, there were greater differences in the Delta-Theta range in the Left Frontal and Right Pareto-Occipital ROIs. There were also greater differences observed between the same conditions in the Gamma range, but between the Left and Right Frontal ROIs (see light orange boxes). As for Low Arousal (LA) conditions Depressed and Relaxed, nearly no differences could be seen relative to the Neutral condition, except in the Delta range in the Left and Right Parieto-Occipital ROIs. Finally, a suppression of the Alpha band could be seen across all conditions and ROIs.

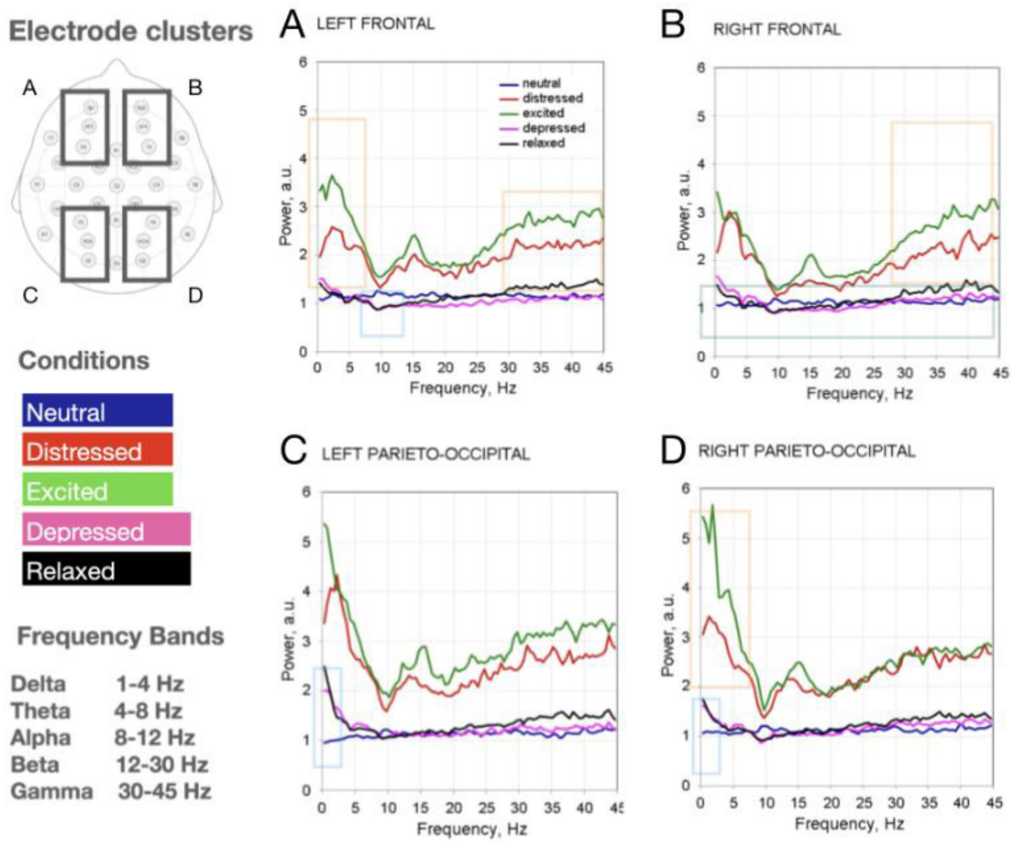

Figure 4: Top left, electrode clusters making up each ROI (A-D) corresponding to Left Frontal (A), Right Frontal (B), Left Parieto-Occipital (C) and Right Parieto-Occipital (D) brain regions. Left center, color key of conditions plotted in the diagrams. Bottom left, frequency band ranges. Diagrams on the right are plotted data representing spectral power of each expressive condition relative to Neutral from each ROI.

Each of the four diagrams represent an ROI, and the plotted data shows the power spectrum per expressive condition relative to the Neutral condition averaged together from all ten subjects over all 2000 trials. Here we were able to see small differences between contrasting conditions. In the High Arousal (HA) conditions Distressed and Excited, there were greater differences in the Delta-Theta range in ROIs A and D. There were also greater differences observed between the same conditions in the Gamma range, but between the ROIs A and B (see light orange boxes). As for Low Arousal (LA) conditions Depressed and Relaxed, nearly no differences could be seen relative to the Neutral condition, except in the Delta range in the ROIs C and D. Finally, a suppression of the Alpha band could be seen across all conditions and ROIs.

Despite the large amount of data collected (2000 trials), this study had a limited number of participants (10 subjects). Analysis by the neuroscientist colleagues from Taiwan (Pousson et al. 2023, 4352) revealed that EEG signals varied between individuals and sessions even though they were performing the exact same task – a property of the EEG signal known as non-stationary – because experience changes over time, a task cannot be repeated in exactly the same way. Thus while these results cannot be generalized, they do provide an authentic early snapshot of regional brain activity during music performance with contrasting expressive intentions. Since EEG recording during music performance remains scarce, even a limited study such as this may be considered a valuable contribution to the scientific literature in both fields, inviting others to replicate or investigate further. This EEG dataset was later analyzed using connectivity measures, revealing dynamics of intra-brain information flow (Ghodousi et al. 2022, 4064). In line with our BCMI design objectives, additional work provided clues useful for developing software that detects and maps expressive intentions in real-time (Ghodousi et al. 2023, 2252).

CURRENT RESEARCH: EEG HYPERSCANNING INTER-BRAIN SYNCHRONIZATION DURING MUSIC INTERACTION

Soon after publishing the results of our first study, our EEG lab was able to acquire a second EEG system from the same maker (Enobio). This gave us the capability to run EEG experiments using the Hyperscanning (HS) technique in which two brain signals are recorded simultaneously (Acquadro et al. 2016). This technique enables psychologists using the EEG method to study human social interaction by observing the reciprocal influence of the signals during cooperation or competition in more ecologically valid conditions (Czeszumski et al. 2020, 3). Music interaction provides an excellent context for HS studies because it involves joint coordinated action and mutual adaptation over a temporal framework (Sänger et al. 2012, 1–2). Our new project utilized this new capability to study music interaction in subject pairs with future aims to harness measures of IBS for multi-user BCMI systems. With this aim in view, our main research objective was to characterize inter-brain dynamics of contrasting types of music interaction tasks, specifically problem solving (playing correctly) and problem finding (improvising) task types.

Various methods have been used in past studies to measure IBS during music making (Gugnowska et al. 2022, 4110–4127). In particular, Phase Locking Value (PLV) has been used to quantify phase alignment consistency between frequency-specific EEG signals from two brains to observe heightened levels of synchronization during rhythmic coordination (Lindenberger et al. 2009, 5–7) as well as desynchronization during motor alignment and joint attention (Jenson et al. 2020, 4; Lachat et al. 2012, 10–11). Another established method, Granger Causality (GC) has been used to determine the influence of one brain signal upon another. This method has been used in past studies to reveal leader-follower influences within a guitar duo (Sänger et al. 2013, 1) as well as asymmetrical role-specific patterns in pilots during flight simulation (Astolfi et al. 2011, 2338–2341). A limitation of past studies has been either a focus on symmetry without causality or a focus on uni-directional causality without considering reciprocal influence, leaving unresolved questions concerning leader-follower inter-brain dynamics during music interaction tasks. For example, how does a leadership role emerge or submerge during improvisation? Or, how does the task goal and structure affect directional connectivity patterns between musicians during coordinated performance? From a neuroscientists perspective, there was an opportunity to integrate both PLV and GC methods in our approach in order to connect findings to past studies and potentially shed light on the present unknowns.

With these opportunities in view, a HS experiment protocol was designed to record EEG data during two contrasting music interaction tasks. We recruited 15 subject pairs, each including a professional percussionist who participated in all 15 recordings.

The first music interaction task was a rhythm learning task performed on electronic drum pads in which the percussionist leads by playing a predetermined 32-beat rhythm from a score while the other subject – without seeing the score – tries to play the rhythm by following and synchronizing with the percussionist over 30 repetitions divided into three runs of 10 trials each.

An experiment protocol (Fig. 5) was designed to include a Baseline (non-interactive resting state), and a Mechanical condition in which the subjects played straight 8th notes in unison, in order to isolate interaction task-specific EEG signals from non-interactive and body-movement related signals. A Rehearsal condition was also included to allow subjects to become accustomed to the recording sequence and the task. Next, in the Familiarization condition the percussionist plays the rhythm alone. Subsequently, in the Rhythmic condition the subjects play ten repetitions together. Finally, in the Recollection condition the other subject (not the percussionist) plays the rhythm alone. The sequence of Familiarization, Rhythmic and Recollection trials were repeated in three runs. The protocol was programmed in software to control the sequence of tasks while adding markers into both EEG data recordings simultaneously, 32 channels each, synchronized sample to sample at a rate of 500Hz.

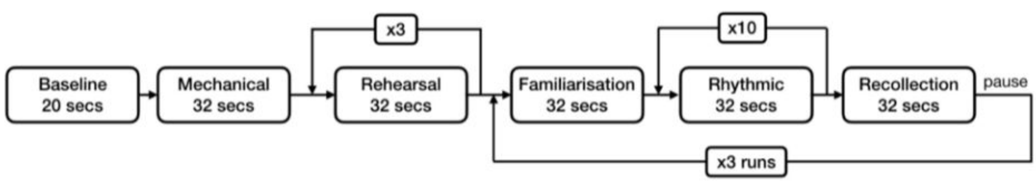

Figure 5: Sequence of the Rhythmic learning task used in our hyperscanning experiment protocol.

The 32 beat rhythm (Fig. 6) was composed in 4 phrases of 8 beats each, at a tempo of 1 beat per minute. Thus each Rhythmic trial lasted 32 seconds. Rhythmic complexity gradually increases across the 4 phrases: the first phrase is easy to imitate, while the fourth is difficult without access to the written score. This was intentional in the design in order to study the learning and synchronization process in the follower. Feedback from post-experiment surveys indicated that some subjects felt that this mode of learning was unfamiliar in academic settings where score reading is the predominant method of learning new music. However, they also acknowledged that it simulated a process of synchronization in group performance settings in which an ensemble becomes more temporally aligned through repetition. Musicologists may also appreciate that the design simulates a natural method of learning by ear and imitation familiar across a wider range of musical cultures regardless of differing notation systems or emphasis on score-reading.

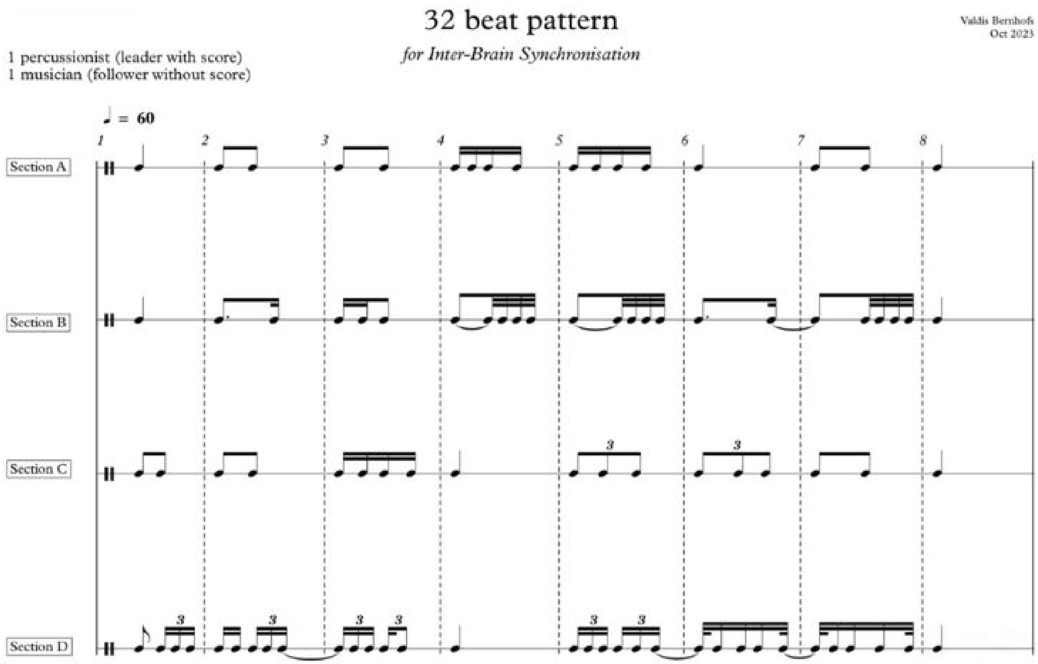

Figure 6: The 32-beat rhythm designed for the Rhythmic learning task used in this study. Complexity is increased over sections A-D.

The second music interaction task was an improvisation task in which the other subject leads using an instrument of their choice while the percussionist supports and responds on acoustic drums. The second task was repeated five times with a duration of two minutes each as shown in Figure 7.

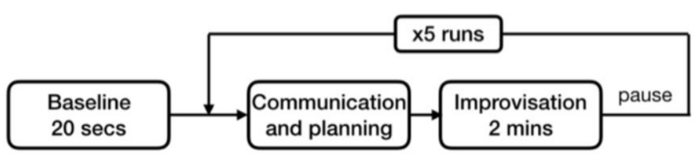

Figure 7: Sequence of the Improvisation task in our study.

The percussionist recruited to the study was a student of the jazz department with many years of experience in improvisation. The other 15 recruits consisted of academic instrumentalists, musicologists, or teachers in training – with relatively less experience in improvisation. During their pre-experiment briefing, many subjects mentioned that they almost never have contexts to improvise in and that they felt a little nervous about being recorded while doing so. Having taken this into consideration, the percussionist was instructed to play a supporting role, allowing the other subject to lead each improvisation. Further, the recording sequence was designed to allow for communication and planning before each improvisation trial. These considerations served to make the less experienced subjects feel more comfortable with improvising and to switch their task focus onto finding a coherent exchange rather than on playing correctly.

This HS experiment design enabled us to capture inter-brain dynamics occurring between all 15 subject pairs during both tasks, while keeping one subject (the percussionist) constant in order to compare differences between the other subjects more accurately. The complete technical details and analysis results from this dataset are in the process of publication this same year and we look forward to sharing that and proceeding towards applying the outcomes to multi-user BCMI system design as a future step. The following section describes outcomes from these two back-to-back investigations and their implications for BCMI system design.

OUTCOMES, IMPLICATIONS AND OPPORTUNITIES FOR BCMI APPLICATIONS

The outcomes of our first study yielded clues for classifying the ongoing EEG activity of a music performer into HA versus LA expressive states. In theory, since the spectral power of HA (Distressed and Excited) conditions were higher relative to Neutral than LA (Depressed and Relaxed) conditions, a BCMI system could be programmed to detect a user's expressive intentions. The numerical data used to plot the results in Figure 4 was used to define target values and thresholds for each expressive state (HA and LA) in each ROI within a visual programming software called Quartz Composer[2]. This software is now deprecated but currently still enables us to visualize and map HA versus LA expressive intentions in real time while playing a music instrument. It achieved less than 30ms latency which made it suitable for live music applications, but adding 500–1000ms temporal smoothing was useful for avoiding occasional noise-induced fluctuations.

An early visualization employed a blue ball on a black field with a horizontal midline as shown in Figure 8. If higher HA values are detected in the ongoing EEG the blue ball rises above the midline, while higher LA values in the signal cause it to descend below the midline. This provided a straightforward means of visual neurofeedback for testing and mapping to musical or visual outputs which could be learned by a new user relatively easily.

[2] https://developer.apple.com/documentation/quartz/quartz-composer

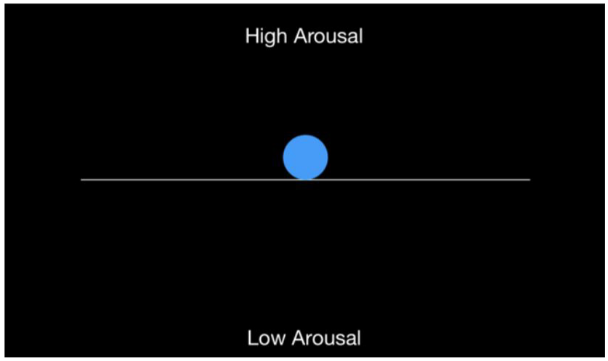

Figure 8: Neurofeedback visualization of a blue ball and horizontal midline dividing High Arousal and Low Arousal conditions. The blue ball moves above or below the line in response to the BCMI system user's ongoing EEG.

One implication of our limited sample size of 10 subjects was that thresholds defining HA and LA conditions may vary for new users. To overcome this, functions were programmed in the BCMI software to allow this to be adjusted for new users and new environments. A new user would begin by setting an individual threshold for Neutral, and then begin to modulate their expressive intentions between HA and LA to move the blue ball into the intended zone. If the blue ball moves not as intended, the user could then adjust their individual thresholds until it does move as intended.

This implies that like learning to play any musical instrument, a BCMI system does take a little time to get accustomed to. In my experience testing and demonstrating this system, it takes some people only 15 minutes to learn to manipulate the blue ball willfully, while it takes most people about 30–40 minutes to simply get used to it. Formal evaluation of this system achieved 70–84% accuracy over 3 rounds of testing with a new group of subjects playing different instruments. We saw potential for this BCMI system for live music performance applications and began testing it outside the lab in real concert settings. For some examples please refer to the next section of this article.

We expect our current EEG hyperscanning study to yield several potential opportunities for multi-user BCMI, possibly leading to applications in the wider BCI field. Specifically, an important future milestone will be to evaluate various task-relevant inter-brain synchronization (IBS) metrics for implementation in new multi-user BCMI software. The current analysis approach uses GC and PLV measures which will in turn inform the development of an IBS-based BCMI. More work is needed to implement real-time calculation of these metrics between multiple brain signals in software. We are optimistic that after identifying, deploying and refining this component, it will open up many new possibilities for musical expression and other forms of non-verbal communication.

Theoretically, if task-relevant levels of neural synchronization within a goal-directed team such as a music ensemble could be displayed back to them in real-time as neurofeedback, they could potentially learn to guide themselves more consciously into a shared state of optimal performance, such as a group flow state. Two real-time IBS visualizations we developed for exploring this theory are shown in Figure 9. This opportunity to visualize or musify levels of group synchronization could also potentially serve as non-verbal cues for observers or audiences. For example, in the context of live performance, imagine a string quartet, each member with a spotlight on them which changes colors in response to their individual brain activity. As the colors modulate a viewer could observe moments of synchronization and desynchronization within the quartet as the music piece unfolds.

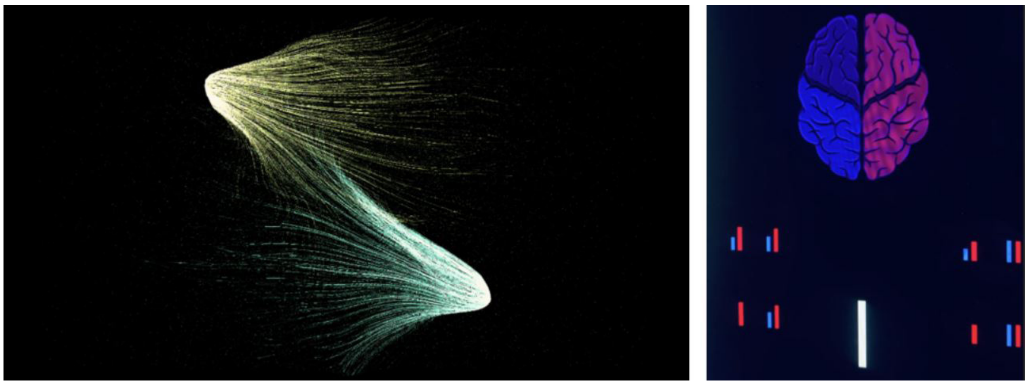

Figure 9: Left, video still of two particle systems driven by online EEG signals from two persons in which synchronization based on HA-LA conditions causes the particle systems to merge. Right, video still of a visual of a brain representing Alpha (blue) and Beta activity (red) from two persons in 4 brain regions each (red and blue bars). As activity becomes more symmetrical, the colors of the brain brighten and the white bar increases in length.

Our team also envisions the possibility of BCI systems that could potentially connect many brains to a shared network enabling EEG-driven forms of non-verbal communication. We see opportunity for such technology to use music or visual iconography as a non-verbal indicator of mood, perhaps similar to the way emoji symbols in digital text-based communication today are a form of emotive shorthand. The HS method has formed the basis for such technology to emerge, and efforts to visualize real-time inter-brain dynamics in performer-performer or performer-listener contexts is a direction of work which may contribute solutions towards wearable neurotech devices in the future enabling non-verbal networked communication. For example, we can imagine future scenarios in which a performer and an audience's inter-brain dynamics play a role in the narrative or stylization of a performance environment. Taking this one step further, when EEG hardware surpasses the limitations of current consumer grade devices, the potential will increase for wearable neurotech devices to become more commonplace methods for non-verbal communication between individuals and teams.

This project is still ongoing with a limited number of participants recorded each year consisting mainly of JVLMA student volunteers matching the study criteria. As always patience is necessary for neuroscience outcomes to bear fruit in the BCMI field.

BCMI DESIGN AND ARTISTIC APPLICATIONS: APPROACH TO ARTISTIC BCI

A BCMI system is a combination of EEG signal acquisition hardware, real-time classification software, and audio/visual feedback as shown in Figure 10. BCMI system designs described in published literature consist of various kinds of software programmed to transform and map the live EEG signal to control musical or visual outputs in real time (Miranda and Castet 2014, 221–254). In this section, several examples are described illustrating how our bridging gaps in interdisciplinary research manifested into artistic BCI applications outside the laboratory.

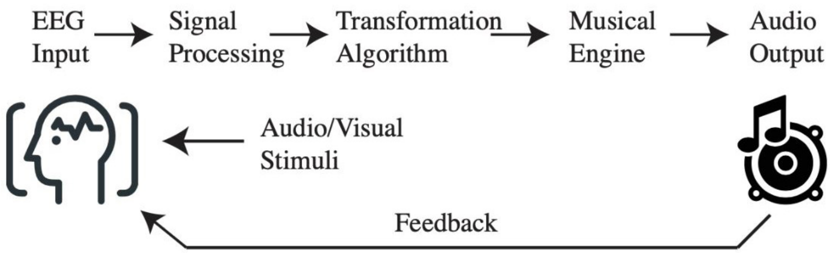

Figure 10: Typical components of a BCMI system perform the steps of EEG input, signal processing, algorithmic transformation, music control, and finally audio output which becomes real-time feedback. Additional audio/visual stimuli may also be presented or tasks may be given to test the interaction.

When crossing into the realm of artistic use, BCI has to play to the strengths of its chosen techniques to serve the narrative. Different BCI techniques provide different levels of active and passive control. Further, different mapping strategies can actuate different control types. In a many-to-one control type, many EEG features are mapped to control a single music parameter, whereas in a one-to-many type, a single EEG feature is mapped to control many music parameters. Some BCIs employ a mixture of both – a many-to-many control type. Evidently, planning an artistic BCI requires a well-chosen technique and control type appropriate for serving the overarching narrative of the artistic work.

An issue in the field of artistic BCI has been the clarity of the user's intentions. A viewer must be able to perceive a relationship between the performer's actions and the resulting sound or visual. If a BCI performer remains motionless as is often the case, how is a viewer to know if the output is actively or passively controlled? A challenge for the field has been to use BCI in such a way that enables a performer to do something easier than by manual means. In other words, if it is easier for a performer to play a note on a piano or raise a MIDI fader, why assign such triggers or controls to a BCI system? The following section includes a brief technical description of how BCI techniques and mapping strategies were implemented and how they addressed these issues and challenges.

MAPPING THE EEG SIGNAL TO CONTROL AUDIO VISUAL SYSTEMS

This section aims to provide an overview of our approach and our choices of BCI technique and control mapping for ease of understanding the examples in the next section. For full documentation of this BCMI software's design and testing processes please refer to Pousson's PhD dissertation available on our institution's website [3]. To clarify how BCMI mapping may be practically achieved using currently available technology, the following terms are explained:

> **MIDI** stands for Musical Instrument Digital Interface and is a communication protocol widely shared by analog, digital and virtual electronic music instruments. The value range of a MIDI CC signal is 1–127. It is typically used to enable communication or synchronization between different electronic music instruments, or used to configure master controls over multiple instruments. It may additionally be used to control visual parameters by driving graphical data visualizations or by manipulating effects and transitions on preloaded videos in live visual software such as VDMX [4].
>
> **CV** stands for Control Voltage, the main method of controlling modular synthesizers. Each module in a modular synthesizer patch performs certain functions controlled using analog electrical voltages delivered by patch cables. Voltage ranges vary between system types, but common ranges are 0V to +5V, 0V to +8V, and -5V to +5V, with a peak-to-peak voltage of 10V. In modular synthesis, modules may function as a sound source, control or modifier. Players of such systems combine modules in creative ways to generate, sequence, filter, and otherwise modify sounds in ways that allow for explorations of atypical kinds of modulation and unique sound shaping that are not possible using prepackaged keyboard synthesizers.
>
> **DMX** stands for Digital Multiplex and is a digital data stream like MIDI. It is typically used to control stage lighting and special effects machines. A standard DMX signal contains 512 channels with a value range of 0–255 for controlling parameters such as brightness, color, focus and movement. Devices that communicate using DMX are typically daisy-chained together with each device assigned a sequential group of channels.

These three communication methods provide a bridge between BCMI software and audio/visual systems and software types. The process of mapping can take place over several stages and software programs depending on what the final output is intended to be. For example, the BCMI software may be programmed to output a single string of MIDI CC values, and within any typical Digital Audio Workstation (DAW) software,

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[3] https://www.jvlma.lv/aktualitates/savu-promocijas-darbu-aizstavejis-dzeikins-edvards-pusons

[4] https://www.vidvox.net/

this single string can be mapped to control multiple MIDI parameters of different ranges and behaviors. On the other hand, it would also be possible to calculate all the desired ranges and behaviors in the BCMI software itself before receiving MIDI CC values within a DAW on separate MIDI channels.

The choice of mapping strategy depends on what the user aims to control. This is similar to the process of designing a virtual music instrument in the node-based MAX/MSP[5] software or creating a patch using analog modular synthesizers. There are many options for routing and controlling sound in both software and hardware. Some ways are more efficient and effective than others depending on how you want to play them.

Our most effective and accurate BCMI software so far was developed based on results from our first brain music study at JVLMA, described in the previous section. In line with typical BCMI systems described earlier (Fig. 10) the main components of our system perform the following functions in real-time:

a) Receive an online EEG data stream,

b) Structure and normalize the data stream into channels per electrode and amplitude values per frequency band,

c) Compare ongoing values with HA and LA values within the four ROIs reported in our study and return a value representing percentage true for each expressive condition.

d) Map HA and LA values to the y-axis position of the blue ball visual (Fig. 8) for immediate feedback as well as to any MIDI, CV or DMX control parameter. This technique enabled active control with accuracy evaluated between 70–84%. It employed a many-to-one mapping strategy to achieve a simple visual feedback (the blue ball). Since it was also possible to map the movement of the blue ball to many parameters, this mapping strategy could be also deployed as a many-to-many control type.

This BCMI design formed a core component for live performance applications where in practice a user would be able to run the software, receive their EEG signals over a network, and map the position of the blue ball to any number of musical or visual controllers. In effect, such a BCMI system could be used in place of live mixing or stage lighting engineers, handing over the responsibility of these support roles to BCMI where they may potentially serve as a reflection of the performer's ongoing neurological state. The following sections include 3 examples of how this design was implemented within artistic works.

Example 1: BCMI performance of a MIDI score

Despite its simplicity, this BCMI system was developed most recently and is included here as an example for its effectiveness in enabling any individual to experience levels of BCI control, regardless of music instrumental ability or even corporeal mobility – it could be used while motionless or in motion.

It was originally conceived as an interactive installation in honor of Estonian composer Arvo Pärt, and featured his piece *Für Alina* performed as a MIDI score looped on repeat. The music is minimal and meditative, using the tinntinnabuli style invented by Pärt – two voices walk in unison in harmony based on a triad rather than a scale, in lengthening then

[5] https://cycling74.com/products/max

contracting phrases. The written score consists of a single page without instrumentation or note durations, and players are instructed to repeat it peacefully, in an elevated and introspective manner, in different octaves, articulations and dynamics.

These parameters could be controlled using our BCMI system by mapping levels of HA to increase tempo, and sound brighter timbre instruments on upper octaves; and LA to decrease tempo, and sound darker timbre instruments on lower octaves within a DAW (Fig. 11). The aesthetic result was envisioned to be an experience in which a user could sit or walk comfortably around a space while the piece modulates in response to their internal expressive intentions over several repeats.

Admittedly, active intentional control was not crucial to this design, and a MIDI playback rendition does fall short of conveying the nuances expected of expert human performance. Nevertheless, this BCMI design offers a convincing experience of BCI control to new users who are first learning how their EEG modulations behave. In the case of an individual user who may not be proficient at playing a music instrument, or a user who suffers from limited mobility, the ability to modulate ongoing parameters of a predetermined music piece was found to be an effective BCMI design. The following examples address these issues more directly at different levels.

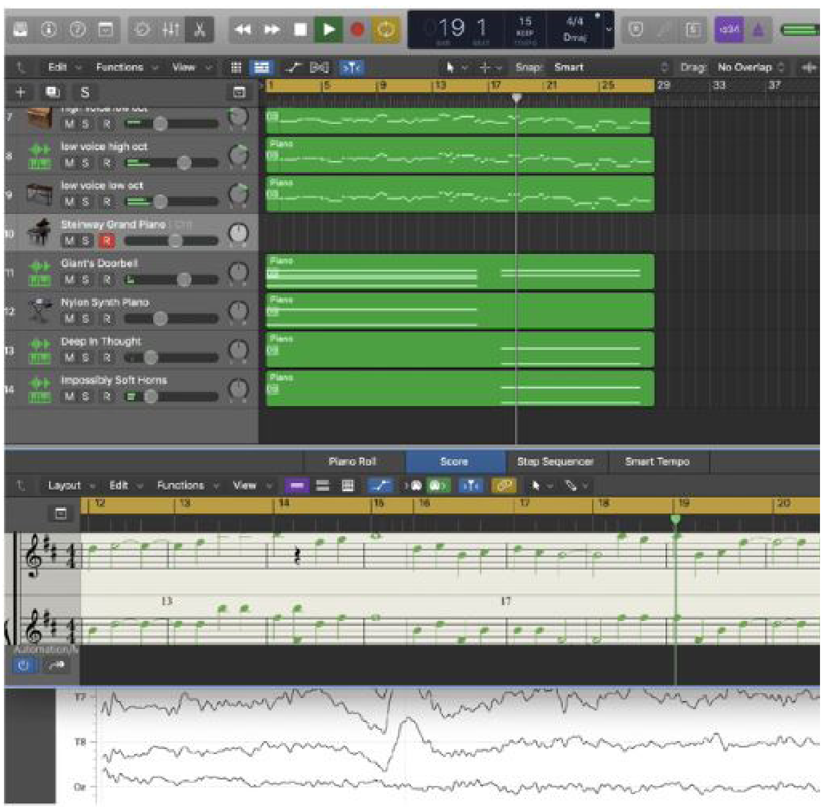

Figure 11: Top left window, MIDI score arranged for several virtual instruments within a DAW. Bottom left window, raw EEG monitor (8 channels). Right window, BCMI software using our HA-LA (blue ball) algorithm. Levels of HA-LA control the tempo of the MIDI playback, and result in different combinations of virtual instruments playing in different octaves.

Example 2: BCMI timpani solo within an orchestral piece

In this example a BCMI system was employed within an academic piece *The Seat of Consciousness*[6], composed by Pousson for the Latvian chamber orchestra *Sinfonietta Riga* which premiered on May 10, 2025. In this scenario, a solo part was to be performed by the composer using EEG signals amplified through a speaker cone placed on the surface of a 26-inch timpani. This concept was inspired by the groundbreaking piece *Music for Solo Performer* by composer Alvin Lucier in 1965 (Christopher et al. 2014, 1142), in which he amplified his EEG signal into percussion instruments.

As shown in Figure 12, this BCMI routed EEG signals from the performer's brain (A), to a computer (B), to an amplifier (C), to a speaker cone (D), to the timpani (E). The performer positions the speaker cone over the surface of the drum and controls the foot pedal (E) to modulate the pitch. The computer transformed the online EEG into audible rhythms the performer can willfully manipulate.

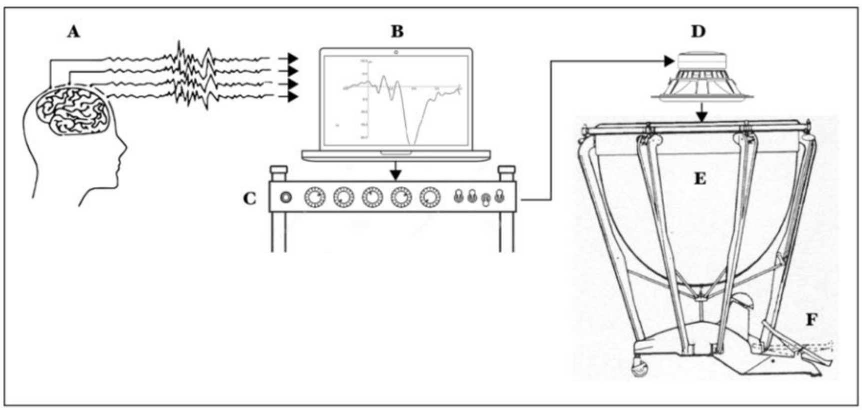

Figure 12: Steps of the BCMI system used to route EEG signals from a performer's brain (A) to a timpani (E) with a foot pedal (F) using a computer, amplifier and speaker cone (B-D).

The timpani solo appears at the beginning of the final movement and was notated as shown in Figure 13. The setup of the equipment and the result are pictured in Figure 14. To enter, the EEG Timpani player, wearing an 8 channel electrode cap, raised the volume on the amplifier allowing rhythms to sound through the speaker cone. The BCMI software calculated HA and LA values, transformed them into a MIDI Continuous Control (CC) value. A DAW software mapped the MIDI CC value to control the rhythmic density and pitch range of percussive attacks using Note Repeater and Arpeggiator MIDI effects in tandem. The resulting sound could be manipulated willfully, modulating from sparse, low pitched rhythms in simple time all the way to a dense complex polyrhythmic patterns with a wide range of pitches. This enabled the player to perform a range of constantly changing patterns throughout the solo. Situated within the narrative of the piece, the EEG timpani solo represented the inner mental process of creative work and aimed to express a human emotion of stillness in profundity, in beholding a complex subject.

[6] https://www.jachinpousson.com/single-post/the-seat-of-consciousness-premieres-at-ljmd

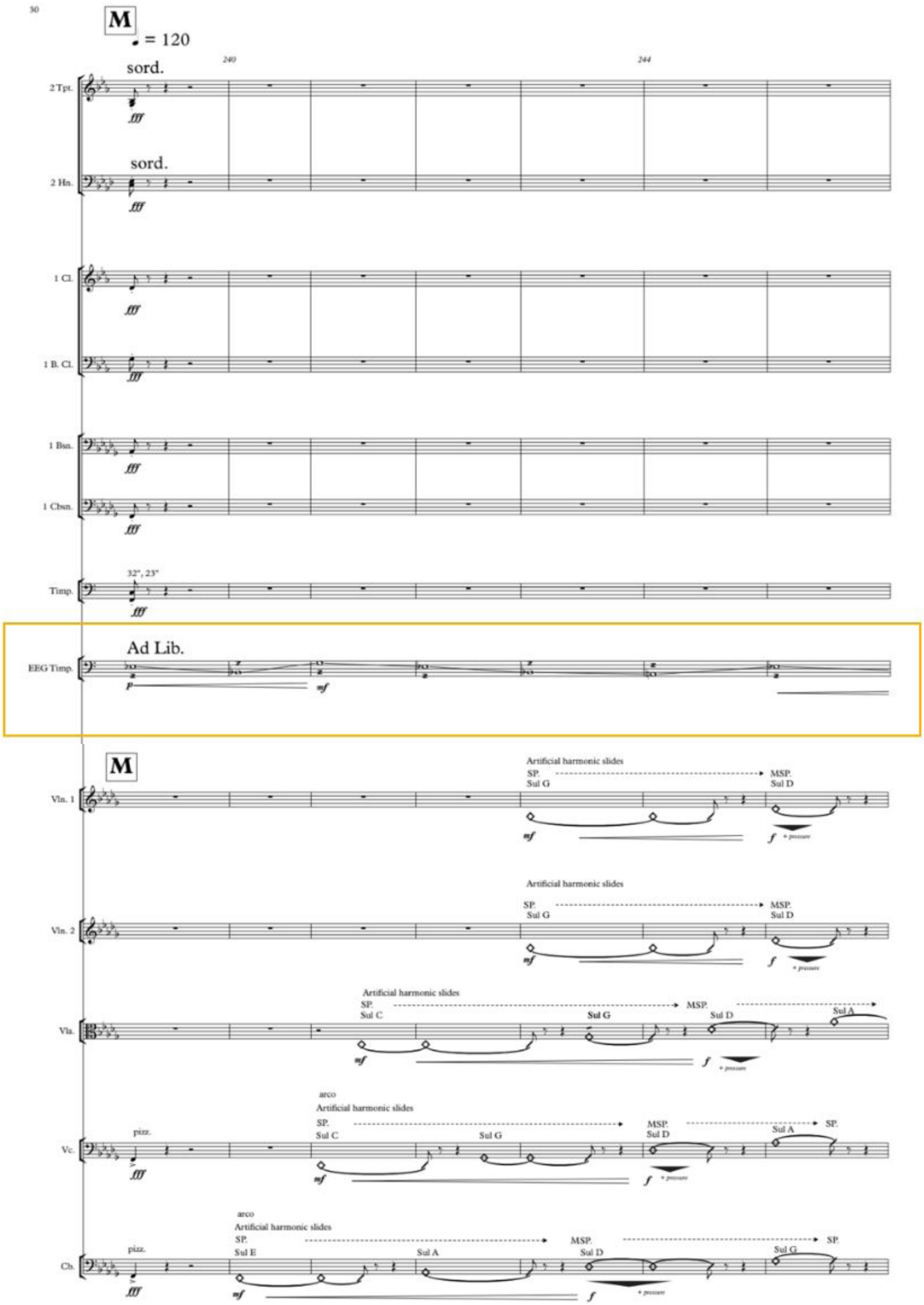

Figure 13: The entrance of the EEG timpani (outlined in yellow) in the orchestral piece "The Seat of Consciousness" composed by Pousson in 2025. The marking "Ad Lib." gives the player freedom to improvise.

This BCMI system enabled a soloist active control with a many-to-one mapping strategy. The complexity of the rhythms striking the timpani were audibly beyond the capabilities of a human percussionist, enabling the user to do what would be otherwise impossible. While the performer remains motionless for reasons related to the narrative of the piece, the same technique could be used to enable a person with limited mobility to use it as a musical instrument. Within a DAW, a user could map HA-LA values to control any MIDI parameter or trigger, opening the possibility to perform, compose or produce using either live or recorded brain activity instead of faders to define automation curves.

Figure 14: Left, BCMI system setup from the performer's perspective. Right, view of the BCMI system in use from the audience's perspective.

The use of BCMI in this piece was subtle but aimed to position it effectively in the context of an orchestral work. Technically, the use of a computer and electronics places this piece on the border of electroacoustic works. Yet it does not fit in that category either since it does not involve a tape (playback) element, and does not require microphones or speakers. It only requires a power source for the amplifier- not more than that required to operate a vibraphone motor on a concert stage. We are fortunate to have modern ensembles such as *Sinfonietta Riga* who are willing to realize experiments such as these.

Example 3: BCMI mapping for live electronics

As aforementioned, a BCMI system can be mapped to control various electronic music and lighting equipment, as well as live visualizations using MIDI, CV and DMX signal communication.

The BCMI software in this example was developed specifically for interfacing with electronic music instruments during an artistic residency by a local modular synthesizer maker called Erica Synths [7]. We called this BCMI software "Neurosynth".

As shown in Figure 15, Neurosynth received 8 EEG channels (7 across the forehead and one in the back), from signal acquisition software Neuroelectrics Instrument

[7] https://garage.ericasynths.lv/articles/jachin-pousson/

Controller [8] (NIC), from the makers of the Enobio EEG system. It was programmed to output 16 EEG parameters as 16 continuous streams of MIDI CC values. A graphical user interface (GUI) was designed to display these ongoing values on a monitor for visual feedback, arranged in a horizontal row from left to right respective to their levels of active to passive BCI control. The far left parameter employed our HA-LA algorithm to output the most active control, labeled "Arousal" – a value ranging from 0-1 in which 0 is LA, 0.5 is Neutral and 1 is HA. Next to the right, HA values were labeled "Excite" and LA values "Calm", in effect re-ranging the initial "Arousal" value to 0-1 for each condition. The "Global" value represented the average power across the entire EEG frequency band spectrum, here labeled Delta, Theta, Alpha, Beta and Gamma. The next three parameters labeled "Synch", "Syn" and Desyn" output values derived by comparing frequency band amplitudes between left and right brain hemispheres. The "Synch" parameter increases as the power spectrum becomes more symmetrical versus less symmetrical between the hemispheres. "Syn" and "DeSyn" re-range this value to 0-1 for each condition. The next five labels correspond to ongoing amplitudes in each spectral band from Gamma to Delta. The final four labels describe output values corresponding to average spectral power from all frequency bands grouped into four regions – "Front", "Right", "Left" and "Back". Each of these parameters output MIDI values on 3 MIDI channels.

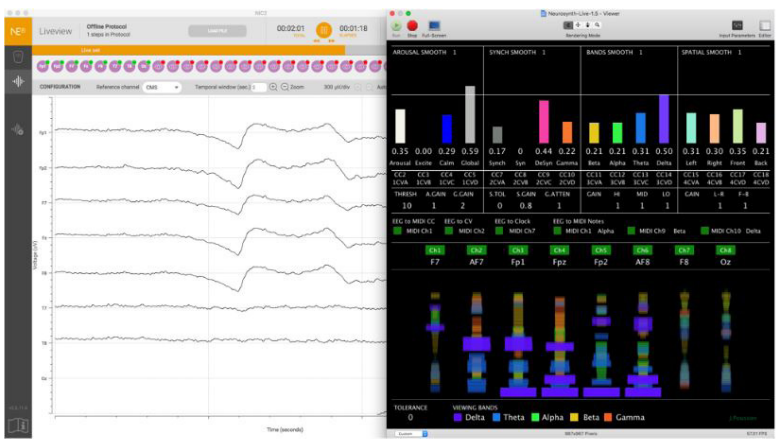

Figure 15: Left window, raw EEG monitor and signal acquisition in NIC software. Right window, Neurosynth software GUI with 16 EEG parameters displayed on top, MIDI and CV mapping displayed in the middle, and a waterfall type data visualization of synchronization events occurring between electrodes over a ten second window, color coded by frequency band.

MIDI channel 1 was assigned to output 16 simultaneous MIDI CC values (CC2-CC18) and these were mapped to control parameters such as Cutoff, Resonance and Envelope on four analog keyboard synthesizers and a drum machine through an audio interface with a 5-pin MIDI cable. MIDI channel 2 was assigned to output 16 CV values in 4 groups using a 4 MIDI-CV converter modules, which effectively retransformed the EEG signal back into voltage in a normalized range for controlling a rack of modular synthesizers. MIDI channel 7 was assigned to communicate with a DAW which provided the master

8 https://www.neuroelectrics.com/nic2

clock for the entire setup. This enabled modulating the master tempo of multiple connected devices using the brain signal alone – a technique we found to be saliently perceivable from the perspective of both the performer and a viewer.

Additionally, the data visualization at the bottom half of the screen was programmed to display the occurrence and strength (amplitudes) of synchronization events between each EEG frequency band and channel. Synchronization events (same frequency band and amplitude appearing in two or more locations) were rendered as colored bars representing each frequency band (Delta to Gamma) appearing in a downward scrolling waterfall type graphic over a ten-second window. These events could be mapped to trigger note-on and note-off MIDI commands, and could thus be used to play pitches of any predetermined scale, or rhythms determined by the density of synchronization events or even quantized to sound in metric time.

This software provided many options for mapping BCI control, both to and between keyboard and modular type systems. Figure 16 shows one of the mapping strategies employed using the Neurosynth interface, from the 8 channel EEG input on the left to hardware devices on the right assigned different roles and functions. In this setup the keyboards and modular system were planned to be played live but sound shaping parameters were controlled by MIDI and CV from Neurosynth. The computer's main role was sound control via MIDI, the keyboards main roles were sound sources while the modular system's role was mainly to modify the sound.

Neurosynth's debut live performance took place in August 2024 at the Erica Synths studio. The performance space also included DMX lighting, and so Neurosynth was updated to map HA-LA values to the intensity of red and blue lights respectively. Additionally, a visual artist on our team, Mārtiņš Dāboliņš, developed a liquid simulation visual which was projected onto the performer's head using head tracking tools and a video camera (Fig. 17, right). This visual changed colors and dynamics in real-time like a kind of aura or halo following the performer's head. This component was also BCI controlled, by patching an Open Sound Control (OSC) output from Neurosynth to the visual artist's computer over a network. The result enabled the performer to control the overall color of the stage and visual in synchronization with audio parameters. When correlated with master tempo, these visual modulations also became one of the most salient active BCI controls from the perspective of a viewer. See Figure 17 for images of the physical setup. The raw EEG signals were also displayed next to the Neurosynth window as seen in Figure 15 to monitor the input.

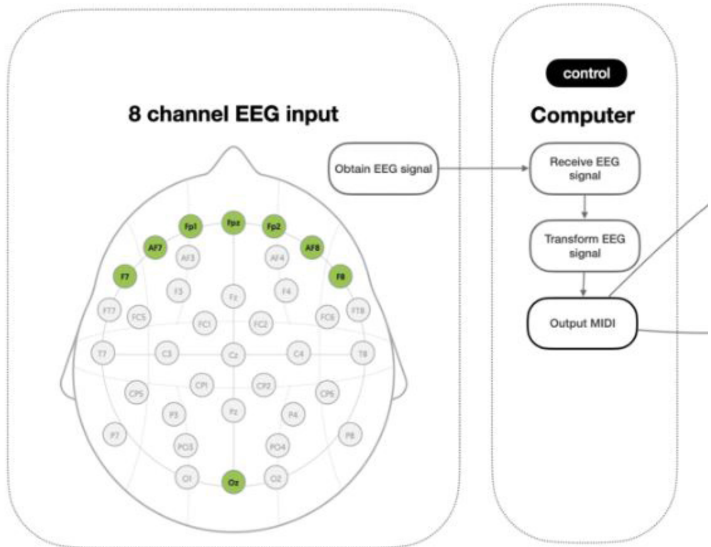

Figure 16: BCMI mapping strategy used by Neurosynth where EEG signals from 8 channels (F7, AF7, Fp1, Fpz, Fp2, AF8, F8, Oz) were received and transformed in a computer before being output as MIDI and CV to control and modify sounds played on analog keyboards and a modular synthesizer system.

Figure 17: Left, setup of 4 analog keyboards on a table and modular system installed on a wall. Middle, EEG acquisition software and Neurosynth running side by side. Right, performer using an 8 channel EEG headband to control music, light color and head-tracking visual projection.

The design and use of Neurosynth to connect to a maximum number of instruments in this setting resulted in versatile mapping tools for interfacing with electronic audio/ visual systems in concert stage environments. In particular, the use of a range of active to passive parameters yielded several key observations. First, active control parameters driven by HA-LA values are most effectively mapped to salient parameters such as tempo and ambient lighting, enabling a viewer to perceive a direct relationship between the performer's brain activity and expressive intentions during performance. A linked modulation of temporal and ambient light color was particularly effective for this purpose. Second, passive control parameters driven by individual or averaged spectral frequency band power such as the Gamma-Delta parameter values, the regional power values, and the global power value were most effective when mapped to control the most subtle parameters in the audio signal. These mainly included modifier type modules such as filters, reverbs, and delays, which could be performed by both keyboard and modular type synthesizers. Third, controls driven by hemispheric synchronization measures such as Synch values were most effective when mapped to modulate parameters with a middle level of salience such as cutoffs, resonances and envelopes. During performance, these modulations are especially audible during moments of switching focus from one physical electronic instrument to another. In particular, this interaction enabled something that was previously impossible – a brief yet noticeable change of timbre and articulation across many sound sources playing at once while in physical transition.

In summary, the three examples described in this section illustrate the potential for BCMI to find situationally appropriate roles in live performance in context of the narrative or intention of the work.

DISCUSSION AND RECOMMENDATIONS

The sciences and the arts have always inspired each other to innovate ways of uncovering or expressing truth, through empirical validity or aesthetic insight respectively. It is important to be persistent and objective when finding ways to work together towards our common goals. A systematic musicologist's role in these efforts is not only to be a mediator between scientists and engineers, but to bring focus to how such technology can benefit musical growth, and enhance music's ability to communicate expressive intentions.

The integration of systematic musicology and neuroscience through Brain-Computer Music Interfacing is more than a technological curiosity – it is a transformative step toward understanding and shaping human musical interaction. By prioritizing ecologically valid performance, expressive intent, and inter-brain synchrony, this research demonstrates that BCMI can evolve into genuine musical instruments rather than laboratory artifacts. The broader implication is clear: if musicians can learn to communicate through their neural states as fluently as through traditional instruments, then BCMI holds the potential to expand human expressivity, cooperation, and creativity.

Developing BCI techniques within the framework of embodied music interaction offers a key advantage – music communicates through an inherently ambiguous language, yet listeners perceive meaning. Consequently, learning to control a BCI through cooperative play emerges naturally in musical contexts, as users learn to express themselves by becoming aware of their own mental states, both in musical synchrony and in interaction with others.

We see the potential for BCMI innovations to benefit the wider field of BCI at the intersection of neuroscience and human-computer interaction. EEG hardware designed for use outside the laboratory such as on concert stages could be beneficial for industries looking to monitor EEG data in other noisy or challenging environments in real time, and even remotely over a network. This could lead to more advanced types of cooperative, co-creative BCI for all kinds of creative teams, or be used as a form of faster-than-speech communication between remote team members. The ability to monitor EEG synchronization metrics of any kind of team could further lead to the discovery of new methods of group neurofeedback for optimizing goal-directed performance.

What sets this research apart from earlier projects which have musified or visualized the EEG is that our approach is from the perspective of music instrument designers. We ask how brain activity can be leveraged in a way that supports rather than hinders human expressivity and emotion during play, and how this may enable new forms of creative cooperation or catalyze group flow through non-verbal cues. These questions aim to empower creativity. In contrast, many innovators in this field approach EEG musification techniques as a tool for wellness or mindfulness applications focusing on self-monitoring or the entrainment of mental states. A novel contribution in our work was the increased effectiveness of mapping strategies, achieving new levels of expressive interaction, in turn enabling BCI to play more intentional, situationally appropriate and salient roles within the narrative of artistic performance or creative processes.

While the concept of using the human EEG signal to create art has been explored increasingly especially over the past two decades, there are still knowledge gaps to fill and technological challenges to overcome before BCI can become more widely available to creative communities.

New collaborations are needed with EEG hardware design and software engineering experts to develop prototypes suitable for either artistic research or performance. More research is needed on this frontier – increased datasets with increased variety of task focuses in order to discover more reliable and accurate active control techniques. Additionally, expertise is needed to evaluate, improve and innovate algorithms for real-time EEG signal processing and transformation steps. If researchers and innovators in these fields can increase inter-disciplinary collaboration towards these aims, we see potential for BCMI system technology to be widely integrated into music instruments of the future, enabling unforeseen levels of expressive agency reflecting neurophysiological states.

Systematic Musicologists, composers, performers, art educators and therapists are needed to help to guide the development of this emerging technology in a direction that catalyzes human creativity and cooperation, and that builds community and culture.

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MŪZIKAS RADĪŠANA AR SMADZEŅU VIĻŅIEM: TILTS STARP SISTEMĀTISKO MUZIKOLOĢIJU UN NEIROZINĀTNI SMADZEŅU–DATORA MŪZIKAS SASKARNES PĒTĪJUMOS

Džeikins Edvards Pūsons, Valdis Bernhofs

Rakstā tiek analizēta sistemātiskās muzikoloģijas un neirozinātnes integrācija, izmantojot smadzeņu–datora mūzikas saskarni (BCMI), uzsverot tās potenciālu mainīt izpratni par muzikālo mijiedarbību teorijā un praksē. Balstoties gan uz senākām tradīcijām – Helmholca un Adlera teorijām, gan mūsdienu neiromuzikoloģijas paradigmām, tas iezīmē EEG balstītus pētījumus kā "trešā viļņa" pieeju mūzikas un smadzeņu izpētē, proti, akcentē ekoloģisko validitāti, emocionālās izteiksmes nodomu un starpsmadzeņu mijiedarbību.

EEG pētījumi Jāzepa Vītola Latvijas Mūzikas akadēmijā, novērojot emocionālas izpausmes klavierspēlē, kā arī, izmantojot hiperskenēšanas metodi muzikālās mijiedarbības laikā, sniedz jaunas atziņas par smadzeņu aktivitāti un starpsmadzeņu saiti un šīs aktivitātes dinamiku. Šie rezultāti tiek izmantoti BCMI sistēmu izstrādē, kas funkcionē kā pilnvērtīgi mūzikas instrumenti, nevis laboratorijas artefakti, ļaujot mūziķiem reāllaikā veidot skaņas un vizuālo vidi un izmantot dažādus neirālos stāvokļus.

Mākslinieciskie koncepti, tostarp orķestra darbi un elektroniskās performances sistēmas, demonstrē BCMI kā zinātniska instrumenta un mākslinieciska medija iespējas. Papildus tehnoloģiskajām inovācijām pētījums uzsver arī institucionālos ieguvumus: iekšējo EEG kapacitāšu attīstīšana stiprina starpdisciplināru sadarbību, veicina starptautisku partneru piesaisti un pozicionē augstākās izglītības institūcijas līderību šīs strauji augošās jomas ietvaros.

Raksts argumentē, ka BCMI ir ne tikai zinātnes un mākslas robežlīnija, bet arī modelis institucionālai attīstībai un starpdisciplinārai pētniecībai mūzikā un neirozinātnē.

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PAR AUTORIEM

Valdis Bernhofs ir Jāzepa Vītola Latvijas Mūzikas akadēmijas profesors un vadošais pētnieks muzikoloģijā. Viņš absolvējis kordiriģēšanu (1992), ieguvis maģistra grādu mūzikas terapijā Heidelbergā (2006) un doktora grādu muzikoloģijā (2014). Pētnieciskās intereses aptver sistemātisko muzikoloģiju, īpaši kognitīvā dzirdes treniņa pieejas, muzikālās apdāvinātības neiropsiholoģiju un akustiskās informācijas apstrādi.

Markus Kristiners ir pēcdoktorantūras pētnieks Grācas Universitātē un Jāzepa Vītola Latvijas Mūzikas akadēmijas pētnieks. Viņa darbs ir starpdisciplinārs, apvienojot lingvistiku, muzikoloģiju, neirozinātni un kultūras studijas, kā arī pētot valodas, mūzikas un kognitīvo procesu mijiedarbību.

Mahrads Godusi ir doktorants Viļņas Universitātes Dzīvības zinātņu centrā (kopš 2022. gada). Viņa pētījumi saistīti ar emocionālo mijiedarbību muzikālajā priekšnesumā un klausīšanās procesā, īpaši izmantojot EEG hiperskenēšanu. Specializējas biosignālu apstrādē, EEG analīzē un mašīnmācīšanās izmantojumā.

Kristīne Grosa ir Heidelberga SRH Universitātes profesore mūzikas terapijā un mākslu terapijās un pētniece JVLMA. Viņas pētījumi saistīti ar mūzikas terapiju, psiholoģiju un neirozinātni, īpaši pievēršoties auditīvai apstrādei, neiroatšķirībām, mūzikā balstītām intervencēm un starpdisciplinārai metodoloģijai.

Reinis Maurītis ir JVLMA doktorants, zinātniskais asistents un Mūzikas pedagoģijas katedras lektors. Viņš studējis mūzikas pedagoģiju un sistemātisko muzikoloģiju un prezentējis pētījumus starptautiskās konferencēs. Pēta sistemātiskās muzikoloģijas un mūzikas izglītības mijiedarbību.

Džeikins Edvards Pūsons ir JVLMA pētnieks. Viņš ieguvis akadēmisko grādu mūzikas kompozīcijā un doktora grādu sistemātiskajā muzikoloģijā. Pētījumos viņa uzmanības centrā ir neirālā aktivitāte mūzikas atskaņošanas laikā, izmantojot elektroencefalogrammu (EEG), kā arī smadzeņu-datora mūzikas saskarnes (BCMI) dizaina izstrāde ķermeniski iemiesotā muzikālajā mijiedarbībā

Marija Šneidere studējusi mūzikas pedagoģiju Manheimas Mūzikas un skatuves mākslas augstskolā un angļu valodu Freiburgas un Manheimas universitātēs. Studijas noslēgusi ar darbu par mūzikas un valodas attiecībām Ģērģa Ligeti mūzikas teātra darbos. Pētnieciskās intereses ietver mūzikas un valodas spēju mijattiecības, muzikālo uztveri un radošo darbību, kā arī svešvalodu apguvi.

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Tatjana Voitova ir JVLMA doktorante sistemātiskajā muzikoloģijā. Viņa ir vadījusi Mūzikas teorijas nodaļu Emīla Dārziņa mūzikas skolā un ir strādājusi par mūzikas teorētisko mācību priekšmetu pasniedzēju. Viņas pētījumi saistīti ar pusaudžu labbūtību, mentālo veselību un psihosociālajiem faktoriem muzikālo spēju attīstībā.