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Centre of Excellence in Music, Mind, Body and Brain

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Music, health, wellbeing, development, rehabilitation, learning, plasticity, education, neuroimaging, multimodality , interaction, music information retrieval, machine learning

Field of research

1. Musicology
2. Systemic and cognitive neuroscience
3. Psychology
4. Education
5. Psychotherapy

Abstract

Centre of Excellence in Music, Mind, Body and Brain (MMBB) studies music as a multimodal human experience and as a versatile engine of change, throughout the life span and in health and disease. Adopting a multidisciplinary empirical approach that combines cognitive musicology, psychology, education, therapy, computer science, and cognitive neuroscience, the research of MMBB merges both basic and applied research perspectives in a concerted effort to determine (1) how the cognitive, emotional, embodied, and interactional experience of music and the brain mechanisms underlying it change over the course of human life and in different disorders, (2) how music-based interventions can be optimized to enhance learning and emotional, cognitive, motor and social wellbeing in educational, everyday, and rehabilitation settings; and (3) what individual, contextual, psychological, and neural mechanisms explain the efficacy of music.

In MMBB, these questions are addressed in 13 study modules, which include both healthy subjects of different age (infants, children, adolescents, adults, seniors) and different developmental (dyslexia, developmental language disorder, autism, attention disorder), psychiatric (stress, depression, anxiety), and neurological (stroke, dementia) disorder populations, comprise both cross-sectional and longitudinal studies and clinical trials, and take place both in laboratory and real world settings, and utilize a unique combination of state-of-the-art quantitative and qualitative behavioural methods, musical and acoustic analyses, computational modelling, electrophysiological (EEG-ANS) and movement (motion capture) recordings, and structural and functional brain imaging (s/fMRI).

Research plan

1 Aim and objectives

1.1 Significance of the research project in relation to current knowledge and the research-based starting points

Music is a universal, biocultural human phenomenon. Not only is it a source of pleasure, aesthetic enjoyment, and recreation, but also a powerful form of multimodal communication and an engine for change that operates at all levels of human experience. Based on behavioural evidence accrued over the past 20 years, the *current knowledge* is that musical engagement and interventions can have wide-ranging benefits on verbal, cognitive, and motor functioning and emotional/social wellbeing, ranging from early development [1] to healthy ageing [2] and in the treatment of developmental (e.g., autism) [3], psychiatric (e.g., depression) [4], and neurological (e.g., stroke, dementia) [5] disorders. In parallel, neuroimaging studies have made major advances in mapping the regions, pathways, and networks that govern the perception, emotional experience, and production of music [6,7] and the neuroplasticity changes induced by musical activities in the healthy brain [8].

Our research at the Universities of Jyväskylä (JyU) and Helsinki (UH) has been *at the forefront* of this advance. Our *developmental studies* have shown that language and music learning starts already before birth [9,10], musical (prosodic) elements of speech enhance statistical learning in infants [11], and regular musical activities enhance auditory memory and language skills in children [12,13] and executive function and emotional wellbeing in adolescents [14,15]. In adults, our *music cognition studies* have mapped the brain networks and connectivity patterns that process musical structure and emotions [16,17] and their malleability induced by musical training [18,19] and by auditory, psychiatric, and neurological deficits [20–22]. Our *motor studies* have mapped the musical and kinematic features and personality traits mediating music-induced movement [23–25]. Our *randomized controlled trials* (RCTs) have shown the emotional and cognitive efficacy of improvisational music therapy (IMT) in depression [26,27], neurological music therapy in brain injury [28], and daily musical activities (listening, singing) in stroke [29,30] and dementia [31,32].

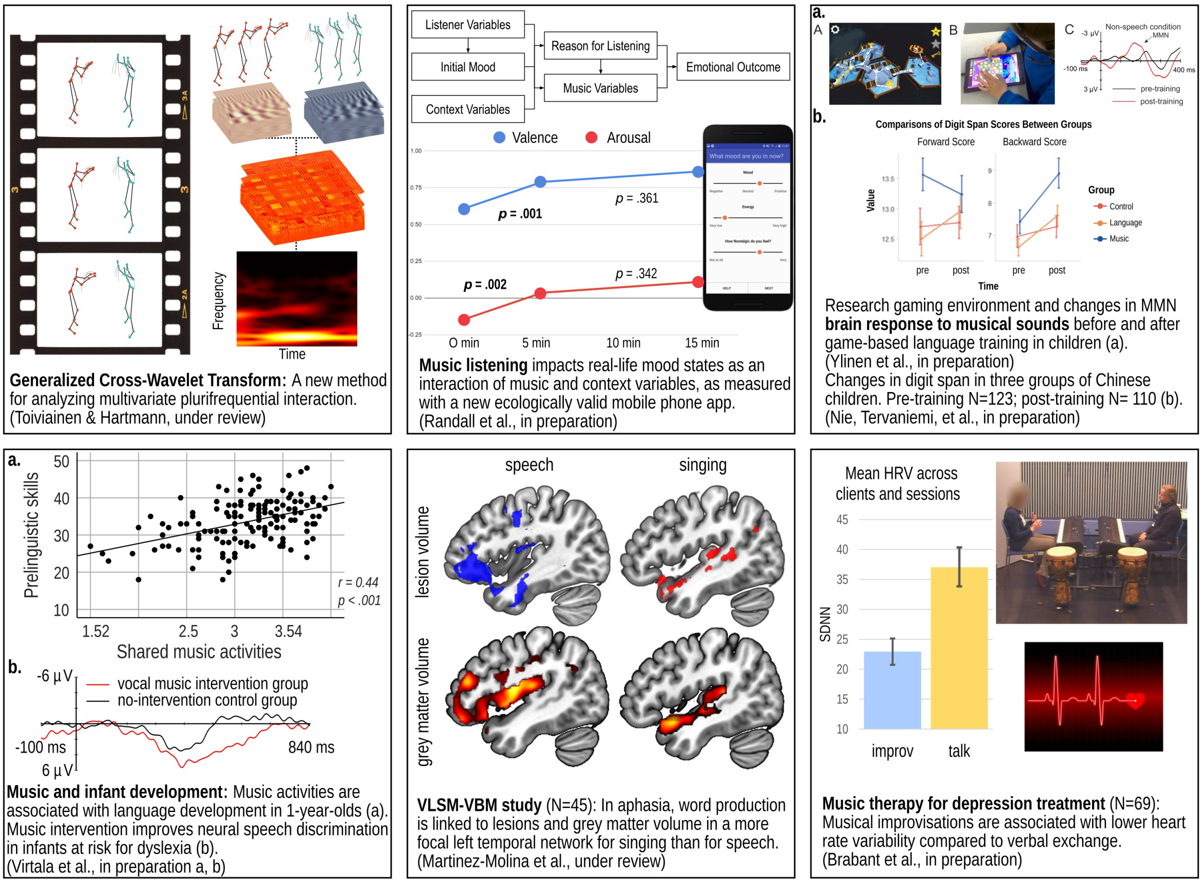
By global standards, the music research conducted in Finland (JyU, UH) by the teams of the proposed CoE (henceforth MMBB) is exceptional and unique in terms of its (i) *broad scope,* combining basic research on musicology and music psychology and applied research on the developmental, therapeutic, and rehabilitative aspects of music; (ii) *interdisciplinary methodology and knowhow*, including advanced computational modelling, music information retrieval (MIR), motion capture (MoCap), neuropsychological, physiological (e.g., heart-rate variability, HRV), and neuroimaging measures implemented within cross-sectional, longitudinal, and RCT studies; and (iii) *extensive scientific output*. According to a recent bibliographical analysis on leading music psychology journals [33], Finland produces, by a wide margin, the highest number of articles and citations per capita, with these articles almost exclusively authored by the teams of the MMBB. Future prospects of our research are outstanding; Figure 1 shows preliminary data and results of our ongoing projects, which lay a solid foundation for the new and innovative research carried out at the MMBB.

Overall, current evidence provides proof-of-concept for the use of music as a versatile, motivating, and cost-effective tool for promoting learning, health, and wellbeing and in the treatment of illness across life, as highlighted in recent consensus reports of the WHO, NIH, and GCBH [34–36]. However, as suggested also by these reports, there are **notable knowledge gaps and limitations** in the current state-of-the-art, both in basic (fundamental) and applied (translational) research:

Gap 1. Lack of unifying framework for music cognition: Across cultures, music has a number of universal features, ranging from its spectral (e.g., pitch) and temporal (e.g., rhythm) characteristics to its cognitive, emotional, motor, and social effects [37,38]. To date, these features have mostly been studied separately from each other and in narrow age groups or clinical populations, without considering their interaction, developmental trajectory, and vulnerability/resilience in different developmental, psychiatric, and neurological disorders. Furthermore, existing models/theories focus on specific aspects of music cognition, such as melodic perception [39], auditory prediction and attention [40,41], or musical emotions [42], resulting in a *fragmented and limited view* of music cognition that lacks integration between the perceptual, cognitive, motor, emotional, and social elements of music and their neural mechanisms across the life-span and in different disorders. **Solution:** We will (i) perform *large-scale research* that systematically maps different aspects of music cognition (auditory, motor, cognitive, emotional) using (ii) *common assessment methods* across all life stages (childhood, adolescence, adulthood, senescence) and in the major developmental, psychiatric, and neurological disorders linked to these stages to identify universals of musical capacity and reactivity to music. As a result, we will (iii) build a first-ever *comprehensive neurocognitive model of music*.

Gap 2. Insufficient focus on natural, multimodal and interactive musical behavior: Although human cognition is fundamentally *embodied* and *situated* [43] and music is a *multimodal* form of *communication* and social *interaction* [44], these levels of human experience have previously proven to be challenging to empirically measure. Furthermore, although evolutionary theories of music often emphasize its social origins and key role in group cohesion, bonding, and prosociality [45], the majority of music research focuses on individuals or dyads, covers only simple musical behaviours, and is limited to artificial experimental and laboratory settings. Therefore, our real-life understanding is very limited and rudimentary regarding the *dynamics* of and the *variability* in how music is used to regulate mood, coordinate movements, and interact socially; how these functions develop and are affected by developmental disorders; and how they support language learning, social-cognitive skills, and emotional wellbeing. **Solution:** In order to understand musical behavior in an ecologically valid manner, we will (i) collect data using naturalistic musical tasks and real-life music interventions, including group contexts, and (ii) develop methods to analyze them to (iii) determine how multimodal and interpersonal interactions drive musical behavior in naturalistic environments, and (iv) how they aid development, learning and wellbeing.

Gap 3. Inadequate knowledge on therapeutic and transfer effects of music: While previous studies have reported positive effects of musical training and music-based rehabilitation in healthy [1,2,11–15,18,19] and clinical [3–5,26–32] populations, the quality of this evidence is limited by *small sample sizes* and lack of proper *control conditions* and longitudinal *follow-up*, especially for the far transfer effects of music [46]. Moreover, focus has been on individual training/rehabilitation provided by a music teacher/therapist, which overlooks the *social interactive power* of music and limits the availability and applicability of music interventions in the real-life educational and clinical environment. Also our understanding of the individual and intervention-related factors and the biological and neural *mechanisms* underlying the rehabilitative efficacy of music in developmental, psychiatric, and neurological disorders remains poor. **Solution:** For establishing effective music interventions, we will (i) optimize existing music interventions to be widely applicable and cost-efficiently scalable for diverse samples (e.g., for groups, for remote contexts) and, in contrast to diagnosis-based approach, to target outcomes most crucial for the person and (ii), discover the individual factors and the musical, psychological and biological mechanisms that underlie the efficacy of music, and (iii) assess these in large-scale, multimethod RCTs.



Generalized Cross-Wavelet Transform: A new method for analyzing multivariate plurifrequential interaction. (Toiviainen & Hartmann, under review)

Music listening impacts real-life mood states as an interaction of music and context variables, as measured with a new ecologically valid mobile phone app. (Randall et al., in preparation)

Research gaming environment and changes in MMN **brain response to musical sounds** before and after game-based language training in children (a). (Ylinen et al., in preparation)
Changes in digit span in three groups of Chinese children. Pre-training N=123; post-training N= 110 (b). (Nie, Tervaniemi, et al., in preparation)

Music and infant development: Music activities are associated with language development in 1-year-olds (a). Music intervention improves neural speech discrimination in infants at risk for dyslexia (b). (Virtala et al., in preparation a, b)

VLSM-VBM study (N=45): In aphasia, word production is linked to lesions and grey matter volume in a more focal left temporal network for singing than for speech. (Martinez-Molina et al., under review)

Music therapy for depression treatment (N=69): Musical improvisations are associated with lower heart rate variability compared to verbal exchange. (Brabant et al., in preparation)

Fig. 1. Examples of **preliminary data** and methodological development associated with the MMBB project.

1.2 Research questions and/or hypotheses

To tackle these gaps, MMBB will adopt a *multidisciplinary empirical approach* that (1) combines musicology, MIR, music therapy and rehabilitation, psychology, linguistics, cognitive neuroscience, educational science, and computer science, (2) incorporates both quantitative and qualitative methods, and (3) merges both basic and applied perspectives. Explored in three interlinked Work Packages (WP1-3, see 2.1), our research will address three broad, fundamental questions (Q1-3):

Q1: How does music cognition and behavior function across life and in health and disease? Specifically, (i) how are different domains of music cognition (perceptual, cognitive, motor, emotional) and multimodal-interactive musical behavior linked at psychological (mind), physical (body), and neural (brain) levels; (ii) how do they vary individually and change across different stages of life (childhood, adolescence, adulthood, senescence); and (iii) how are they affected by the major developmental [autism spectrum (ASD) and language development disorders (LDD)], psychiatric (depression, anxiety, stress/burnout), and neurological (stroke, dementia) disorders linked to these life stages? Q1 relates to Gaps 1 and 2 (see 1.1).

Q2: How can music support positive development and prevent adverse development? Specifically, (i) how do musical activities and music-based interventions aid the development of auditory, cognitive, and language skills and (ii) facilitate emotional self-regulation and social interaction in everyday life (hobbies, home settings) and in educational (school) and vocational (work) settings; and (iii) how can they be used to prevent or mitigate adverse trajectories in childhood development (ASD, LDD, learning disability) and in adolescent and adult wellbeing (stress management, loneliness)? Q2 relates to Gaps 2 and 3 (see 1.1).

Q3: How can music aid functioning and recovery in mental and neurological illnesses? Specifically, (i) how do music-based interventions enhance emotional/social, cognitive, verbal, and motor functioning in psychiatric (depression, anxiety, stress/burnout) and neurological (stroke, dementia) disorders; (ii) how can existing music-based interventions for these disorders be optimized for their clinical cost-efficacy, individualized targeting, and wide-scale applicability by combining different therapy elements and through group-based and remote (digital) rehabilitation applications; and (iii) what psychological and neural mechanisms drive their therapeutic efficacy? Q3 relates to Gaps 2 and 3 (see 1.1).

1.3 Expected research results and their anticipated scientific impact and potential for scientific breakthroughs:

The results will provide a comprehensive picture, on both descriptive and explanatory levels, of the influence of music as multimodal activity on humans throughout the lifespan, in both health and disease and in both short- and long-term. Specifically, MMBB research will make groundbreaking advances in theoretical, empirical, methodological, and intervention domains of music research.

Theoretical/empirical: We will create a first-ever comprehensive *neurocognitive model of music,* encompassing both developmental and clinical aspects. Using a common battery of musical tests and neuroimaging measures across study modules, we will collect and publish the *largest-ever structured data set* (N=2000) of perceptual, cognitive, motor, and emotional musical behavior and their neural correlates (N=500), laying the empirical foundation for the model. Importantly, the model (i) covers all core domains of music and can bridge previous theories of music cognition [39–42]; (ii) incorporates a lifespan (from 5 to 90 years) perspective and can be integrated with existing models of maturation and ageing, such as the "last-in-first-out" retrogenesis model [47,48]; and (iii) connects music behavior to specific brain regions and networks and can identify neural substrates causally linked to music [49,50] as well as uncover the pattern of impairment and preservation of musical capacity in developmental, psychiatric, and neurological disorders. Finally, when coupled with longitudinal data from music intervention trials, we will be able to (iv) identify musical skill and reactivity profiles that predict educational/therapeutic gains from music interventions and (v) reveal the psychological and neural mechanisms underlying their efficacy.

Methodological/intervention: We will develop and integrate a number of *methodological tools* and *learning/therapeutic music applications* that are (a) empirically tested for their efficacy using robust research paradigms and (b) can be directly applied in future research and practice for education, prevention, rehabilitation, and clinical care, including group settings in real-life environments. These comprise (i) a comprehensive musical assessment battery and psychometric tools for mapping musical reactivity; (ii) novel methods for measuring multimodal entrainment to music in naturalistic settings; (iii) cutting-edge tools for analyzing acoustical and movement data; (iv) innovative music-based serious games and individual and group interventions for children to support language, cognitive, and emotional-social development; (v) a training platform for teachers for using music in early, primary, and special education; (vi) a novel receptive-expressive music therapy method for depression, anxiety, and stress/burnout patients; (vii) innovative digital, multicomponent music interventions for stroke and dementia patients; and (viii) a musical preference mapping tool and old-time song library for dementia care.

1.4 Scientific renewal and added value:

The above *breakthroughs* will establish a benchmark for future fundamental and applied research on music and also for the development of music-based learning applications and interventions, thereby renewing our understanding of music as an engine of change in human life. The added value for science of the MMBB comes especially from (i) bringing together a *wide range of disciplines* with complementary expertise, creating a centre unique on global level in terms of structure and concentration; (ii) performing *multicenter data collection* to acquire large samples and pooled data to answer broader, more fundamental research questions; (iii) carrying out *longitudinal studies* of sufficient time span possible due to the 8-year funding period of the CoE; and (iv) sharing *methodological knowhow* and developing unique state-of-the-art multimodal methods.

2 Implementation

2.1 Work plan and schedule:

Figure 2a displays the conceptual framework of MMBB. The organizational structure comprises three **thematic Work Packages (WP1-3)**, addressing the main research questions of MMBB (Q1-3, see 1.2), and one **general WP (WP4)** for project management and communication. The thematic WPs comprise **13 Modules (M)** (see Fig. 2b), which focus on specific research questions linked to each WP (see 2.2). The main task of WP1-3 is to (i) facilitate integration between the Modules via data, information, knowledge, and knowhow sharing in all stages of implementation; (i) pool data and synthesize results across Modules; and (iii) merge and assimilate their findings for theoretical formulation and practical exploitation in developmental, educational, and rehabilitation settings.

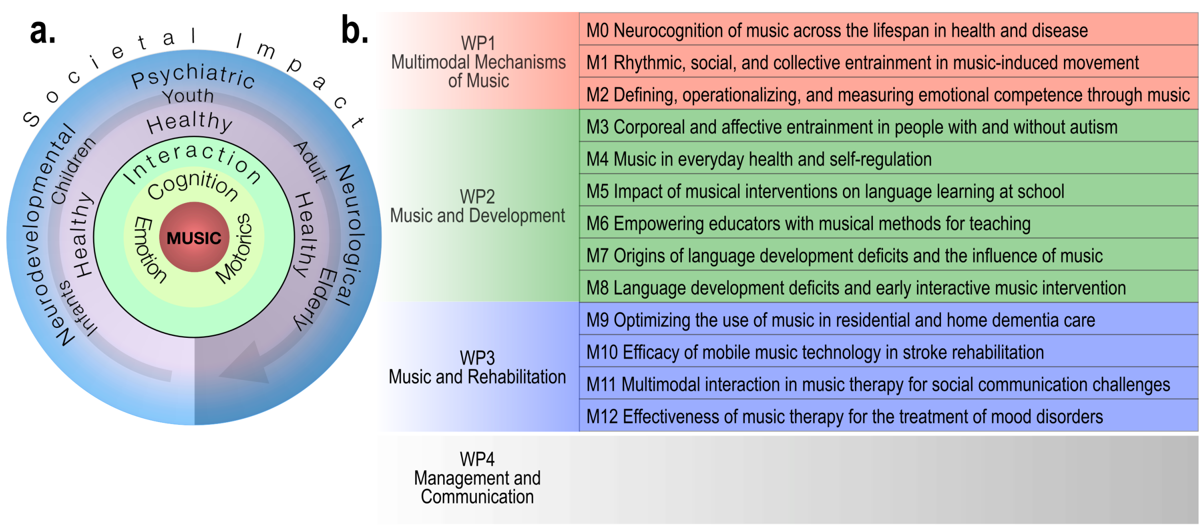


Fig. 2. (a) conceptual framework of MMBB and (b) its organizational structure into Work Packages (WP) and Modules (M).

WP1: Multimodal mechanisms of music (led by PT, initials refer to project personnel listed in 3.1) will answer research question Q1 (see 1.2). To this end, it will (i) coordinate the development of *MMBB-MB* and *MMBB-BB measurement batteries* (see 2.2) and the subsequent data collection with them; (ii) develop generic experimental and naturalistic protocols to measure and analyze multimodal and interactive music processing in both laboratory and naturalistic settings; and (iii) coordinate data collection and analyses in M0-2. Based on the empirical findings from M0-2, WP1 will (iv) develop an overarching neurocognitive model of music, encompassing all stages of life and major developmental, psychiatric, and neurological disorders linked to each life stage. Finally, WP1 will (v) incorporate these findings to pre- and post-doctoral training, both within JyU-UH and internationally (e.g., via Summer School for PhD students).

WP2: Music and development (led by MH) will answer Q2. To this end, it will (i) lead the development of novel music-based learning tools and wellbeing interventions to foster communicative, social-emotional, and cognitive skills in educational and preventive contexts. It will also (ii) oversee the design of the event-based sampling, survey, and RCT methods and the behavioral, physiological, and neural outcome measures used in M3-8, and (iii) coordinate their data collection and analysis to ensure high-quality, comparable data. By pooling data on outcome measures and baseline MMBB-MB & MMBB-BB from M3-8, WP2 will (iv) perform a large-scale meta-analysis that maps the effects and mechanisms of music-based methods in developmental and educational settings. Finally, WP2 will bring this knowledge into practice by (v) producing training material (guidelines, MOOC) and organizing training events (lectures, workshops) targeted for students / professionals of the development and education field.

WP3: Music and rehabilitation (led by TS) will answer Q3. To this end, it will (i) lead the development of novel/adapted music therapy and technology-assisted music rehabilitation tools for psychiatric (depression, anxiety, and stress/burnout) and neurological (stroke, dementia) disorders, aimed at optimizing their efficacy and broadening clinical applicability. It will also (ii) oversee the design, methodology, and outcome measures of the RCTs that determine the efficacy of the interventions used in M9-12, and (iii) coordinate their data collection and analysis to ensure high-quality, comparable data. By pooling the data on outcome measures and baseline MMBB-MB & MMBB-BB from M9-12, WP3 will (iv) perform a large-scale meta-analysis that maps the clinical efficacy and mechanisms of music-based rehabilitation in psychiatric and neurological disorders. Finally, WP3 will translate this knowledge into clinical practice by (v) producing training material (guidelines, MOOC) and organizing training events (lectures, workshops) targeted for students and professionals in the fields of music therapy, nursing, and rehabilitation.

WP4: Management and communication (led by PT, TS, MH) aims at systematic and coordinated project management & communication actions. **Management** focuses on (i) successful recruitment of talented research personnel (heeding equality and diversity, see 4.2) and their fluid mobility between JyU and UH; (ii) good control of personnel resources and budget (supported by HR / financial administration services of JyU and UH); (iii) active monitoring of progress and results with regard to expected impacts, deliverables, and milestones; and (iv) identifying new funding and collaboration opportunities. **Communication** focuses on (v) effective *dissemination* of research results to scientific community and stakeholders (e.g., educational and clinical professionals, patient organizations, policy makers) via publications, conferences (see below), and an MMBB website; (vi) broad *communication* of the MMBB and its key findings to the general public via outreach activities (e.g., MMBB science fair), participating in public campaigns (e.g., Brain Awareness Week), and high visibility in printed (newspapers, magazines), electronic (TV, radio, web), and social (e.g., Facebook, Twitter) media; and (vii) opportune *utilization* of the MMBB outcomes for commercial development, improving policies, and tackling societal problems.

Efficient **integration between WPs and modules** will be ensured at several levels: *Data collection*: by designing experiments to comprise common test batteries whenever applicable; *Data sharing*: by using common data sharing and storing platforms (e.g. Funet, Nextcloud); *Information and knowledge sharing*: by utilizing communication and project management platforms (e.g. Teams, Trello) for communication; *Data analysis*: by applying advanced statistical and multimodal fusion methods (see 2.2). *Knowhow sharing:* by organizing regular meetings between the researchers of MMBB. Practical management issues will be led by the **Steering Board** consisting of PT, TS, MH, JE, SS, TK (see 3.1), also including representatives from all personnel groups. The Steering Board will monitor, plan, and further develop the scientific work; facilitate collaboration between WPs and Modules; organize researcher training; and deal with research-related ethical issues. The board will meet virtually once a month and in person twice a year.

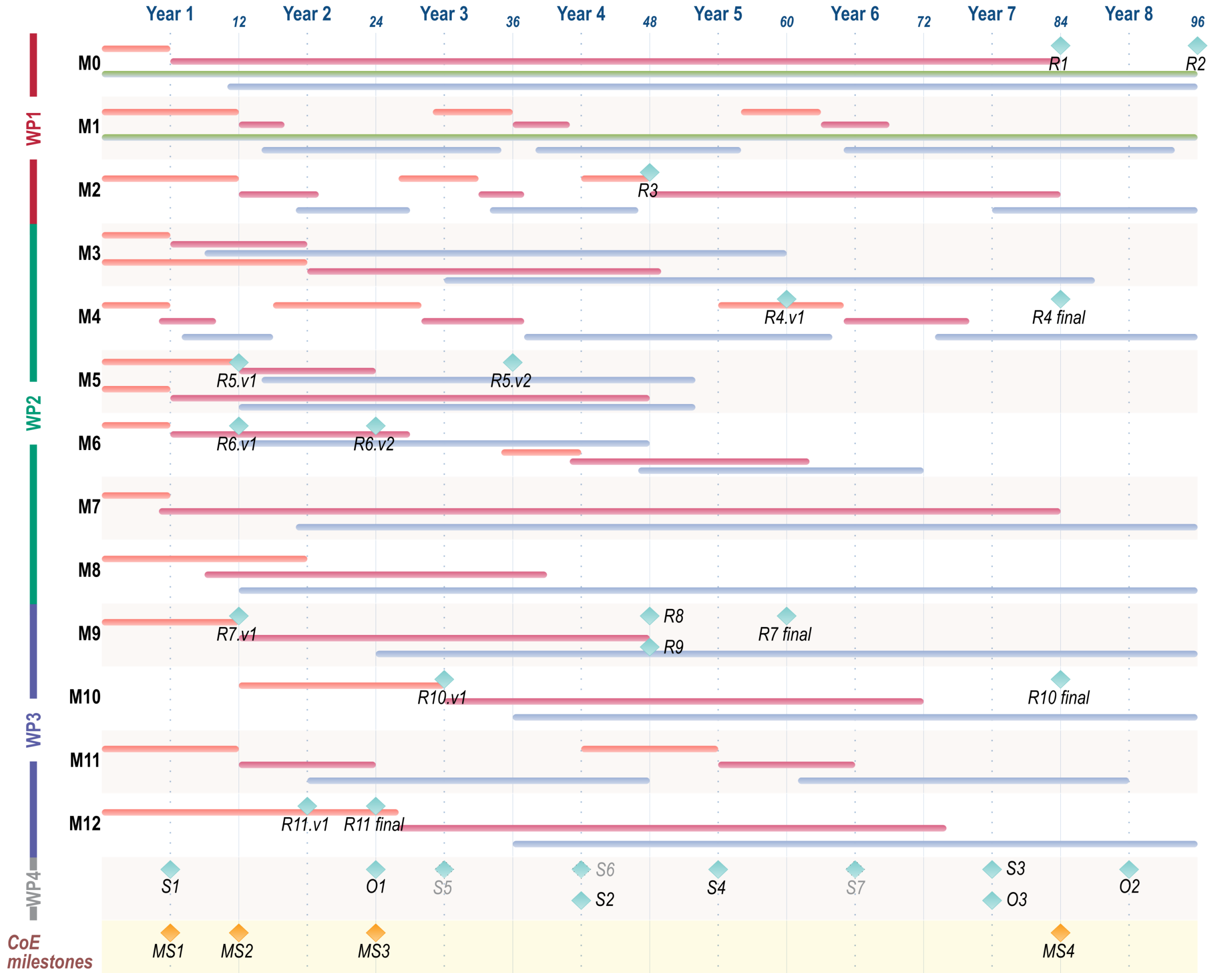


Fig. 3. Schedule of the project, including key non-publication deliverables (turquoise) and CoE-level milestones (yellow). WP = work package. M = module. Tasks: preparation (orange); data collection (red); method development (green); analysis and results (blue).

Project milestones and deliverables. During the funding period we estimate to produce 102 original, 4 methodological, and 31 protocol/review/meta-analysis/theoretical *articles*, of which 11 in high impact factor (IF 8+), 49 in medium-high IF (4-7), and 77 in medium IF (2-3) journals. Additionally, we will implement analysis methods developed in MMBB and publish them on open access platforms (JYX). A breakdown of this output is provided in the Module descriptions (see 2.2). Additionally, we have *CoE-level milestones* and key *non-publication deliverables* as follows (see Figure 3): **CoE milestones (MS).** MS1: MMBB-MB & MMBB-BB batteries design completed (month 6). MS2: All ethical permissions obtained (month 12). MS3: All modules have started the data collection (month 24). MS4: All modules have finalized the data collection (month 84). **Key non-publication deliverables.** ***WP1***. R1: Tools for analyzing acoustical and movement data published (M0, month 84). R2: MMBB-MB dataset released (M0, month 96). R3: Music as Emotional Resource scale released (M2, month 48). ***WP2***. R4: Music-listening interventions for daily health promotion (M4; Version 1 in month 60, final version in month 84). R5: Music-based language learning games (M5; Version 1 in month 12, Version 2 in month 36). R6: Training platform for teachers (M6; Version 1 in month 12, Version 2 in month 24). ***WP3.*** R7: Digital music intervention for persons with dementia (M9; Version 1 in month 12, Final version in month 60). R8: Musical preference mapping tool for dementia care (M9, month 48). R9: Old-time song library for dementia care (M9, month 48). R10: Digital music intervention for stroke patients (M10; Version 1 in month 30, Final version in month 84). R11: Receptive-expressive music therapy method (M12; Version 1 in month 18, final version in month 24). ***WP4.*** *Scientific meetings.* S1-3: Three international symposia (months 6, 42, 78) with the collaborators and SAB members as guest speakers. S4: Summer School focusing on the topics of MMBB targeted for PhD students (month 54). S5-7: Organization of three major international conferences (to be confirmed), namely *Neurosciences of Music* (S5, estimated 2024), *European Music Therapy Conference* (S6, estimated 2025), and *Conference of European Society for Cognitive Sciences of Music* (S7, estimated 2027). *Outreach activities.* O1: Edu-MOOC (month 24, see 5.1). O2: Rehab-MOOC (month 90, see 5.1). O3: MMBB science fair (month 78).

Distribution of personnel resources is itemized in 3.1.

2.2 Research data, materials and methods:

The research questions (see 1.2) will be addressed in **13 implementational Modules** (M0-12, described below), which rely on both laboratory and real world settings. The data collected comprises both **common measures** (included in each Module) and **module-specific measures**. All modules will explore, wherever plausible, the relationships between common measures and module-specific measures.

Common measures: In WP1, we will design the **MMBB Musical Battery** (MMBB-MB, see Fig. 4), which (i) measures basic hearing, perception and memory, rhythmic timing, singing production, movement, and emotion; (ii) comprises both standardized tests and customized tasks developed in WP1 (together with cutting-edge analysis tools); and (iii) is applicable across age (5-90 years) and clinical groups. This large-scale (N= 2000) behavioural data will be used jointly with the module-specific measures (see below) to address Q1.

In a subsample of M1-12 participants (N=500), we will also collect structural and functional magnetic resonance imaging (s/fMRI) data with the 3T Siemens scanners of the HUS Medical Imaging & Advanced Magnetic Imaging centres (UH) and Hospital Nova of Central Finland (JyU) utilizing a common imaging protocol. This **MMBB Brain Battery** (MMBB-BB, duration 30 min) comprises (i) 3D T1 images (MPRAGE, 5 min) and (ii) high angular resolution diffusion images (HARDI, 10 min) as well as fMRI with T2* gradient-echo EPI sequences acquired (iii) in resting-state (5 min) and (iv) while listening to an unfamiliar song (a modern tango) [51] and a self-selected pleasurable song [52] (10 min). This enables us to explore the focal and network-level structural-functional correlates of performance in MMBB-MB and the dynamic neural processing of musical features (combined with MIR) and music-induced pleasure and reward.

Basic hearing (10 min): Audiometry testing (L) Duration discrimination (L)[a] Pitch discrimination (L)[a]	**Perception & memory (20 min):** MBEMA battery (3 subtests)[b]: Scale subtest (O) Rhythm subtest (O) Memory subtest (O)	**Rhythmic timing (10 min):** BAASTA battery (3 subtests)[c]: Unpaced tapping (O) Paced tapping to music (O) Synchronization-continuation (O)
Singing production (5 min): Recorded production tasks for acoustic analysis: Production of vocal tones (L)[d] Singing familiar song alone and along with model (L)[e]	**Musical movement (10 min):** Tasks with MoCap analysis[f]: Unpaced walking (L) Paced walking to music (L) Spontaneous bouncing, swaying and dancing to music (L)	**Musical emotion (20 min):** Tasks based on JyU song library[g]: Recognition of basic emotions from music (L) Emotion induction with music (L, facial movement & ANS recording)

[a]Hyde (2004) *Psychol Sci*; [b]Montreal Battery of Evaluation of Musical Abilities (MBEMA), Peretz (2013) *Front Syst Neurosci*; [c]Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA), Dalla Bella (2017) *Behav Res;* [d]Hutchins (2010) *JASA;* [e]Dalla Bella (2009) *JASA*; [f]Hartmann (2019) *Sci Rep*; [g]Eerola (2010) *Psychol Music*

Fig. 4. MMBB-MB Musical Battery. Duration: 75 min [30 min online (O), 45 min in lab setting (L)].

Module-specific measures: These measures are used to answer the specific research questions of each Module. **Musical (MUS):** Performance in music perception, production, and memory tasks; questionnaires on musical engagement; computationally extracted musical features; and vocal recordings. **Behavioural (BEH):** Performance in non-musical (cognitive, language, motor) tests; mobile experience sampling; and questionnaires on mood, functioning, language development, quality of life (QoL), learning, psychiatric and neurological disorders, social-emotional skills, and psychosocial wellbeing. **Movement (MOV):** Kinematic data using optical MoCap, inertial sensors, or video recordings in individuals and groups. **Neurophysiological (NEU):** Event-related potentials (ERPs) and neural oscillations from electroencephalography (EEG), autonomic nervous system (ANS) responses. **Brain imaging (BRA):** s/fMRI data (grey and white matter volume, structural & functional connectivity, brain activation patterns). **Genetic (GEN):** DNA samples, identification of candidate genes of brain disorders and their associations with neurocognitive measures.

Analysis methods. Associations between data modalities will be analyzed, in addition to standard statistical methods, by means of advanced multivariate methods, such as Bayesian multilevel structural equation modelling, linked and parallel independent component analysis (ICA), canonical correlation analysis (CCA), partial least squares (PLS), and dynamic systems theory.

The 13 Modules (M0-12) are described below. The leader of each module is indicated after the module title in parentheses (see 3.1). Figure 5 shows the involvement of each research team in each module along with the module-specific measure and study type

	Team participation						Module-specific measures	Study types
Module	PT	TS	MH	JE	SS	TK		
M0	PCAR	PCAR	PCAR	PCAR	PCAR	PCAR	MUS, BEH, MOV, BRA	CS
M1	PCAR	P	PR		P		MUS, BEH, MOV, BRA	CS
M2	A	P	PR	PAR	PCAR		MUS, BEH, MOV	CS, LO
M3	PCAR	P	PCAR	PAR	PAR	PC	MUS, BEH, MOV	CS, LO
M4	A	P	PCAR	PCAR	PCAR		MUS, BEH	CS, LO
M5	A	P	PCAR		PAR	PCR	MUS, BEH, NEU	LO
M6	A		PCAR	PA	PCAR		MUS, BEH	LO, RCT
M7	A	P	PCR			PCAR	MUS, BEH, NEU, BRA, GEN	LO, RCT
M8	A	P	PAR	P		PCAR	MUS, BEH, NEU, GEN	CS, RCT
M9	PAR	PCAR		C			MUS, BEH, MOV, NEU, BRA	RCT
M10	PAR	PCAR		P			MUS, BEH, MOV, BRA	RCT
M11	PAR	PCR		PCAR	PAR		MUS, BEH, MOV, NEU, BRA	CS
M12	PAR	PCR	P	PCAR	PAR		MUS, BEH, MOV, NEU, BRA	RCT

Fig. 5. Module-wise team participation matrix; module-specific measure and study types. P=preparation, C=data collection, A=analysis, R=reporting; MUS=musical, BEH=behavioural, MOV=movement, NEU=neural, BRA=brain imaging, GEN=genetic; CS=cross-sectional, LO=longitudinal, RCT=randomized controlled trial.

M0 Neurocognition of music across the lifespan in health and disease (PT, TS)

Background. Different modalities of music (perceptual, cognitive, motor, emotional) have been studied mostly in isolation and in narrow age and clinical groups, using varying methods, which prevents exploring relationships between the domains and across age and different developmental, neurological, and psychiatric disorders. ***Research questions***. *RQ1*: How are perceptual, cognitive, motor, and emotional modalities of music interlinked at behavioural and structural / functional neural levels? *RQ2*: How do these modalities characterize or discriminate different age groups and diagnostic populations? ***Methods***. *Design.* Multicenter cross-sectional study. M0 will finalize the design of MMBB-MB and MMBB-BB batteries, coordinate their data collection in M1-12, develop novel analysis methods for MMBB-MB / Singing Production and Musical Movement tasks and MMBB-BB / music listening task (implemented and released as open-access easy-to-use software), and perform data analysis. *Participants*: N = 2000 (MMBB-MB), N=500 (MMBB-BB), from M1-12. *Measures*: MMBB-MB, MMBB-BB. *Analysis:* Multimodal, multivariate, and multiscale methods to analyze behavioural (test performance), acoustic (MIR), movement (e.g., cross recurrence quantification, cross-wavelet transform), and neural (sMRI: voxel-based morphometry, tractography; fMRI: resting-state and task-based networks, functional connectivity, focal activation patterns) data and their cross-modal associations (e.g., dynamic partial least squares correlation, deep learning) within/between groups. ***Deliverables***. 8 peer-reviewed articles:

6 original, 2 methodological; 1 in high IF, 3 in medium-high IF, and 4 in medium IF journals. Open access software and algorithms for analysis of musical features and movement, MMBB-MB and MMBB-BB batteries and their corresponding datasets.

M1 Rhythmic, social, and collective entrainment in music-induced movement (PT)

Background. The tendency to move to music is regarded as a human universal serving unique social functions [53,54]. Key knowledge gaps in music-induced movement research include effects of age, sensorimotor modalities, group size, interaction type (offline/online), movement nature (choreographed/improvised), and experimental setting (inside/outside lab) on entrainment. ***Research questions and hypotheses***. *RQ1*: What is the influence of age on rhythmic entrainment? *H*: Children entrain less, followed by seniors and adults, respectively. *RQ2*: How does collective entrainment depend on multimodal information presence, interaction type, and group size? *H*: Higher coordination with music present, during imitation, and in group conditions; *RQ3*: How can multimodal interaction in naturalistic environments be quantified? *H*: Markerless-based visuomotor models yield optimal interaction accuracy. ***Methods***. *Design*: Two cross-sectional lab/field studies. Study 1 (locomotion/dance): variance across age groups in full-body rhythmic entrainment. Study 2a (choreographic imitation): effects of auditory condition (no music, metronome, music) and group size on imitation. Study 2b (free dance): the silent disco paradigm (i.e., wireless headphones) for auditory manipulation; the role of sensory couplings (auditory, visual, haptic), explicit leader/follower relations, and group size on actual, self-, and other-perceived interaction. Multiset cross-spectral techniques are devised for data analysis. *Participants*: N = 250, age 5-80 y (movement tasks); N = 300, age 10-80 y (online perceptual study). *Measures*: MMBB-MB, MMBB-BB, marker-based and markerless tracking, musical feature analyses, questionnaires (e.g. personality, perceived interaction). ***Deliverables***. 11 peer-reviewed articles: 8 original, 2 methodological, 1 review; 5 in medium-high IF and 6 in medium IF journals. Open access algorithms.

M2 Defining, operationalizing, and measuring emotional competence through music (SS)

Background. Throughout the lifespan, music offers a resource for emotional awareness and regulation; emotional skills vital for coping, mental health, and social interaction [55]. Yet, scientific knowledge is still limited on how, when, and for whom music engagement fosters emotional competence and health benefits, or, by contrast, negative outcomes. ***Research questions and hypotheses***. *RQ1*: How can emotional competence-oriented music use be validly defined and measured? *H*: Latent variable approaches, informed by qualitative work, can achieve a valid and reliable scale of emotional competence through music. *RQ2*: How does emotional competence through music vary across individuals and contexts? *H*: Sociocultural background determines how music functions as a resource; music contributes to emotional competence more in youth than adults/seniors; *RQ3*: Does emotionally competent use of music support emotional wellbeing? *H*: Competent uses of music buffer against rumination, avoidance, and self-blame and support emotional wellbeing. ***Methods***. *Design*: Study 1 is an interview study to afford conceptual insight into music as a catalyst for emotional competence in different populations (culturally diverse, minorities, age groups). Study 2 includes surveys designed to construct and validate a modular *Music as Emotional Resource (MER) scale*. Study 3 is a longitudinal (3-year) survey using MER to track dynamic relations between emotional competence- or incompetence-oriented music use and social-emotional outcomes. *Participants*: age 15-80 y; N=50 (Study 1); N=500 (Study 2); N= 500 (Study 3). *Measures*: MMBB-MB & MMBB-BB, self-reports, music feature analysis, scale development through reliability tests and convergent and discriminant validity testing, latent growth models for longitudinal data. ***Deliverables***. 9 peer-reviewed articles: 8 original, 1 review; 2 in medium-high IF and 7 in medium IF journals.

M3 Corporeal and affective social entrainment in people with and without autism (PT)

Background. Entrainment refers both to rhythmic synchrony with another person and to physiological and psychological processes which create shared affect. Corporeal and affective entrainment are believed to play important roles in music cognition [56], and both relate to social-cognitive functioning (SCF). Notably, both social functioning and the two modes of entrainment are disrupted in autism spectrum disorders (ASD) [57]. Still, the associations between corporeal and affective entrainment and social functioning remain poorly understood. ***Research questions and hypotheses***. *RQ1:* How do corporeal and affective entrainment develop over the lifetime and how do they relate to SCF, in people with and without ASD? *H:* Entrainment and SCF will correlate, developing most in childhood and youth, stabilizing in adulthood, mildly deteriorating in old age. *RQ2:* How does early music engagement relate to the development of entrainment and SCF? *H:* Early childhood music classes enhance entrainment and SCF in children with and without ASD (incl. those diagnosed later). ***Methods***. *Design*: Study 1: Cross-sectional study of sensorimotor and affective entrainment and social cognition. Dyads aged 5-80 y (N = 150) with ASD subgroup (N = 40) are recorded using MoCap while joint drumming, singing, and dancing, and assessed using age-appropriate SCF measures. Study 2: Longitudinal study, children aged 3-4 y (N = 120), with ASD subgroup (N = 20), receive entrainment-focused music in preschool. Controls: non-rhythmic movement group, passive control group. 2-y intervention (1-2 cohorts). *Measures*: MMBB-MB, MoCap, accelerometers, heart-rate variability, sociocognitive measures. ***Deliverables***. 11 peer-reviewed articles: 8 original, 3 methodological; 1 in high IF, 3 in medium-high IF, and 7 in medium IF journals.

M4 Music in everyday health and self-regulation (SS)

Background. Music serves as a relaxing, motivating, and atmosphere-creating soundtrack for daily life. While people actively use music to mitigate perceived loneliness, manage stress, and support desired energy levels [58], evidence is lacking on the interplay of individual, situated, and musical determinants of the efficacy of music to achieve such self-regulatory goals. ***Research questions and hypotheses***. *RQ1*: How and when music helps to manage loneliness, stress, and diurnal rhythms of sleep and awakeness? *H*: Social surrogacy, emotion-evoking, arousal modulating, and movement-inducing qualities of music function as impact mechanisms. *RQ2*: Do short-term music listening interventions increase capacity to manage loneliness, stress, and stable and sufficient sleep cycles? *H*: Short-term music-listening interventions significantly reduce perceived loneliness, stress, and sleep cycle difficulties, especially in youth. ***Methods***. *Design*: Study 1: Focus-group interviews to identify self-perceived determinants of music's efficacy in self-regulation. Study 2: Mobile Experience Sampling Method (m-ESM) to measure moment-to-moment changes in self-reported stress, arousal, and loneliness as a result of music listening episodes; design and implementation of a personalized recommendation system for using music in daily health promotion. Study 3: Three two-arm (test group - control group) RCTs to study short-term (1-month) music-listening interventions for combating loneliness, stress, and disturbed sleep cycles. *Participants*: Adolescents and adults (age 15-80 y). Study 1: N=40, Study 2: N=300, Study 3: N=360. *Measures*: MMBB-MB, interviews, surveys, m-ESM reports with music tracks, self-reports of stress, sleep quality, and perceived loneliness, qualitative analysis methods, music feature analyses, multivariate statistics. ***Deliverables***. 10 peer-reviewed articles: 8 original, 2 reviews; 2 in medium-high IF and 8 in medium IF journals. Open access implementations of the personalized recommendation system.

M5 Impact of musical interventions on language learning at school (MH)

Background. In educational contexts, the efficacy of music exposure has been shown in several domains, especially in modulating auditory brain functions and processes [12]. Conversely, language training has been shown to accelerate music sound processing [59]. There is a need to investigate the interplay between various musical dimensions and language learning effects, and study the moderating role of native language upon the possible impact of music on language learning (native and English). ***Research questions and hypotheses***. *RQ1*: How do different aspects of music (rhythm, melody, movement) used in language learning games and group activities (native and in English) affect learning? *RQ2*: Is the effect mediated by native language type (quantitative Finnish, tonal Mandarin Chinese) *H:* The effects of music and language training differ depending on native and target language properties, type of activity, and aspect of music. ***Methods***. *Design*: Study 1: Language learning games for word recognition and for pronunciation in native language and English, utilizing different musical dimensions (rhythm, melody, harmony), a control game without music, and a passive control group. Study 2: Active group music settings and active control groups (traditional language lessons and arts). *Participants*: Children aged 3-6 y (N=60) and 7-12 y (N=200) from Finland and China. *Measures*: MMBB-MB, language skills (data from the games, language testing). ***Deliverables***. 8 peer-reviewed articles: 6 original, 2 reviews; 2 in medium-high IF and 6 in medium IF journals. Guidelines for game design and group activities to promote language learning and 4 games made available for free for language learning.

M6 Empowering educators with musical methods for teaching (MH)

Background. Many teachers feel that their competence for using music in educational settings is low [60]. The effects of equipping four teacher groups (early childhood educators, class teachers, special education teachers, and science and math teachers) with musical skills and scientific evidence on the effects of music are therefore investigated. ***Research questions and hypotheses***. *RQ1*: Does a music training programme (MTP) in teacher education increase musical competence and lead to more extensive use of musical activities in teaching? *H:* MTP will lead to increased competence and use of musical activities in all teacher groups. *RQ2*: What are the effects of an increase of musical methods (MM) upon pupil learning? *H:* The increase of MM in teaching increases pupils' motivation, engagement and agency. ***Methods***. *Design*: MTPs will be designed to support teacher's capacity to use music, tailored to the four teacher groups. MTPs will be implemented at UH and JyU and will include singing and body percussion, accompanying instruments, and music technology, addressing musical competence as collaborative, creative and participatory action. *Participants*: Teacher students (Part 1, N=60 + exchange students N=20), in-service teachers (Part 2, N=80), and their pupils (N=1600). *Measures:* Teacher students' and in-service educators: MMBB-MB, confidence of musical competence, use of MM in teaching, views on MM's possible benefits before and after the different types of training. Pupils: questionnaires, teacher reports, self-reports for motivation, engagement and agency (pre, during, post the adopted MM in teaching). ***Deliverables***. 9 peer-reviewed articles: 6 original, 3 review/position papers (national); 2 in medium-high IF and 7 in medium IF journals. Visibility in 10 media appearances targeted for teachers, open international training platform for in-service teachers with separate MOOCs for the four teacher groups, 1 book for teachers.

M7 Origins of language development deficits and the influence of music (TK)

Background. Language and literacy skills, vital for interaction and learning, develop inadequately in LDD (developmental dyslexia and developmental language disorder; prevalences 7-10%), compromising learning and career [61]. Their origins are still debated due to their complex geno- and phenotypes, necessitating a test of the prevailing phonological and implicit-learning deficit hypotheses with multimethodological, developmental, and longitudinal approaches and the influence of music on these deficits. ***Research questions and hypotheses***. *RQ1*: How do familial LDD risk and environmental issues including music activities influence language development from birth to school-age? *H*: The developmental path in LDD is influenced both by the genetic makeup and protective environmental factors such as music. *RQ2*: Which perceptual-cognitive deficits most strongly underlie LDD and how does music alleviate them? *H*: Phonological and implicit processing deficits are key problems. *H*: Vocal music improves language and reading-skill development by particularly supporting phonological processing. ***Methods***. *Design*: Developmental longitudinal (DL, from birth to school-age, ongoing) and longitudinal (L) projects.

Vocal music or placebo intervention for 6 months after birth (DL)/in the 1st grade (L). *Participants*: Age 7-8 y; Typically developing children (N=50, DL/100, L), children with LDD (N=100, L), or LDD risk (N=150, DL). *Measures*: MMBB-MB, MMBB-BB, speech-elicited ERPs in paradigms applicable since birth developed at CBRU; neuropsychological, language, reading-skill, and DNA tests; questionnaires. ***Deliverables***. 13 peer-reviewed articles: 11 original, 2 reviews; 3 in high IF, 7 in medium-high IF, and 3 in medium IF journals; also 2 publications for interest groups and general public.

M8 Language development deficits and early interactive music intervention (TK)

Background. The foundations of speech and reading skills are laid in infancy. LDDs compromise their early development [61], particularly phonology. Music interventions have shown promise in language rehabilitation in typically developing and dyslexic children [62], but large-scale RCTs with small children and those at risk for LDDs are lacking. Such studies are vital to design effective, optimally targeted preventive interventions. ***Research questions and hypotheses***. *RQ1:* What are the effects of a social and active music intervention versus a similar non-musical intervention on early language development? *H*: Music intervention is superior for language development. *RQ2*: What is the role of parental well-being and parent-child interaction in these effects? *H*: Increased parental well-being and parent-child interaction partly explain the improved language. *RQ3:* How are these effects influenced by LDD risk and timing of the intervention? *H:* Effectiveness of the intervention may depend on the type and extent of LDD risk. *H:* intervention may support different functions at different ages, e.g. phonology more in infants than toddlers; beneficial effects on toddlers may be more wide-ranging overall due to their greater ability to participate actively. ***Methods***. *Design:* Two-arm RCT. *Participants:* Typically developing (N=30+30) and LDD risk (N=30+30) infants (age 6-12 m) + toddlers (age 12-18 m), total N=240. *Measures:* behavioural (reading + language tests, interviews, questionnaires), speech-elicited ERPs, DNA tests. ***Deliverables***. 8 peer-reviewed articles: 6 original, 2 review/position papers; 2 in high IF, 3 in medium-high IF, and 3 in medium IF journals; also 3 publications for interest groups and general public.

M9 Optimizing the use of music in residential and home dementia care (TS)

Background. Dementia prevalence and its societal burden is growing quickly as the population ages. Music is an effective tool for supporting cognition and mood in dementia [5,31], but its real-life availability in dementia care and understanding of why it works are still poor. Digital music interventions may provide a cost-effective solution for using music across the care continuum. ***Research questions and hypotheses***. *RQ1:* Can a novel digital music intervention (DMI) support cognitive/emotional wellbeing in different stages of dementia (mild to severe)? *H:* DMI and conventional music therapy (CMT) improve mood and QoL in all stages and cognition (memory) in mild stages compared to standard care (SC). *RQ2:* How is music cognition affected in different stages of dementia and does it mediate the efficacy of music interventions? *H:* Musical emotions and memories are preserved in all stages and linked to better efficacy. ***Methods***. *Design*: 9-month, three-arm RCT. *Participants*: 180 persons with dementia (age 60-90 y) who have moderate-severe dementia and live in a care home (N=90) or mild dementia and live at home (N=90), randomized to DMI, CMT and SC groups, and healthy controls (N=30). *Intervention*: Group music sessions (10 weeks, 2 times/week) with receptive (listening) and active (singing, movement) components [31] implemented live by a music therapist or live / virtually using an interactive HILDA digital music platform developed together with a company (Kardemummo). *Measures*: MMBB-MB, MMBB-BB, neuropsychological tests, questionnaires (mood, QoL, QALY, burden), EEG-ANS responses to sound changes and music. ***Deliverables***. 12 peer-reviewed articles: 9 original, 3 review/position; 2 in high IF, 5 in medium-high IF, and 5 in medium IF journals; also 5 publications for interest groups and general public. Music-based dementia care tools (DMI, musical preference mapping tool, old-time song library).

M10 Efficacy of mobile music technology in stroke rehabilitation (TS)

Background. Music-based interventions using receptive (music listening) and expressive (instrument playing, singing) components can enhance cognitive, emotional, motor, and speech recovery after stroke [5,29,30]. In practice, the use of music in stroke rehabilitation is still uncommon due to lack of resources and expertise. There is a need for a unifying music intervention platform that would be easily and widely applicable, customizable, and cost-effective. ***Research questions and hypotheses***. *RQ1:* Can a novel multicomponent music intervention enhance motor, speech, cognitive, and emotional recovery after unilateral stroke? *H:* Music intervention enhances recovery more than standard care. *RQ2:* What neural mechanisms explain its efficacy? *H:* Rehabilitative effects are linked to neuroplasticity changes in targeted auditory-motor, language, and fronto-limbic networks. ***Methods***. *Design*: 6-month, two-arm RCT. *Participants*: 100 subacute/chronic stroke patients (age 30-80 y) with left (N=50) or right (N=50) lesions, randomized to music intervention and standard care control groups. *Intervention*: Music intervention (8 weeks, 5 times/week) utilizing a tablet computer, headphones, wearable KAiKU music glove/strap; four apps for music listening (streaming) and training of hand/arm movements (using real-time musical feedback), speech (using singing-based training), and attention and executive function (using playing-based training), developed together with companies (Careus, Outloud). *Measures*: MMBB-MB; MMBB-BB (also motor task-fMRI); motor, cognitive and language tests; questionnaires (mood, functioning, QoL, QALY). **Deliverables**. 12 peer-reviewed articles: 9 original, 3 review/protocol; 2 in high IF, 5 in medium-high IF, and 5 in medium IF journals; also 3 publications for interest groups and general public. Digital music intervention platform for stroke rehabilitation.

M11 Multimodal interaction in music therapy for social communication challenges (JE)

Background. Diverse client needs are met in music therapy (MT) by taking advantage of different interaction modalities and types of musical engagement. The populations most frequently served by MT include major depressive disorder (MDD) and autism spectrum disorders (ASD) [63], which have in common communication and social connection difficulties. However, research is limited by small sample sizes, incomplete understanding of multimodal processes, and lack of comparisons between MT settings, activities, and diagnostic populations. ***Research questions and hypotheses***. *RQ1*: How do different client-therapist interaction modalities relate to developmental, cognitive, emotional, and demographic features of clients? *H*: Clients with a more severe condition will exhibit lower interaction with therapists. *RQ2*: What is the effect of different MT activities upon psychological, behavioral and physiological descriptors of clients? *H*: Clients with ASD and MDD will display positive outcomes after playing and listening to music. *RQ3*: How do individual and group MT differ for psychiatric and developmental populations? *H*: Lower symptom severity in ASD and MDD predicts positive outcomes in group MT. ***Methods***. *Design*: Two cross-sectional mixed methods studies (1. MDD, 2. ASD), following a 3 x 2 within-subject factorial design: three MT activities (music improvisation, music listening, and playing pre-composed music) and two single-session therapy settings (individual/group), in randomized order. *Participants*: N=125, age 16-80 y (MDD); N=125, age 5-80 y (ASD). *Measures*: MMBB-MB, MMBB-BB; musical, movement, and physiological (HRV) measurements; mood and arousal level following each MT activity; diagnostic questionnaires; post-session interviews. ***Deliverables***. 10 peer-reviewed articles: 8 original, 2 reviews; 4 in medium-high IF and 6 in medium IF journals.

M12 Effectiveness of music therapy for the treatment of mood disorders (JE)

Background. Several systematic reviews suggest that music therapy (MT) is effective in the treatment of mood disorders [4]. However, receptive (music listening) and active (music improvisations) methods have mostly been studied separately from each other, and their combination has been neglected. Furthermore, psychiatric outcome measures have been overemphasized, whereas discipline-specific indicators (musical, kinematic, physiological measures; participant perspectives) have been underused. Lastly, there is a need for larger sample sizes and more coherent clinical approaches. ***Research questions and hypotheses***. *RQ1*: What is the effect of different MT methods (active, receptive, combined) upon mood disorder symptoms? *H*: Significant overall effect of mood disorder treatment favouring the combined MT group, followed by the receptive group and the active group, respectively. *RQ2*: How do psychiatric outcome measures and MT-specific process and outcome indicators (subjective client experiences, and multimodal client-therapist interaction) relate to each other? *H*: Clinical improvement associated with higher musical and kinematic interaction, higher HRV, and positive client experience at the end of therapy. ***Methods***. *Design*: Three-arm RCT, 3-month intervention with two follow-up points (3 months and 1 year). *Participants*: 240 patients with depression, anxiety, burnout, stress-related disorders (age 18-65 y). *Intervention*: Active, receptive, and combined (active-receptive) music therapy (12 sessions, 2 times/week). Measures: MMBB-MB, MMBB-BB, psychiatric outcome measures, MT-specific process and outcome indicators. ***Deliverables***. 10 peer-reviewed articles: 9 original, 1 protocol paper; 3 in medium-high IF and 7 in medium IF journals. Two publications for MT professionals and general public online.

2.3 Risk assessment and alternative implementation strategies:

Participant recruitment and drop-out prevention. Crucial challenges for the success of the work plan are recruiting a sufficient number of subjects (especially from clinical populations), keeping them motivated to adhere to study protocols and follow-ups (in longitudinal studies), and carrying out the outcome measures successfully. We will overcome these challenges by working with large educational/clinical units and third-sector patient organizations to enable wide-scale, efficient recruitment, and we will plan the studies to be highly motivating. They will be executed by experienced music professionals, together with trained research personnel and educational/clinical staff by utilizing robust, previously tested outcome measures and experimental paradigms. Typically, music intervention studies have very low drop-out rates [19]. We have also developed means to enhance the commitment of the participants and thus have had low drop-out rates. The PIs have extensive experience of music studies in healthy and clinical populations as well as active collaborative networks in the educational, cultural, and health care fields, which is crucial for the successful implementation of the work plan. If the COVID-19 related restrictions with study subjects persist to the CoE period, we will carry out a mitigation plan that we have developed based on international expert recommendations [64,65]. In addition, we will consider alternative implementation of the studies using online experiment platforms at JyU & UH, on which we already have technical readiness and expertise. The music interventions can also be delivered virtually using video communication or as home-based / remote rehabilitation.

No positive results on the effects of the music interventions: Intervention trials may not yield expected outcomes. In our studies, this risk is mitigated by (i) strong proof-of-concept for benefits of music from previous studies, (ii) carefully designed protocols and implementation of interventions (therapists, components, frequency, intensity, etc.), (iii) adequate sample sizes (power), and (iv) extensive outcome evaluation (primary & secondary) covering all potential effects. Also, (v) clinical and demographical factors of responders and non-responders can guide further subgroup analyses which may show significant effects. Finally, even if interventions yield null results (not expected), the data provides valuable results for the fundamental research objectives (Q1).

Challenges of naturalistic paradigms. *Naturalistic music stimuli* are complex and multidimensional, which in some cases may render difficult to disentangle the contributions of individual elements to the measured responses. However, our team's level of experience in dealing with such complexity is exceptional, as evidenced by previous publications [51,66]. Methods to deal with this complexity include dimensionality reduction, feature selection (also based on perceptual tests), cross-validation, and follow-up experiments with more controlled settings based on collinearity analyses. Using a *naturalistic procedure* is challenging. For instance, free movement to music often contains high between-subject variability in a high-dimensional feature space. To obtain common patterns from these data requires careful pre-processing, including transformations to proper frames of reference and suitable dimensionality reduction. Again, our team is experienced in dealing with this variation [25,67,68].

2.4 Research environment:

University of Jyväskylä allocates strategic funding for the CoE. The amount of the funding is 200.000 € per year during the funding period of the CoE. The usage of the strategic funding is flexible and it may be used from the beginning of the CoE and as exit funding (years 2030-31) to enable a controlled transfer of CoE impact to the society. The research environment at the Department of Music, Art and Culture Studies of JyU has been purposefully developed and includes, among other things, a motion capture laboratory (80 m2) with a 15-camera Qualisys optical motion capture system, a 64-channel electroencephalograph (EEG) system, two music therapy clinics, and a professional-quality recording studio. JyU is committed to fund the development of this infrastructure by 100.000 € per year. Additionally, JyU hosts an MEG scanner and will have access to a 3T MRI scanner at Hospital Nova of Central Finland.

University of Helsinki / Faculty of Medicine is committed to support the CoE, both with research infrastructure and funding (80.000 € per year during CoE period, applicable also as exit funding 2030-2031). The research environment comprises the state-of-the art research facilities of the Department of Psychology and Logopedics and the Cognitive Brain Research Unit (CBRU), an internationally distinguished centre for cognitive neuroscience, which has several times been in a CoE. CBRU laboratories are equipped with several high-resolution and mobile EEG systems, coupled with integrable transcranial magnetic stimulation (TMS), autonomic nervous system (ANS), and eye-tracking devices, and behavioural measurement systems. CBRU also has excellent technical and IT support, access to MEG and 3T MRI scanners at the nearby HUS Medical Imaging Centre and AMI Centre, and close contacts to the pediatric, psychiatric, neurological, and geriatric clinics of the HUS district.

University of Helsinki / Faculty of Education commits to support CoE by offering the research infrastructures, via strategic funding (50.000 €/year for 8 years, applicable as exit funding until 2031), and via opening positions to the CoE topic area. The faculty has been ranked as the highest European non-English-language faculty of education [69] due to its multidisciplinary, high-level research environment comprising 4 mobile EEG and >50 ANS equipment used in schools and kindergartens, two teacher-training schools committed to host interventions and data collection, and well-equipped observation classrooms. The faculty is also a founding member of Helsinki Institute for Social Sciences and Humanities (HSSH). HSSH is a new strategic profiling action of the University of Helsinki creating an internationally pioneering multidisciplinary research environment for data-intensive research and methodology development in social sciences and humanities.

3 Applicant, research team and collaborators

3.1 Project personnel and their project-relevant merits:

Petri Toiviainen (JyU, CoE Director, Prof. of Music, PhD in Musicology in 1996) is an expert in naturalistic research on music-induced movement and music-evoked brain responses as well as complex multivariate methods, and has 165 refereed publications (7800 citations, h index 43, Google Scholar GS). He was the leader of Finnish CoE in Interdisciplinary Music Research (2008–13) and held an Academy Professorship (2014–18). **Teppo Särkämö** (UH, CoE Deputy director, Subproject leader, Assoc. Prof. of Neuropsychology, PhD in Psychology in 2011) is an expert in neuropsychology, clinical cognitive neuroscience, and music-based rehabilitation, and has 68 refereed publications (3256 citations, h index 25, GS). He has been awarded the Cortex Prize (FESN, 2017) and an ERC Starting Grant (2018) for his pioneering studies on music, ageing, and neurological rehabilitation. **Minna Huotilainen** (UH, Subproject leader, Prof. of Educational Sciences, PhD in Acoustics and signal processing in 1997) is an expert in educational neuroscience and the effects of music on the brain and learning and has over 170 refereed publications (13 000 citations, h index 64, GS). She has been awarded J.V. Snellman Prize and Sokrates Prize for her societal impact. **Jaakko Erkkilä** (JyU, PI, Prof. of Music Therapy, PhD in Music Therapy in 1997) is an expert in clinical music therapy with qualifications as clinical music therapist and psychotherapist (advanced level). He has conducted RCTs on improvisational music therapy and developed music therapy intervention models. He has 36 refereed publications and 83 other publications (3100 citations, h index 21, GS). **Suvi Saarikallio** (JyU, PI, Assoc. Prof. of Music Education, PhD in Music Education in 2007) is an expert of music as emotional development, self-regulation and youth wellbeing. She has 68 refereed publications (3260 citations, h index 27, GS). She has pioneered in constructing conceptual models and psychometric assessment scales of music as emotional and health-relevant behavior. **Teija Kujala** (UH, PI, Prof. of Psychology, PhD in Psychology in 1996) is an expert in neural basis of language, its developmental disorders, learning, and plasticity. She is the Chair of Cognitive Brain Laboratory, an UH infrastructure, and shares the Directorship of Cognitive Brain Research Unit (CBRU). She has been awarded the Philips Nordic Prize for research within neurodevelopmental disorders. She has 167 refereed publications (11570 citations, h index 62, GS).

Led by the 6 PIs, the core research personnel of MMBB is from four research groups: Finnish Centre for Interdisciplinary Music Research (FinMus, JyU); Brain Music and Learning (BML, UH); Music, Ageing and Rehabilitation (MART, UH); and Neuroplasticity of Language (NeoLanG, UH). The PIs' teams comprise the following members: **Team PT**: 3 PhDs (Martín Hartmann, Marc Thompson, Iballa Burunat), 3 doctoral students (DS); **Team TS**: 3 PhDs (Aleksi Sihvonen, Noelia Martinez-Molina, Lilli Kimppa), 5 DS; **Team MH**: 3 PhDs (Mari Tervaniemi, Tanja Linnavalli, Caitlin Dawson), 2 DS; **Team JE:** 3 PhDs (Emily Carlson, Olivier Brabant, Esa Ala-Ruona), 3 DS; **Team SS**: 4 PhDs (Geoff Luck, Henna Peltola, Margarida Baltazar, Will Randall), 3 DS; **Team TK**: 2 PhDs (Paula Virtala, Sari Ylinen), 4 DS. In addition, the teams have access to sufficient laboratory engineer workforce. We will actively apply for funding from other sources, including ERC and foundations.

The strength and synergy of the MMBB comes from the combination of high-level research experience and advanced methodology of its PI partners and teams on (i) music cognition, psychology, and therapy (JyU); (ii) musical development, learning, and education (UH Faculty of Education), and (iii) musical deficits and rehabilitation, neuropsychology, and clinical neuroscience (UH Faculty of Medicine), which is highly complementary and enables the fluent translation of fundamental and applied music research from the laboratory to both educational and clinical settings. Especially the expertise and pioneering work of JyU in developing cutting-edge tools for analyzing musical features, movement kinematics, and emotions (e.g., MIR and MoCap Toolboxes [70,71], soundtrack datasets [72]), neuroimaging of natural music processing [17–19,51], and music therapy applications [26,27] makes it very feasible to adapt and expand these methods for the large-scale educational and clinical studies in WP2-3, led by the UH partners. Crucially, the expertise of UH partners in longitudinal developmental, geriatric, and intervention studies employing diverse brain research methodology (e.g., EEG, MEG, s/fMRI) enables exploring the neurobiological and -plasticity effects of music across the life-span. The JyU and UH teams have a long-standing and prolific collaboration, including many joint publications and PhD supervisions.

3.2 Collaborators and their project-relevant key merits:

Scientific collaborators. The MMBB will collaborate with esteemed experts representing a wide interdisciplinary spectrum, including members of **two Nordic Centres of Excellence**: Music in the Brain at Aarhus U. (Elvira Brattico, brain correlates of music processing), and RITMO at Oslo U. (Olivier Lartillot, computational musical feature analysis). Additionally, our collaborators include leading **music psychologists**: Laurel Trainor (McMaster U.; musical development), Marcel Zentner (U. of Innsbruck; music and emotion), and Peter Keller (Western Sydney U.; entrainment and interaction) as well as experts on **music and language** (Paul Iverson, UCL; Tao Sha, Beijing NU). Furthermore, we collaborate with reputed **neuroscientists**: Antoni Rodríguez-Fornells (U. Barcelona; neuroimaging, music-based rehabilitation), Simone Dalla Bella (U. of Montreal; music motorics, singing, Parkinson's disease), and Istvan Winkler (Hungarian Acad. Sci.; auditory perception). Finally, our collaborator group incorporates experts on **music therapy research** (Jos De Backer, KU Leuven) and **molecular genetics** (Juha Kere, Karolinska Institutet). Their detailed contributions and commitment letters are in the electronic application form.

National educational/clinical collaborators. Psychiatry, neurology, neonatal, and geriatrics units of the Hospital Districts of Helsinki-Uusimaa (HUS), Central Finland (KSSHP), and Southwest Finland (VSSHP); National third-sector organizations [Finnish Brain Association (Aivoliitto), Alzheimer Society of Finland (Muistiliitto), Finnish Parkinson Association (Parkinsonliitto)], Finnish Society for Music Education (FiSME); Education, social services, and health care divisions of Cities of Helsinki, Espoo, Vantaa, and Jyväskylä; Department of Phoniatrics, Helsinki University Hospital. **Industrial collaborators:** Finnish SME companies developing language learning, recreation and rehabilitation applications and services (Hokema, Outloud, Careus, Sentina, Kardemummo, [73–77]).

4 Responsible science

4.1 Research ethics:

The implementation adheres to the General Data Protection Regulation (GDPR), the Finnish (TENK) and European (ALLEA) guidelines on research integrity. Participation is voluntary, free of cost, and based on informed consent (from the subject and/or legal guardian). The freedom, integrity, and autonomy of all participants are respected throughout the studies, and data collection is performed in close collaboration with child participants' professional and family caregivers. At each step, the participants' willingness to continue participation is ensured and they are monitored for signs of discomfort; withdrawal from study is possible at any point and will not affect the treatment of the persons. The methods are safe and non-invasive and involve no harmful stimuli or procedures. All collected data is used only for research purposes, always retaining the anonymity of the subjects. The research protocols are reviewed by the ethical boards of the universities and hospital districts in Helsinki and Jyväskylä prior to onset of data collection. We will pre-register hypotheses, methods, and analyses on the Open Science Framework [78]. Additionally, all clinical trials will be registered in an international trial registry (e.g., [79]).

4.2 Equality and non-discrimination:

Gender balance within MMBB is equal with female/male ratio exactly 50/50% in PIs and about 50/50% in all personnel. Our PIs represent different career stages from early associate professor to experienced full professors. Our recruitment processes promote multifaceted diversity and equality. All personnel will receive equality and non-discrimination training. Decision making in the consortium is open, with regular meetings for all personnel, and with representatives from all personnel groups in the steering board. A regular feedback system is used, and a dedicated whistleblower channel will be implemented for the consortium. The impact of our research on society increases equity in terms of wellbeing, societal understanding, and participation in education for many marginalized groups including individuals with, e.g., autism, dyslexia, delayed language development, and immigrant background. We produce MOOCs, books and courses for different groups of professionals to be used in their work for equality and non-discrimination.

4.3 Open science:

Publication and dissemination plan. During the funding period we estimate to produce 103 original, 23 review, 1 protocol, and 4 methodological *articles*, of which 73 will appear in medium IF (2-3), 44 in medium-high IF (4-7), and 11 in high IF (8+) journals; a large (N=2000) multimodal *dataset*; and open-access *software* for data analysis. Given our previous publication record and the impact of the studies, we have good chances of publishing in top-level journals of the field (e.g., *Nat Neurosci*, *PNAS*, *Brain*, *Curr Biol*). The most important papers will be published as open access (gold OA) and all papers will be deposited in the repositories (green OA) of JyU (JyX) and UH (Helda). The obtained results will also be disseminated in (i) major conferences in music (e.g., ICMPC-ESCOM, NeuroMusic), neuroscience (e.g., SfN, OHBM), education (e.g., AERA), neurology (e.g., ESO-WSO) and geriatrics (e.g., AAIC), (ii) targeted lectures and non-refereed publications for non-academic stakeholders such as patient NGOs (e.g., Aivoliitto, Muistiliitto), educational and cultural organizations (e.g., SMOL national music teachers' union, SML association of Finnish music schools), and the general public, and (iii) generally in printed, electronic, social media, and a dedicated MMBB website.

Data management. ***Data collection:*** The collected data comprises both non-digital data (e.g., tests, questionnaires) and digital data (motion capture, EEG, and s/fMRI data, audio and video recordings) collected at the educational / clinical units and at the research labs in Jyväskylä and Helsinki. ***Data use:*** Data are used for research purposes only, retaining the anonymity of the subjects. ***Data storage and protection:*** Data are pseudonymized (ID-coded), handled confidentially, and stored in locked rooms and cabinets and/or in password-protected computers with up to date firewall and virus protection and encrypted hard drives at the research units, and can be accessed only by research team members. Online data transfer is made using encrypted and secure connections. Data are backed-up in a network-attached storage (NAS) space designed for sensitive data. Data storage time is 10 years after which data are archived in anonymized format. ***Data availability:*** To enable wide utilization and replicability, data collected in the Modules and scripts used in the analyses will be made openly available upon the publication of the results when possible, utilizing common platforms (e.g., [80,81]). The FAIR Guiding Principles for scientific data management and stewardship [82] will be followed. ***Data ownership:*** Data are fully owned by the host institutes (JyU, UH) and managed by the PIs. There are no IPR issues, with the exception of gaming studies. The management of game IPR will be established in the Consortium Agreement (CA), respecting the principle that IPR belongs to the generator of each idea.

4.4 Sustainable development objectives:

The outcome of the MMBB research will be highly valuable in promoting (i) equal prospects for well-being, (ii) a participatory society for all, and (iii) a sustainable society. First, the MMBB research can help in optimizing the way music, as an affordable and ubiquitous resource, is used in supporting health and functional capacity and enabling better QoL and lifelong learning, also in persons with a developmental, psychiatric, and neurological disability. Second, by mapping the musical capacities of persons with disability and uncovering the ways music can be used to enrich their lives, MMBB research supports human dignity, equality, tolerance, and the human right to participate in cultural activities. Finally, by fostering the development of new music-based tools for communities, MMBB research strengthens social cohesion and the creation of pleasant and healthy living environments. All activity in the MMBB will be resource-wise and we have committed our actions towards carbon-neutral and sustainable solutions for research by, for example, restricting excessive travel (e.g., by virtual meetings) and use of materials.

5 Societal effects and impact

5.1 Effects and impact beyond academia:

Rehabilitative impact: Psychiatric and neurological disorders carry a massive individual and societal burden; depression, anxiety, stroke, and dementia are among the leading causes of disability [83]. The prevalence of these disorders is rapidly growing, posing a huge challenge to the already strained health care system. Language and developmental disorders are also pervasive, threatening educational and career paths and leading to alienation from the society. We will optimize existing music therapy and rehabilitation methods to make them more effective and easily and widely applicable, which can greatly increase their clinical use world-wide. To ensure translation from laboratory to clinic, we will (i) work with pediatric, psychiatry, neurology and geriatric units and patient organizations in all stages of WP3; (ii) disseminate our findings to stakeholders and general public through non-refereed publications, lectures, and open courses (MOOC); and (iii) integrate the methods to the training programs of music therapists and rehabilitation/care personnel.

Wellbeing-related impact: Social-emotional skills have been argued to advance success, participation, and wellbeing, but the related impact mechanisms in development and prevention are still scientifically poorly understood. MMBB research creates knowledge on how the non-verbal, affective, and embodied levels of human behavior can be approached as an objectively quantifiable phenomenon, assessed as a mechanism of change for wider outcomes. Understanding the functions of music as a facilitator of learning, prevention, and rehabilitation will inform how these levels of human behavior lay grounds for the wealth and prosperity of a society. Our interventions provide practical, cost-effective, innovative, and target-group appropriate solutions for addressing social exclusion, burnout, sleep-wake disorders, and detrimental developmental paths.

Commercial impact: The digital music-based learning and rehabilitation tools (music games for children in M5; mobile music technology for stroke patients in M10; digital music intervention, musical preference mapping tool, and old-time song library for persons with dementia in M9) developed together with our industrial partners (Hokema, Careus, Outloud, Sentina, Kardemummo, [73–76]) will provide them an important way to branch out and develop new products and services and improve their competitiveness in the growing e-learning and e-rehabilitation market for education and healthcare. Additionally, implementations of our analysis and visualization methods will be publicly available, helping to advance multifarious industrial domains such as music, healthcare, wellbeing, and education.

6 References

6.1 References

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