REAL-TIME MUSICAL SONIFICATION IN REHABILITATION TECHNOLOGY

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Abstract
Instant feedback with musical sounds can make us more aware of how we move. Converting motion into an auditory display can inform about arm position, posture, or performance quality, for instance. Musical feedback can help relearn gross and fine motor functions. It can compensate for weak proprioception and guide and promote social interaction. In addition, music causes motion to the rhythm with functional relevance. Musical sounds are motivational in repetitive and independent exercises due to their playful and emotional character. Thus, music provides an interactive and flexible tool in a rehabilitation context. With a literature review, I study applying the idea of producing music with motion to improve independence and functionality. I examine real-time transformable musical sounds in rehabilitation and cross-modal training technology and the interaction models for pseudo-supervised workouts in day-to-day circumstances. Now, virtually everybody carries a precise kinematics meter, a smartphone that has enabled new adaptations for people suffering from various deficiencies. Applications help with chronic pain, relearning or stabilizing gait, and visual impairment, for instance. Then, sonifying motion with emotion is feasible too. Advanced systems recognize affective states and combine the data with algorithmic composing. Thus, active, expressive therapy can employ sonification as a creative utility. We can shape gestures, alter moods and make music by moving. Music engages complex mechanisms activating our bodies and minds, contributes to the connection between perception and action, and involves embodied cognition. Therefore, it is a pervasive tool.

Keywords interactive real-time sonification, movement sonification, sonification of motion and emotion, sonic interaction, acoustic cueing, acoustic feedback, affective computing, motor relearning

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Tiivistelmä

Liikkeeseen perustuva musiikillinen palauteääni voi tehdä meidät tietoisemmiksi tavasta jolla liikumme. Kun liike muunnetaan sen äänelliseksi vastineeksi, ääni voi kertoa kehon tai raajojen asennosta sekä liikkeen laadusta. Musiikillisen palautteen avulla on mahdollista oppia uudelleen karkea- tai hienomotorisia taitoja. Ääni voi myös kompensoida heikosti toimivaa asentoaistia, ohjata toimintaa tai edistää sosiaalista kanssakäymistä. Toistuvissa itsenäisissä harjoitteissa musiikki motivoi leikillisen ja tunteisiin vetoavan luonteensa takia. Lisäksi musiikki on interaktiivinen ja hyvin joustava työkalu kuntoutuksessa, jossa voidaan hyödyntää myös vaistonvarainen liike musiikin tahtiin. Tässä tutkielmassa tarkastelen kirjallisuuskatsauksen kautta, miten liikkeellä luotu musiikki voi parantaa toimintakykyä. Käsittelen reaaliaikaista musiikillista palautetta kuntoutusteknologiassa ja aistinkorvauslaitteissa sekä musiikillisia interaktiomalleja harjoitusten ohjaajana. Nykyään liikkeiden mittaukseen tarvittava tekniikka on myös älypuhelimissa, mikä on mahdollistanut uusia ratkaisuja erilaisiin terveystilanteisiin, esimerkiksi näkörajoitteisten, kipupotilaiden sekä kävelyn uudelleenoppimisen avuksi. Kehittyneet järjestelmät myös tunnistavat tunnetiloja ja yhdistävät tiedon algoritmiseen säveltämiseen. Koska musiikilliseen ääneen voidaan sisällyttää sekä liikkeen tekninen laatu että sen sisältämä tunne, voidaan palautteen avulla sekä muokata liikeratoja että säveltää liikkuen, esimerkiksi aktiivisessa ilmaisuterapiassa. Musiikki aktivoi mieltä ja kehoa vaikuttaen havainnon ja toiminnan jatkuvaan prosessiin osana kehollista kognitiota. Siksi se on monipuolisesti vaikuttava työkalu.

Asiasanat sonifikaatio, interaktiivinen reaaliaikainen sonifikaatio, liikesonifikaatio, akustinen vihje, akustinen palaute, affektiivinen laskenta, motorinen uudelleenoppiminen

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1 INTRODUCTION

Musical sounds are expressive, enjoyable, and motivational. They cause motion to the rhythm. Rhythmic components can also accentuate gait, and pleasant sounds coax behavioral change. On the other hand, real-time motion sonification as instant feedback helps notice and change harmful motion habits by supporting pacing and raising self-awareness. Sonification means creating auditory displays, sonic counterparts to data, visual elements, different functions, or motion. Sometimes the equivalents have musical components. In this work, taking a literature review, I concentrate on movement-sound coupling, musical sonifications, and their utility, versatility, and interactive efficacy, providing an excellent tool in a rehabilitation context.

Instant feedback with musical sounds can make us more aware of how we move. Converting motion into an auditory display can inform about arm position, posture, or performance quality, for instance. Musical feedback can help relearn gross and fine motor functions. It can compensate for weak proprioception and guide and promote social interaction. In addition, music causes motion to the rhythm with functional relevance. Musical sounds are motivational in repetitive and self-reliant exercises due to their playful and emotional character. Thus, music provides an interactive and flexible tool in a rehabilitation context. With a literature review, I study applying the idea of producing music with a motion to improve independence and functionality. I examine real-time transformable musical sounds in rehabilitation and cross-modal training technology and the interaction models for pseudo-supervised workouts in day-to-day circumstances. Now, virtually everybody carries a precise kinematics meter, a smartphone that has enabled new adaptations for people suffering from various deficiencies. Applications help with chronic pain, relearning or stabilizing gait, and visual impairment, for instance. Then, sonifying motion with emotion is feasible too. Advanced systems recognize affective states and combine the data with algorithmic composing. Thus, active, expressive therapy can employ sonification as a creative utility.

We can shape gestures, alter moods and make music by moving. Music engages complex mechanisms activating our bodies and minds, contributes to the connection between perception and action, and involves embodied cognition. Therefore, it is a pervasive tool.

Making music generally presents motor behavior with a nuanced and precise output based on the quality of motor controls. Here, I study how to apply the idea of producing music to any motion, grand and subtle, or to regular, mundane activities such as domestic chores, where the motion-induced sound can help improve functioning, and proprioception, the sense of the body's position and balance. The method is proven impactful with chronic pain, relearning or stabilizing gait, and handwriting, for instance (Singh et al., 2017; Cochen De Cock et al., 2021; Véron-Delor et al., 2018). Furthermore, studies show that using musical sounds in sensory substitution devices for the visually impaired activates three-dimensional, spatial imagination uncovering the effect of cross-modal training on neuroplasticity (e.g., Ward & Meijer, 2010; Banf & Blanz, 2013). Thus, the nervous system adapts and optimizes its limited resources in response to physiological changes, injuries, new environmental demands, and sensory experiences (Pascual-Leone et al., 2005).

Music is a pervasive brain stimulator. Firstly, it contributes to the connection between perception and action. The impact on the dynamic system, the interrelation of our internal processes and the outer world, underlines the embodied paradigm (Maes et al., 2014). Embodied cognition emphasizes the role of the human body as a mediator in meaning formation (Leman, 2016), and the theoretical framework covers music perception. The complex entity of integrating sensory, motor, affective, and cognitive systems in musical experiences provides the neuroscientific basis for embodied music cognition paradigms (Zatorre et al., 2007). Consequently, music promoting self- and environmental awareness has extensive functional relevance, as does action-related cognition (Maes et al., 2014).

The concept of interactive auditory feedback for sensorimotor learning, for instance, encompasses fields from rehabilitation to sports exercise, neuroscience, arts, and product design. Music is a particularly apt facilitator for several reasons. Real-time motion sonification can support performance by utilizing the perception-action feedback loop. Music can express a nuanced motion with emotion and engage complex mechanisms activating our bodies and minds (Juslin & Västfjäll, 2008). Musical scales are structural, anticipatory schemes that create a context and are efficiently interactive (e.g., Shephard, 1987; De Lucia et al., 2009), as are recurring events in the flow (Huron, 2006). Implicit musical metrics map well to kinematic parameters.

The auditory display should enable perceivable alteration, guide unambiguously and yet not be too simplified (Ahmetovic et al., 2019). However, creating such musical sounds is challenging. In an interactive system, action alters the sound, and the transformation informs the user of what to do next or differently. Defining relevant information is essential, as is the question of how the musical signal can convey that as accurately as possible. Designing a nuanced, optimally interactive sound to express motion and emotion in real time is interesting for musical aspects, technical implementations, and embodied cognition. These three elements combined anchor my study approach, the many benefits of musical sounds in technology that improves functionality and well-being.

Each year, the Social Insurance Institution of Finland (Kela) provides rehabilitation services to over a hundred thousand people. In 2021, with over hundred and fifty thousand rehabilitants, the costs were almost 450 million. Kela enables various types of rehabilitation to help people with illnesses or impairments that weaken their ability to function in work and daily life. Circumstances differ, whether the reason is sensory impairment, musculoskeletal disorder, rheumatoid arthritis, or general or neurological illness. Currently, the largest rehabilitation group, constituting over two-thirds, is mental and behavioral disorders. Musculoskeletal disorders form the second largest group, with around ten percent of the rehabilitants, followed by neurological disorders with seven percent. (Statistics, Kela 26.9.2022). In addition to Kela, rehabilitation services are available through different organizations, such as authorized pension providers, municipalities, and insurance companies. The economic impact is significant. Yet, the funding is limited, and if that yields to, let us say, supervised therapy once a week, that alone does not suffice. Independent activity is essential, and music and musical sounds as feedback can assist, guide, and motivate self-reliant workouts. I am interested in the potential of music in rehabilitation technology, clinical and commercial use, and the interaction models creating a pseudo-supervised training session in daily domestic circumstances, keeping up the consistent workouts. The hybrid of independent exercises and professional supervision presumably results in multiplicative effects, speeding up the process of improving functionality.

This topic seemed relevant due to several recent developments and disruptions, technical and social. Computing capacity, synthesis tools, and computer music develop constantly. Thus, we can create real-time musical sonification, sonic feedback, melodies, or compositions mapped on motion quite effortlessly (Scholz et al., 2016; Giomi, 2020). Nowadays, virtually everybody carries a precise kinematics meter, a phone with inertial sensors, oscillators, and gyroscopes that can measure rotation and acceleration moreover model gait and trunk motion (e.g., Singh et al., 2017; Ahmetovic et al., 2019; Cochen De Cock et al., 2021). In general, smartphones have enabled new technologies, such as ultrasonic communication contributing to many adaptational solutions for people suffering from various impairments. Medical equipment is expensive, whereas smartphones and smartphone applications are obtainable.

New technologies help measure and analyze bodily movements when studying the connection between music perception and action (Toiviainen et al., 2010), signification processes (Godøy & Leman, 2009), or augmented feedback (Hunt, 2013). Yet another feasible aspect is sonifying body language with emotional content (Giomi, 2020). Motion capture techniques differ, but generally, analysis systems track the movement of body segments and joints and apply established motion functions to quantify key movement patterns (Hunt, 2013). Advanced systems combine affective computing and algorithmic composing (Landry & Jeon, 2020). Thus, systems recognize, process, and simulate affective states. Accordingly, active, expressive therapy with artistic features can employ sonification as a creative tool. We can shape gestures, alter mood, and compose by moving.

In the present work, I will discuss sound and interface design and sound synthesis on a general level through specification guidelines, for even simple metric displays and musical interaction models can provide efficient performance feedback. Often implementations detected motion data with basic inertial measurement units (IMUs) or smartphone inertial sensors, sometimes with subsequent analysis executed with tools such as MATLAB. Real-time musical sounds mapped to the motion were frequently accomplished with a visual real-time programming language such as Max/MSP or Pure Data. Interestingly, even straightforward musical scales positively affected the performance (Ahmetovic et al., 2019; Nikmaram et al., 2021), but on the other end, complex solutions linked concatenating motor sequences to granular synthesis with an adjustable time window with a nuanced outcome (Bevilacqua et al., 2018). However, technology evolves rapidly, especially in machine learning, and devices shrink and segue to commercial use. Therefore, instead of focusing on a specific technology, I examine interaction models and similarities in different approaches.

In this work, I study transformable real-time musical sonifications as auditory feedback and their benefits when employed in rehabilitation technology. In the following chapter, I will present the research method, problem, questions, and hypothesis. Then, in the third and fourth chapters, I introduce different aspects of the underlying theoretical frameworks, first on psychoacoustics, followed by embodied cognition, affect regulation, and dynamical music interaction models, including sensory, motor, affective, and cognitive systems. In the fifth chapter, a selection of functional applications with the real-time sonification of motion, emotion, and scenery creates musical sounds empowering health and well-being by enhancing self-perception and environmental awareness. In addition, the studies uncover motivational factors important in independent rehabilitation exercises, eventually improving mobility and quality of life. After the section dedicated to applied sciences, I summarize the phenomenon in the sixth chapter's conclusive discussion.

2 RESEARCH METHOD AND LITERATURE

The research method is an integrating literature review (Salminen, 2011: 8). The aim is to describe the phenomenon critically from different perspectives. Moreover, explore existing solutions, the underlying theoretical models, and prospects. I searched for the literature in the Jyväskylä University library and subsequent databases, such as Association for Computing Machinery, ACM. Bibliographic information, abstracts, reviews, and the full text for articles published in ACM periodicals and proceedings are available in the ACM Digital Library, with selected works published by affiliated organizations. Another significant publisher constituting my references is the International Conference on Auditory Display. ICAD is a forum for presenting research on the use of sound to display data, monitor systems, and provide enhanced user interfaces for computers and virtual reality systems. It focuses on auditory displays encompassing the areas of perception, technology, and various applications. This work concentrates on real-time musical sonifications deployed in rehabilitation technology. In addition to the searches and publishers mentioned, I used the ResearchGate, a European commercial social networking site for scientists and researchers with a semantic search engine that uses internal resources and external databases, such as PubMed CiteSeer, arXiv, and NASA library. I will use mainly peer-reviewed articles but some conference papers and non-reviewed technical and commercial reports.

Sonification research derives from diverse areas, being inherently interdisciplinary with different facets ranging from computer science to psychology, from sound design to data mining. Discipline-specific jargon has led to unagreeable definitions for the complex concepts within the research area. Due to this background, the width of the phenomenon, and technology-driven experiments, the results with single research word sonification were arbitrary. Attributes like interactive sonification, real-time sonification, movement sonification, gait sonification, sonification of motion and emotion, sonic interaction, or acoustic feedback resulted in better, relevant findings, so I could better drill into the topic even though music rarely appeared on the headline level. Practical applications utilizing sonification are under many domains, and terms often reflect their time. Articles that involved, for instance, auditory cueing, auditory display, sonic mapping, perception and action, sensory substitution, cross-modality, multimodality, and assistive technologies deepened the scope. The application field seemed scattered and somewhat unregulated, and the variety of propel head prototypes was overwhelming. However, the theoretical models presented in this work are essential for understanding how and why real-time modified musical sounds have true potential in rehabilitation.

My references include two comprehensive roadmap anthologies, the Sonification Handbook and The Routledge Companion to Embodied Music Interaction. The Sonification handbook compiles the vast interdisciplinary field of sonification into four thematic categories augmenting each other. The first part discusses perceiving sound, psychoacoustics, and cognition, and the second part addresses source data and sound synthesis. The third part on user interface design leads to practical applications covered in the fourth chapter, but a lot has happened in the technical field since its publication in 2011. Selected articles describing technical implementations extend and cover the following ten years. Secondly, the Routledge compilation represents the branch of embodied cognition that is an appropriate framework when coupling perception, action, and real-time musical feedback in the rehabilitation context. These collections represent a wide variety of theoretical interaction models and underlying psychoacoustic principles that form the basis for specifying assisting and rehabilitation technology. Technology evolves, and we have come a long way from converting single pixels or two-dimensional axis to beeps and sweeps to turning entire scenes into living musical soundscapes and displaying dynamic interactions or subtle motion with emotion with musical sounds. Thus, the research problem is integrating interdisciplinary literature from a musicological perspective to see if there are recurrent elements in the varying empirical studies using real-time musical sound as instant feedback and reflecting the instances in the theoretical framework.

The three main research questions are:

1. What are the factors for successfully implementing real-time musical sonification rehabilitation applications in daily domestic exercise?
2. How can we tighten interdisciplinary cooperation to proceed from an idea to practice with proper specifications and make a supervised home exercise plan, follow-up, and verified metrics?
3. Based on statistics and research results, what are the prospects and possible economic impacts of active independent rehabilitation exercises resulting in multiplicative effects with professional therapy, speeding up the process of improving functionality?

Although musical sounds are generally motivational, fun, intuitive, and pleasant, I presume there are several, sometimes unexpected, usability issues in everyday life. The user interface and controllers must be accessible and serviceable in different situations, one-handedly, etcetera. Therefore, starting independent exercise requires support and assistance. It might be challenging to show the impact of various factors in long-term rehabilitation, including therapy sessions, domestic workouts, and natural physical recovery. In addition, the mean average age of a stroke patient, for instance, might be somewhat high, and facing technology can cause a range of reactions.

Neuro-rehabilitation raises specific questions compared to, let us say, orthopedic patients with no neurological limitations by assumption. However, I did not restrict the study to one type of diagnosis or rehabilitation. Namely, from the musical sonification perspective, the regular post-stroke reaching exercise might not differ dramatically from the audio-aided reaching routine for the blind or stretching motion with chronic pain. I was interested in musical interaction supporting different functions, such as walking or arm swings, and the methods' applicability and possible limitations in different situations. Also, producing music in real-time with body motion can convey several layers of implicit information, providing prominent tools in a therapeutic setting. Disclosing the background, near real-life incidents and research I have met at Jyväskylä University inspired this work. Seeing the persistence and willpower to do daily rehabilitation exercises and to find new, enjoyable, and motivating ways to keep going, propels the study. The goal is to understand how real-time transformable musical sounds providing feedback and supervision can support regaining a better functioning body and mind and explore existing practical solutions with promising results.

Thus, in this work, I will concentrate on the efficacy of real-time musical sonification and feedback and their potential in everyday use, exercises, and domestic tasks, guiding performance and interaction, strengthening self- and environmental awareness, moreover serving embodied cognition. Music-supported therapy acts on many levels, encompassing motor, cognitive, and emotional mechanisms (Sihvonen et al., 2017). Neurologic music therapy in stroke rehabilitation, for instance, is a notable supplement to conventional physiotherapy. However, the effects of music-supported therapy are not always consistent. This study is not music therapy work per se. I will focus on interaction models and user-centered design with the theoretical framework of embodied music cognition and psychoacoustic principles and the factors behind discrepant results in different studies.

3 INFORMATIVE MUSICAL SOUND

Music communicates through sound, and it is expressive beyond words. Music can convey quantitative and qualitative information, raise awareness, and describe context, space, and activities in real-time. Musical structures include perceptual metrics and modifiable temporal and spectral components. Regarding rehabilitation or assistive technology, the musical metrics are relatively easy to map to kinematic parameters and the tempo to individual settings. In addition, music engages emotional and cognitive processing with all-encompassing activation, providing a considerable tool in rehabilitation. When predictable progressions and musical cues guide action and transforming sounds inform action-feedback loops, simultaneously strengthening the sensorimotor coupling, the theoretical framework of embodied cognition applies well. Namely, the framework assumes that intelligent behavior requires goal-directed interactions with the environment (Leman, 2007).

According to the original definition by Kramer and colleagues (1999), sonification means converting the data relations into an audible output where we can still hear the ratios. Furthermore, they describe how sonification supports interpretation and communication, which reflects the importance of cognitive processes in creating and perceiving these auditory displays. Thus, sonification can represent a counterpart for a graph in an audible world with a direct, simple sound signal, but it can be much more complex. When including musical components such as tonal and modal features, sonifications can convey information, meanings, and emotions with multiple mechanisms (Juslin & Västfjäll, 2008). The sonification phenomenon derives from a vast, multidisciplinary realm (Hermann et al., 2011). However, the theoretical basis relies on psychoacoustics and cognitive sciences, and next, I will go through the essentials.

Informative signals are beneficial compared to speech because they are relatively strong in noisy environments, overcoming attentional burdens and language differences (Dingler et al., 2008: 2). To further elaborate, voiced speech, a typical adult male with fundamental frequencies from 85 to 155 hertz and a female from 165 to 255 hertz, is relatively low, in the bass range. Musical sounds are generally intuitive and understandable, although music theory, impressions of major and minor scales, and tempi, for instance, can have an intentional role in the auditory display. Cultural background, musical education, and individual differences may affect signal interpretation, but prior knowledge has shown a minor impact, and short training periods have excellent results (e.g., Ahmetovic et al., 2019; Abboud et al., 2014; Banf et al., 2016; Neuhoff et al., 2002). Even though I use general terms of sonification and auditory display in the present work, I will concentrate on musical sounds and structures and their benefits in rehabilitation and guiding action.

3.1 Musical metrics, mapping and sense of direction

Perception of the environment includes identifying, organizing, and interpreting multi-sensory information. That results in a representation of the circumstances shaped by learning, memory, expectation, and attention. (Spada & Bigand, 2017: 262.) Thus, when perceiving, we build meanings in a process where embodied cognition works actively with the environment (Thompson & Stapelton, 2009).

Wiener and colleagues (2009) identified three layers of cognitive tasks in perceiving the environment, where the first is a point in space, such as a target, obstacle, or danger like stairs. These points can be recognized with various applications and marked with sounds, notifications, or warnings (Bujacz et al., 2016; Presti et al., 2019). Alarms and warning signals are apparent, seizing our attention and making us precautious, but they are rarely musical or interactive, like sounds that support learning and exploring should be.

The second level of perceiving the environment is knowledge about the route (Wiener et al., 2009). Proceeding, passage, and rotation can be sonified in various ways, such as by altering frequency, panning, or volume (Dubus & Bresin, 2013; Spagnol et al., 2018). The pitch is perhaps the most common sound dimension for displaying data, presenting relatively easy mapping and transformability. However, we cannot always generalize the scaling because sometimes the intuitive direction of the sound depends on the information or the listener (Walker, 2002; Mauney & Walker, 2010). When Walker and Lane (2001) studied the conceptual connection between data and sound, there were some contrasting differences between the sighted and the visually impaired. When Noordzij and others (2006) examined the ability to form a spatial mental model, blind people performed better after listening to a route-like than a survey-like description, opposite to the sighted. Therefore, empirical studies with the intended end-user group have a paramount role in the practical applications for sound-assisted functions and rehabilitation. Sounds must meet the listener's expectations to support the interpretation and optimal performance.

There are also other practical matters concerning mapping and scaling. Instead of conveying the information with arbitrary frequency shifts, the changing input data value can have a discrete output fixed to musical scales that are fathomable cognitive structures. The musical scale or melody builds in our moment-to-moment experience based on the previous events and therefore does not require remembering or comparing single values (e.g., Krumhansl, 1982; Jordan & Shepard, 1987). Furthermore, while the most sensitive hearing area is between 1000 and 5000 Hertz (Walker & Nees, 2011: 25), determining the width of the frequency band, the range of the minimum and maximum values, is relevant. However, the frequencies between 2500 and 5000 Hertz are generally considered unpleasant for high energy, so in some sonification software, the upper bandwidth limit is at 1568 hertz, g^3, or G6 in international standard notation, in the realm of violin and piccolo (Wright et al., 2013; Abboud et al., 2014). If we need to compare information flows within this range, choosing different instruments with distinctive tones to display them is convenient. That is, utilizing spectral information. However, when music is polyphonic, our auditory cortex encodes the higher of two simultaneous tones more robustly, according to the so-called high-voice superiority effect (Hove et al., 2014).

Respectively, there is the low-voice superiority effect. Encoding rhythmic timing information actualizes at the low musical range, clearly below the sensitive hearing area. (Hove et al., 2014.) Bass-ranged instruments set the rhythmic foundation effectively. For instance, the lower end of double bass, bass guitar, and tuba fall into the sub-bass frequency area between 16 and 60 hertz, and the bass frequency range is from 60 to 250 hertz. Thus, choosing the frequency scope depends on the intended action too. When examining the low-voice superiority effect, Hove and colleagues (2014) used stimuli with the fundamental frequency of 196 Hertz (g/G3). These neural-based functions and practical boundaries eventually link to implementations concerning usability and pleasantness, critical issues with consistent, long-term use in mind.

Metric, gaugable feel, or context information is essential in interpreting the auditory display of data or function, and music has its means. As discussed, relative measurableness can originate from rhythmic components, including duration, volume, and pitch, and tonal progressions create meters by harmonic changes. Smith and Walker (2002) showed that even a simple metronome click makes a context to an auditory display of data, forming perceptual x-axis ticks that enhance the listener's estimation of the maximum value of the auditory graph. Thus, the metronome made the sound measurable, a worthy feature in representing kinematics. However, even though Walker and Nees (2011: 18) state that we perceive other sound attributes in a continuum, and some, such as tones categorically, Wishart (1996: 80–81) specifically introduced tone progressions in computer music, stating that our hearing experience evolves in multidimensional sound space, where the proximity principle creates a sense of distance, transition by moving from a tone field to another, even though harmonicity is not applicable. Transforming a tone, that is, its spectral qualities means figuratively stretching one sound so far that it turns into another. The tone progression soundscape method is one interaction model in assistive and rehabilitation technology (e.g., Banf et al., 2016; Bevilacqua et al., 2018).

Music is a multifaceted tool for presenting contextual information, changing values, and spatial and temporal dynamics. While doing so, music targets several brain areas, from the neocortex to the reward system, and synchronizing separate, functionally independent brain areas impacts brain plasticity and strengthens connectivity and sensorimotor learning (Spada & Bigand, 2017: 266). Musically aided motor control can employ compensatory brain functions and minimize strain on the impaired neural pathway (Véron-Delor et al., 2018), but it also evokes spatial imagination (e.g., Ward & Meijer, 2010). In addition, unlike the environmental perception that generally occupies vision, musical feedback on actions does not add a cognitive burden to the motor task (Bevilacqua et al., 2018). Compared to visual feedback or instructions on a screen, for instance, auditory feedback provides supplementary sensory information about relative limb positions and enables free movement training. Since we perceive meter, rhythm, and time variants with great sensitivity and hear the rhythm of movements more precisely than we can see them (Effenberg et al., 2016), even simple, straightforward musical ideas that amplify motion can serve in rehabilitation too.

3.2 Improving environmental awareness and self-perception

One elementary difference between seeing and hearing is that our ears distinguish sounds into integral parts, but when looking around, we perceive the scenery as a whole. This integration is the third level of perception by Wiener and others (2009). Our auditory system detects sound sources, picks up, and recognizes words and melodies effortlessly, despite noisy environments. Thus, we can use signals in many ways and for many reasons to help understand the surrounding world. For instance, if our vision is restricted or occupied with other tasks. For the blind, perceiving the environment is effectively discontinuous. They integrate discrete pieces of information by touching and hearing, with preferably uninterrupted and continuous stimuli (e.g., Cattaneo et al., 2008; Ahmetovic et al., 2019). Conveniently, that is the nature of music. Thus, musical soundscapes and cues can help piece together the representation of the environment and compensate for sensory deficits.

When Coleman and colleagues (2008) derived a general mapping tool for sound design from office milieu soundscape by interviewing and evaluating the listeners' keywords, the semantic information revealed the importance of sound sources in everyday listening. Sounds can function on the edge of our awareness, raising our general consciousness and motivation (Cohen 1994 a & b). They keep us oriented and aware of what is happening around us, also out of sight. However, listening to sounds does not merely activate identifying the sound source. It prepares us to react to the sound.

De Lucia and colleagues (2009) examined how sounds subconsciously lead us to (re)actions when cognitive presentations link to action plan schemes. When action representations interact with auditory object recognition processes, the reaction time is significantly shorter (De Lucia et al., 2009), which has importance in our daily lives (e.g., Ahmetovic et al., 2019). Maes and others (2014) discuss forward modeling processes of planned actions. Likewise, according to Effenberg and colleagues (2016), motor learning improves when synchronously processed auditory input integrates into emerging internal models. In other words, as Sihvonen and colleagues (2017) state, music-supported therapy might be effective because patients create internal expectations about musical structures and consequently improve movement timing. Thus, predictable musical sounds can compensate for executive dysfunction. Also, entrainment relies on a psychological model of the progression and predicting events (Madison et al., 2017: 23). Otherwise, reacting to an abrupt stimulus would cause at least a hundred-millisecond delay (Kauranen & Vanharanta, 1996; de Lucia et al., 2009).

When Ahmetovic and colleagues (2019) compared different types of sonifications guiding turning in an indoor navigation system for people with visual impairment, the goal was to reach the target angle as accurately as possible. The study investigated how different end-users perceive sonifications and how learning, musical and cultural background impact user performance. Eighteen blind people from two diverse cultural groups participated. While notable performance differences emerged between the two groups, a C major scale outperformed the baseline solution ping in both, significantly reducing the average rotation error. In addition, the musical scale was more appreciated than the other techniques, strengthening the assumption that people with visual impairment prefer continuous guidance to single-impulse notifications or typical radar intermittent sound. Although the rotation study took place in a quiet room, very different from a regular busy city environment, the conclusions' relevance lies in depicting a case study of real-time sonification and the advantages of continuous, predictable sound improving one's orientation and environmental awareness. Equally valuable to usability are the aesthetics and intuitiveness of a musical structure.

In addition to being aware of the surrounding world with sounds and signals, auditory feedback can improve our self-perception and make us more conscious of how we move. Self-perception relies on proprioception, the sense of body position and movements, posture, and balance (Spada & Bigand, 2017: 262). The information is gained primarily from the sensory nerve system with the inner ear input concerning balance. This sense is unconscious and mainly coordinated by the cerebellum. (Spada & Bigand, 2017: 261.) While some conditions cause dysfunctional proprioception, sonifying motion, gestures, and expressions into musical sounds can compensate for it. Sounds can inform about limb position, posture, optimized pacing, trajectories, and performance quality.

Then, utilizing the connection between perception and action is particularly appropriate. That means an interactive real-time sound manipulation method for improving performance. After all, perception and action share resources in functional brain architecture (Hommel et al., 2001). In a music-motion action loop, taking action changes the baseline sound, and the sound informs the user what to do next or differently (Serafin 2011, 94). Thus, the real-time audio feedback supports performance and enables correcting trajectories, actions, and orientation (e.g., Godbout & Boyd, 2010; Scholz et al., 2016). From the standpoint of neurological rehabilitation, Sihvonen and colleagues (2017) state that music-based interventions generally have an impact because the underlying mechanisms for the desired outcome share neural resources and systems for reward, arousal, learning, affect regulation, and activity-driven plasticity.

Sounds can function on the edge of our awareness like the high-voice superiority effect stems from the sensory periphery (Hove et al., 2014). Thus, instead of using acoustic information as obvious error feedback in motor learning, luring the behavioral change can happen below conscious cognitive processing. Effenberg and colleagues (2016) generated subtle, subconscious auditory movement information for acceleration and improving sensorimotor performance. Mapping kinematic and dynamic motion parameters to electronic sounds produced a continuous audio-proprioceptive interconnective loop. Using a rhythmic, musical sound to improve movement quality or cause functional entrainment can be beneficial, specifically for cyclic movements such as walking, running, cycling, or swimming (e.g., Effenberg et al., 2016; Eriksson & Bresin, 2010). Entrainment refers to synchronizing body movements, brain activity, and other psychological phenomena to music (Madison et al., 2017: 22). Real-time motion sonification is an intriguing question considering embodied cognition, technical implementations, and musical issues, such as sound design and composing. The sound must be intuitive for guidance and complex enough to provide discernible alteration or sometimes even subconsciously tempting.

3.3 Functional aesthetics

For general usability, the sounds of any user interface should be enjoyable. Kramer (1994: 52–53) remarked that we could decrease noise tiredness with better aesthetics. Later, Vickers and Hogg (2006) claimed that aesthetics contribute directly to understanding the message by making listening easier. They refer to sonification as *Ars Informatica*. In older assistive technology, the soundscapes have been quite a raw sine wave pulsation, virtually intolerable in long-lasting use. However, new applications use more musical sounds and pleasant sampled instruments to present colors, shapes, and scenes (Revuelta Sanz et al., 2014: 7-8).

Studies suggest that using a recognizable musical instrument instead of a sine-wave pure tone and discrete pitches rather than a continuous frequency range affects the listener's perceptions of musicality. Musicality, on the other hand, impacts perceiving the emotional content, aesthetics, engagement, and usability. (Landry & Jeon, 2020.) Thus, one of the many advantages of musical scales facilitating interaction is that they are generally more pleasant and less annoying than non-musical random frequency changes, beeps, and bleeps (Neuhoff, 2011: 79; Ahmetovic et al., 2019). Pleasantness is an aesthetical evaluation that implicitly implies that musical scales are cognitively rather effortless.

Typically sensory substitution applications sonify visual features by reading the view from left to right. This so-called sweeping technique is a natural choice because sounds cannot represent all visual information at once, or it would create a cacophony. A sweep creates a dynamic soundscape, where we can hear colors, luminaries, shapes, locations, and depth impressions. A single pixel can represent, for instance, hue, saturation, and lightness, the HSL components linked to tone and volume. The pitch usually expresses the location on a vertical axis, and the horizontal axis represents time. Some applications use the pentatonic scale to soften the dissonance of the simultaneously played notes (Abboud et al., 2014). The sensory substitution devices and sonification applications that represent the visual world with musical sounds have been shown to facilitate interaction and improve spatial imagination for the visually impaired (e.g., Merabet et al., 2009; Ward & Meijer, 2010; Banf & Blanz, 2013). The aspect of promoting plasticity and neurorehabilitation is remarkable.

Beyond bare data conversion, aesthetics, subtleness, and usability are notable themes when designing interactions and equipment for rehabilitation and assistive technology. Robust, clumsy devices can hinder implementation by being impossibly impractical or embarrassing in public, and audio guidance can fail because sounds affect our feelings, forming a motivational factor in rehabilitation. The potential of musical sounds in assistive and rehabilitation technology is recognized, and the topic has gained attention. There have been various prototypes, often the clinical or commercial use in a long-term scope, but not yet widespread launches. There are several reasons for this. For instance, the sensory substitution equipment user requests revealed that they were considered expensive, awkward, usability poor, and the sounds unpleasant or annoying (e.g., Elli et al., 2014; Revuelta Sanz et al., 2014; Osinski et al., 2021; Hamilton-Fletcher et al., 2022). In physical rehabilitation, the equipment has to be subtle, compact, and preferably one-handedly operable.

Recently, gadgets have shrunk, and separate devices have often become unnecessary since many applications run on smartphones. Equally salient for usability are the evolutionary, more aesthetic soundscapes. Musical sounds are generally efficient because they involve cognitive and emotional processing in several brain areas. Since auditory and premotor cortices couple in musical contexts, supporting mobility is effective (Zatorre et al., 2007; Damm et al., 2019). Nevertheless, reactions to music are very complicated, as I will discuss in the affect regulation chapter (4.1). In addition, neurological disorders causing sensory and executive dysfunctions may cause discrepant results that challenge the qualifying process for new technologies. Next, however, I will introduce music therapy studies with the concept of embodiment and computational approaches to help understand the role of real-time musical feedback in rehabilitation.

4 MUSICAL INTERACTION FOR MOTI(VATI)ON

Music's ability to influence and regulate our affective states is one of its most significant functions (e.g., Saarikallio & Erkkilä, 2007; Laiho, 2004). The affective state is a term used for describing moods, emotions, and feelings (Baltazar & Saarikallio, 2016), and it refers to the experience of feeling an underlying psychological state. We have short-term emotions and less intense, more obscure longer-term moods with no identifiable reason. However, regulating emotions can eventually influence our general state of mind. Music's emotional content is contagious, but so is its rhythm. "Music stimulates muscles, mind, and feelings in one go," as Mainka (2015) put it. Music is a full-brain exercise but a whole-body experience too. Music is associative, making you remember. It is motoric, initiating motion, and vegetative, giving you the chills. We can feel and communicate it physically, and simply imagining music triggers our motor systems (Halpern & Zatorre, 1999).

4.1 Music-influenced mood and motivation

Music can influence how we feel by evoking emotional reactions. When Juslin and Västfjäll (2008) uncovered the underlying mechanisms, they described the brainstem reflex as the most primitive response to acoustic features. Subsequently, rhythmic entrainment gradually adjusts our internal body rhythm with the music and makes us move. However, musical expectancy and aesthetic judgments contribute to how we go with the flow. Evaluative conditioning pairs music with positive or negative stimuli, and contagion means that we mimic or absorb the emotional content of the music. Musical experiences also engage emotions and cognitive processing connecting to episodic memory, events in our past. Thus, our minds exhibit inner images when listening to music, and we associate certain music, genres, or artists with particular times in life. (Juslin and Västfjäll, 2008; Juslin, 2013.) Musical sounds console as such, but also through nostalgia by reminding of other people involved, resulting in a feeling of company and comfort. Therefore, situational factors and extra-musical information like context or descriptions of the music's meaning can influence these mechanisms (Vuoskoski & Eerola, 2015). Contextual information about music can intensify emotions, probably via visual imagery. Thus, not all musical content is musical.

In a therapeutic setting, embodied music listening facilitates multi-modal imagery for comfort and inspiration to catalyze change. When the body participates in meaning formation, a musical experience may therapize, disentangle thoughts and feelings, and eventually liberate. (Bonde, 2017: 276.) Likewise, Kosslyn and colleagues (2006) state that mental images depict information with a functional role in cognition, such as problem-solving, creativity, and memory. However, memory, the contribution of individual experiences combined with subjective taste, sets challenges in defining a suitable and motivational piece of music. Relaxing or motivating music to one might not be that to another. Neither is music equally meaningful to everyone. Personality traits, cultural background, musical training, and even the prevailing mood have a role in listening and reacting to music (Vuoskoski & Eerola, 2015). In addition, musical features such as tempo, key, genre, rhythm, emotional tone, and overall performance contribute to affective responses. No single mechanism can account for all music-induced emotions. Various theories are relevant to these cognitive, neuro-affective, and musical dimensions that also have a role in specifying technical solutions. However, identifying factors helps to set the outlines.

Affect has two psycho-physiological dimensions, valence, and arousal (Russell, 1980). Valence is a positive-to-negative evaluation of the current state, and arousal means high or low energy, depending on the prevailing state of our nervous system. Motivational intensity is the ability to prompt an outcome, approach the positive or move away from a negative. High valence with high arousal means being excited or enthusiastic, whereas high valence with low arousal means being serene or relaxed. Thus, being tense, nervous, or stressed means low valence with high arousal. Lethargy or depression equals low and low. Understanding, recognizing, and modifying our affective states is salient for mental health and functioning. That is where music can help. Bruscia (2014, 40-41) defines that the music used for therapy is not just operating on us but the whole inner and interconnecting experience as a process with a product in that context. Music-based interventions can affect different functions, such as motor performance, speech, or cognition (Sihvonen et al., 2017). However, therapy depends on the music, moreover, how the client experiences it, so the therapist needs to make an individual plan, observe, supervise, and re-evaluate their work throughout the therapy process.

Let us now get back to musical expectancy, another element impacting our reactions and motivation. Huron (2006) states that successful prediction of structural events evokes positive cognitive responses, where familiarity and repetition are the keys. We can assume motivation links to the rewarding consequences of meeting expectations, anticipating a specific feature that the musical continuum confirms (Huron, 2006). Then, musical tension relates to arising emotions of processing musical structure, the build-up, and the delay or violation of predictions leading to pending, unresolved, unease sounds (Koelsch, 2014). The tension and release scenario can guide action (e.g., keep stretching till you reach the consonance), and repetition in music pairs well with repetitive exercises and synchronizing movement. Also, anticipating a musical event means preparing to act (De Lucia, 2009). Synchronizing motion with an external rhythm is a double task requiring temporal processing of the rhythm and the action (Grahn & Brett, 2009).

In chapter five, where I introduce empirical studies with rehabilitation technology applications, we can see how these mechanisms impact musical interaction, motivation, and performance. Thus, inner images and mental constructions, individualized settings, musical expectancy, motivational aspects, and the dual task of tracking the beat and synchronizing motion all feature in the conducted studies.

4.2 Emotion-influenced musical performance

Music can induce emotional reactions in the listener, both positive and negative, often referred to as felt emotions. Respectively, an emotion expressed in music and perceived by the listener is a perceived emotion. Thus, musical sounds evoke emotions, but it also works the other way around. Music flows in and impacts us, but when the musical idea flows out, the musician's gestures provide cues for temporal and structural issues (Goebl & Palmer, 2009; Clarke & Davidson, 1998), expressive intensity, and phrasing (Vines et al., 2011). Musicians also convey their intention and emotions with gestures (Desmet et al., 2012; Maes et al., 2014). The bodily musical expression instantiates inner processes, including affect, motivation, intentions, and metacognition. It also reflects personality, musical training, and the external environment with its conventions. Seeing the musical expression as an extension of the inner vortexes or order, for that matter, aligns with the interconnection repairment idea Bruscia (2014) presented: music operates on the inner experience and connections between others and the environment.

When Van Zijl and Luck (2013 a & b) conducted studies where musicians focused on different performing aspects, such as technical execution, expressiveness, and emotion, the technical take was the most motionless. After hearing a fictitious sad story behind the composition, the emotional aspect increased the player's motion and consequently affected the sound. Trained musicians move more economically than amateurs. Generally, however, the perception of musical intensity links to movement size (Nusseck & Wanderley, 2009). Therefore, technical virtuosity alone does not necessarily make the music, and emotion, a human factor, is required. Nevertheless, musical expression is revealing, intentionally and unintentionally. Therefore, sonified body motion that enables a straightforward musical expression for instrument-illiterate or -disabled is a notable addition to the therapeutic repertoire.

Interestingly, clinical music therapy improvisations have been amenable to computational analysis and modeling for the systematic connections between emotional responses and musical content. In the study Luck and colleagues (2009) conducted, the computational method predicted eighty percent of music therapy clients' mental disorders from their improvisations. Fifty clients with diagnosed mental retardation, developmental or neurological disorder performed over two hundred slider improvisations resulting in forty-three recurring and extractable features. Subsequently, a function analysis produced two significant parametric functions with three main categories of predictor variables. They were pitch, temporal aspects, and tonal clarity versus dissonance. The case study supports the implementation of computational music analysis in music therapy. Not everybody is musically experienced or trained, so the frequent musical features must tell something fundamental about how certain circumstances manifest in music and motion.

4.3 Overt music-induced movement

The human body is a superb mediator of many things. It is also a dynamic system, a kind of converter with individual specifications, where the successful entrainment, motion initiation, and expression depend on the musical quality, subjective evaluation, and personality of the listener. In addition, past experiences and corporeal states contribute to engagement and assessing musical sounds and sound patterns. The idea of the musical input with physical output impacting the sound, and gradual modification by looping, is intriguing from the standpoint of implementing real-time musical feedback. What kind of music is appealing and why, what is the instant physical reaction like, what do the outcome gestures tell, and can we shape them with music by targeting the inner state or setting an external goal for supporting performance? Even though sensorimotor schemes control expressive reflexes and learned responses (Leman, 2016), attention, contextual knowledge, and intentional movement may supplement them. Therefore, responses are modifiable.

In everyday life, most people move to music, and according to several studies, it is universal (e.g., Levitin, 2006; Repp & Su, 2013). We can move to a wide variety of tempi (Large et al., 2002), but the preferred pulse is around two hertz, our natural movement rate (Parncutt, 1994; van Noorden & Moelants, 1999). Senn and colleagues (2018) state that regularity causes action and transfers to sensory-motor behavior. Eventually, the way rhythm manifests in our body motion is surprisingly overt, and expressivity is essential in understanding personality and individual differences (Gross, 1999). Body motions and walking, too, can indicate personality types (Sun et al., 2018).

Studies have shown systematic relationships between different aspects of music, personality type, and body movements. For instance, when Luck and colleagues (2010) examined music-induced motion in participants representing five personality traits, each trait correlated with a different movement pattern. The personality types were openness, conscientiousness, extraversion, agreeableness, and neuroticism. Based on the optical motion-capture system data, musical excerpts from different genres, varying in rhythmic complexity and tempo, produced five motion components: local and global movement, head speed, hand flux, and hand distance. Extraversion and neuroticism evoked the most apparent correlations underlining systematic relationships between personality traits and movement characteristics. Here, rock was associated with head speed and no notable global, large-area feature, whereas electronic dance music evoked rhythm, local limb action, and head speed for extroverts. Latin made people move around the room the most while keeping their heads relatively still. Unexpectedly, openness seemed to have the weakest effect on movement characteristics despite the general appreciation of new experiences and ideas.

On their part, Toiviainen and colleagues (2010) examined how music-induced motion indicates music's pulsations on different metrical levels. The principal component analysis of the motion data revealed correlations between musical metrics and movement patterns. Study participants listened to a piece of music in 4/4 time, played at varying tempi, and moved to it for a request. Torso movement, vertical hand movement, and mediolateral arm movements were synchronized with the primary pulse, while rotation and the upper torso lateral flexion designated beats two and four. Music-induced motion showed simultaneously synchronized cycles on several metric levels. Central parts of the body instantiated hierarchically higher, slower metrics with gross body movements (the torso oscillates slower for its mass and large dimensions). Extremities responded to hierarchically lower, faster information.

It would be interesting to explore further how we could deliberately exploit these systematic connections and layered metric components to provoke specific motion dimensions in a rehabilitation context, even though it might not be all that straightforward. Namely, musical training and familiarity with the overall musical style also play a crucial role in the musical experience, as do expectations and general meter perception (Fitch, 2016). For instance, musicians move better synchronized with high-syncopation music than non-musicians (Witek et al., 2017). Thus, the results imply that for providing the best possible support for performance, therapy applications need several genres to enable individualized settings regarding taste-related motivation and personality characteristics. However, the evidence of the systematic relationships between music and motion patterns in these studies means that the functional use of music in rehabilitation technology has unemployed potential.

5 APPROACHES AND APPLICATIONS

Frequent motor or cognitive activities stimulate neuroplasticity and recovery (Sihvonen et al., 2017). Thus, healthy neural networks form new synapses and reorganize the injured connections. On the other hand, sensory substitution devices and sonification applications representing the visual world with musical sounds facilitate interaction and evoke spatial imagination for the visually impaired (e.g., Merabet et al., 2009; Ward & Meijer, 2010; Banf & Blanz, 2013). We can see these results through the enacted lens with the neuroscientific aspect of brain plasticity, another intriguing aspect of this multidisciplinary phenomenon.

Several controlled studies have examined music-based (music listening, singing, playing) interventions in rehabilitation. Although the volume of evidence considering stroke and dementia is most substantial, music-based interventions have been impactful in supporting cognition, motor function, and emotional well-being in several neurological conditions, such as Parkinson's disease, epilepsy, or multiple sclerosis (Sihvonen et al. 2017). Hitherto, most rehabilitation technologies have been available in supervised exercise sessions and premises, but computing capacity, synthesis tools, and computer music develop and yet turn mundane and affordable. Now, virtually everybody has a precise kinematics meter, a phone with inertial sensors, oscillators, and gyroscopes to measure motion, rotation, and acceleration, to model gait or trunk motion. Thus, separate devices are often unnecessary. Smartphones have enabled many new solutions and provided chances to do independent pseudo-supervised rehabilitation exercises. Real-time musical sonification, sonic feedback mapped to motion, and even compositions based on movement are feasible (Giomi, 2020). Latency-free auditory feedback helps improve functioning, proprioception, motoric skills, and social interaction.

Sonification can enhance and optimize movements in different ways. It can provide external cues and instant feedback in gross-motor exercises such as walking or swinging arms and equally apply to fine-motor control improvement. While some implementations use depictive or naturalistic real-time feedback, others give comparative error feedback. Some provide subconscious motion manipulation and some obvious sonic instructions with cues. The feedback type relates to motivation (error feedback versus encouraging feedback).

Real-time feedback reflects motion acoustically when kinematic data is measured and mapped to output sound by a function. Thus, moving causes an instant change in the related sound, influenced or created by the user. Acoustic error feedback requires defining a range of parameters and comparing the measured values to them. Sound signal can appear distorted if the motion is dysfluent, for instance, or it indicates crossing the threshold. Cues present a structure, a temporal one, discrete steps, or dissonant sounds to imply that the completion is unfinished. The essential question in sonification is defining relevant information and how the musical signal can convey that as accurately as possible. The guiding sound should be perceivable, meaningful, unambiguous, and yet not too simplified to facilitate precise interpretation (Ahmetovic et al., 2019).

Next, I will introduce therapeutic technologies, including cross-modal training devices, where the real-time sonification of motion, emotion, space, and events create changing musical sounds and soundscapes. The studies reveal the effect of music on self-perception and environmental awareness, participation, and independence. However, the rehabilitation domain features specific perceptual issues and usability questions that need consideration.

5.1 Gross motor skills — quality and completion of performance

Music is sentimental and emotional, evoking dreams and emotions and altering moods. Moreover, music listening is a cognitive task where we recognize patterns, instruments, or a particular song. Hence, unsurprisingly, listening to one's favorite music enhances brain recovery, perception, attention, and memory after a middle cerebral artery stroke (Särkämö et al., 2008). Considerable cognitive limitations, such as changes to speech, understanding, and learning, are common post-stroke deficiencies. In addition, gross-motor impairments, weakness of upper-limb motion on the opposite side of the lesion, and difficulties with body posture, walking, and balance are typical. Stroke is one of the leading causes of long-term disability worldwide (Katan & Luft, 2018). In Finland, it is one of the most common disorders, with an estimated twenty-four thousand first events annually (Stroke, Duodecim, 26.9.2022).

Activity and independent daily exercise are necessary for recovery (Kristensen et al., 2016). Task-specificity, motivation, and feedback improve motor relearning. Intrinsic feedback, the sensory-perceptual information based on vision, proprioception, and audition, is often disturbed after a stroke. However, with external feedback, the functionality might increase. (Molier et al. 2010.) Physical exercises that include strength, balance, and gait are monotonous and demanding. Therefore, exploring ways to support independent workout routines is relevant.

Music and physical activity have a symbiotic relationship. While self-selected, motivational music reduces perceived exertion in repetitious workouts requiring endurance (Karageorghis & Priest, 2012), the impact enhances further when we make music with the exercise movements (Fritz et al., 2013). Fritz (2017: 280) introduced a musical feedback technology that combines physical exercise with musically expressive performance. He refers to musical agency, action with an external goal or effect, and states that the mixture is often associated with experiences of musically evoked euphoria. Results indicate that using the method releases endorphins much more efficiently than previously observed in regular sports activities. Within only ten minutes of making music while exercising, mood increased significantly compared to conventional workouts (Fritz et al., 2013). The effect lasted for a substantial time, suggesting hormones were involved. In addition, pain sensitivity went down during the workout, which is the desired effect in rehabilitation, where the patients prefer avoiding pain during the necessary, repetitive exercise.

Even though troubles with gross motor functions are typical after stroke, efficient and motivating therapies are scarce, as Scholz and colleagues (2016) note. They state that real-time musical sonification seems convenient for workouts because the sound concurrently motivates and informs about the relative arm position. Thus, the instant, continuous feedback amplifies the human action observation system. In a ten-day trial, Scholz and colleagues assessed, for instance, the participants' upper extremity functions and arm movement smoothness before and after. The rehabilitants started by exploring the sound effects of arm swings with the C major scale, and in the end, they played simple melodies with coordinated arm movements. They reported improved hand functions, motion smoothness, and decreased joint pains. The associative sound compensated for lost proprioception and made them more aware of how they move. Later, Nikmaram and colleagues (2019) repeated the arm-swing study with lighter equipment. They remarked that the clinical benefits of the technique might be limited, but it is a notable addition to current neurorehabilitation methods due to motivational factors and inexpensive hardware. Rehabilitants thought the routine was enjoyable, and motivation had a significant role, a substantial factor also when implementing solutions to daily domestic exercises.

Arm swing has a substantial role in gait stability, and reduced arm swing, a common symptom of Parkinson's disease, links to the increased risk of falls. While the upper and lower extremities impact each other in locomotion, improving arm swing affects entire gait kinematics, including stride and trunk rotation. Mainka and colleagues (2021) examined a mobile phone application that converts arm swing acceleration into closed-loop musical feedback. In the study, participants first wore six light inertial measurement units on the spine, breastbone, and extremities and later a phone on the wrist to collect data on gait, arm swing acceleration, and range of motion. The music was first matched to the individual comfortable walking pace and then adjusted to optimize the locomotor rhythm. The musical base had a clear rhythmic structure, a salient beat, and a stable tempo. However, six audio layers, including melody, harmonic accompaniment, snare, hi-hat, kick drum, and bass represented different motion components in varying the feedback flow. The music mix turned gradually more complex according to increasing sensor values. The app had four different tempi settings (106, 112, 118, and 125 bpm) but not an alternative musical genre to electro-pop. The musical feedback affected gait kinematics instantly, leading to a notable increase in the arm swing range of motion on the affected side (+529,5 % change compared to the baseline). The motion range, trunk rotation, stride length, and symmetry of arm swings increased. Thus, larger motion amplitudes with music led to more regular bilateral arm swings improving motor control.

Bevilacqua and colleagues (2018) also applied gesture-based digital musical instruments for stroke rehabilitation and evaluated the system for clinical settings in cooperation. They created an interactive system for sonifying reaching exercise, a regular repertoire for stroke patients often performed on a table by slowly moving the arm from one segment to another. Three inertial measurement units (IMUs) attached to each arm collected movement data, streaming it to a laptop in real-time. The sonification program written with Max7 generated the musical feedback. MuBu for Max library enables interactive machine learning and different sound synthesis techniques, such as granular and concatenative synthesis, combining short samples of recorded sounds (Schnell et al., 2009; Roads, 2004). Bevilacqua and colleagues (2018) compared three sonification methods, each with a specific mapping. The first solution linked reaching distance with a continuously changing pitch or tempo of a regular beat pattern, implemented with soft granular synthesis. In the second scenario, the arm movement played a complete musical phrase, and a maximum forward movement triggered four distinct notes and the backward movement the following four. The environmental model took through soundscapes with wind, rain, and birds, and it was the most favored model, followed by musical phrases. The direct motion mapping to pitch and tempo was perceptually apparent but least appreciated for being uninteresting and not motivating. As discussed, overall sound quality and interaction model are essential for motivation, and this case with eight participants was no exception.

Preliminary results of the reaching exercise study showed that sonification tends to slow movements. That has occurred in other studies. For instance, in a rotation task, C major scale interaction model made people with musical backgrounds pay more attention to sounds and rotate slower but more accurately (Ahmetovic et al., 2019). There, ascending scale notes led to the target angle, and after crossing it, the scale started to descend. People with non-musical backgrounds usually swayed back and forth on the highest note to ensure orientation, slowing the overall performance. However, learning the scale improved the rotation time significantly. Contrasting the outcome to results with musical expectancy, predictive timing, and forward modeling processes (De Lucia et al., 2009; Maes et al., 2014; Effenberg et al., 2016), the results are not necessarily contradictory. When sensory feedback facilitates motor learning, there are two goals, processing information on the quality of the performance and information on the completion of the task. Therefore, fast execution is not always better, and by concentrating simultaneously on the sounds and self-perception, the motion can be deliberately slow and more exact. Thus, when encountering a perceptual threshold, demarcation, change, stop, turn, angle, maximum point, etcetera, reacting to it goes with better precision. Also, environmental sounds without discrete musical steps may cause unhurried listening.

Getting beyond melodic arm swings and slides, *Danse Avec Moi* is a game that sonifies dance moves, providing real-time audio feedback for motoric relearning and stabilizing movement with a neurodegenerative disease such as Alzheimer's. Therefore, in addition to technical specifications, it has been necessary to consider patients' cognitive and physical restrictions. Everyone moves according to individual capabilities, and four optical accelerometers track the motion. Dance workouts gradually strengthen striding back and forth and sideways, turning, sitting, and getting up from a chair. The aim was to assess different sonifications, such as walking bass or traditional songs in MIDI format that enables adjusting the tempo to gestures, to see how the method fosters steadiness, ongoing training, and endurance to take the solution to care institutions and home-based workouts. (Spada & Bigand, 2017: 264–265.)

Likewise, Nikmaram and colleagues (2019) note that future research should address long-term plans and evaluate workout frequency and strain according to patients' needs and preferences. They even suggest algorithm-based evaluation of impairment severity, psychological status, and motivational drive. Nadri and colleagues (2019) had the same idea of combining advanced techniques for efficient synergy and achieving an ideal result. Few hybrid solutions that integrate different techniques, algorithmic detection, and perceptual and semantic schemes have shown impressive results in facilitating brain plasticity (Banf et al., 2016).

Musical sonification as auditory feedback can help improve motor skills. Music strengthens the connection between perception and action (Hommel et al., 2001), and audio feedback enhances self-awareness during the performance. Generally, musical sounds motivate by their enjoyable or playful character that impacts behavioral change (e.g., Godbout & Boyd, 2010; Newbold et al., 2016). Therefore, it is a promising method for motor relearning and enhancing neurological rehabilitation. However, conditions differ, and loss of motor skills, weakness, and clenched or clumsy hands cause apparent usability issues with gadgets and controllers, wearable technology, gloves, straps, batons, etcetera, leading to the need for assistance.

Furthermore, neurological disorders, such as aphasia or amusia within the picture, challenge designing user interfaces and can interfere with the intended musical interaction. Organizing the reaching exercise sonification study, Bevilacqua and colleagues (2018) ran the Montreal Battery of Evaluation of Amusia (MBEA). Typically, a person suffering from amusia has difficulties perceiving small, less than whole-tone changes in the succession resulting in troubles with distinction or recognition of melodies. Noticing other acoustic features, such as tempo or volume, is usually intact. Depending on the location of the lesion, amusia can affect several musical features or be specific with pitch or beat detection, recognizing music, or the emotional reactions it evokes. Congenital amusia is rare, whereas acquired amusia is relatively common, with an estimated half of the patients with an acute cerebral stroke. (Sihvonen et al., 2021.) Therefore, when examining how different end-users perceive sonifications in a rehabilitation context, the form of the musicality test requires special consideration. For generalizations, Nikmaram and colleagues (2019) excluded people with aphasia or additional neurological, psychiatric, or cognitive deficits in their arm-swing sonification study. The participants had an acute or subacute unilateral stroke but could perform arm movements without assisting with another arm. Thus, the study has limitations in real life, where the baseline situation is usually not nearly as good. However, choosing patients who might use self-rehabilitation programs is somewhat justified.

5.2 Relearning gait by adjustable and enjoyable external cue

Various conditions can affect walking characteristics. Internal motor programs govern the gait and contain control information for activating muscles with the right intensity and timing. While motor sequence learning turns a series of actions into automatic behavior, attentional resources can take on higher-level tasks. (Hunt, 2013.) Sensory-based motor adaptation is required to respond to environmental changes. Since subliminal patterns have developed over the years, behavioral change is demanding. Real-time audio feedback helps raise them back up to awareness for modification.

Audio feedback on motion enhances self-awareness during the performance. Traditional movement retraining interventions involve verbal feedback on movement to merge the new routine into the motor program. That is efficient, as is visual feedback, such as mirrors or video recordings, but these methods provide limited discrete and quantifiable information on kinematics. (Hunt, 2013.) Therefore, real-time sonification representing kinematics can enhance the desired motor relearning. Musical feedback strengthens the relearning process and affects motivation by mood regulation, but in addition, the midbrain reward system is also involved (Turner & Desmurget, 2010). According to Foerde and Shohamy (2011), the basal ganglia dopamine pump boosts feedback-dependent learning processes, and using audio feedback as an immediate reward is relevant for restoring the network, as they noted in patients with Parkinson's disease. Predicting pleasurable outcomes and acting to obtain them is motivating. Due to these factors, motor and hormonal activation, musical and rhythmic cues have direct, instant, and longer-term benefits on Parkinsonian gait (Ghai et al., 2018).

Generally, people walk faster and take longer strides with music than with metronome stimuli (Styns et al., 2007). Metronome provides obvious metrical information and is an exact, relentless phaser but a poor motivator. A discrete and uncompromising click or a strictly fixed tempo can sometimes harm the exercise. When Wittwer and colleagues (2013) compared metronome and rhythmic music as external auditory cues for walking, music was more efficient due to emotional aspects and motivational engagement. Also, the typically unstable Parkinsonian gait becomes more confident and steady with live musical stimuli (Spada & Bigand, 2017: 265). In addition to accentuating components, another inherent element of music, a continuous sound, leads evidently to better gait fluency than simple, discrete clicks (Young et al., 2016).

However, Parkinson's symptoms vary individually, and results with musical stimulation are inconsistent in different studies (e.g., de Dreu et al., 2012; Cochen De Cock et al., 2018; Dalla Bella, 2020). Rhythmic auditory cueing is often beneficial but can also distract gait, likely due to executive dysfunction (Wittwer et al., 2013). Synchronizing motion with an external rhythm requires temporal processing of the rhythm and the action, but difficulties with rhythm perception and synchronization are common in Parkinson's disease affecting this dual task (Grahn & Brett, 2009; Benoit et al., 2014). Working with the same issue, Cochen de Cock and colleagues (2018) uncovered some factors behind positive and non-positive responses. They noticed that while some participants increased speed and took longer steps with musical cues, others, even with almost intact baseline gait, got confused and worsened their performance. Patients who could track the beat enhanced their routine, but if not, walking was disturbed.

Interaction and initiating motion require integrating sensory information about the environment and our bodies (Véron-Delor et al., 2018). That is how we set muscle forces for the intended movement. Yet, a deficit in sensory feedback processing can affect initiating motion, as often happens with Parkinson's disease. It is the second most common neurodegenerative disorder after Alzheimer's, leading to motor and non-motor symptoms (Jankovic, 2008). Rehabilitative programs generally require consistent motion practice in daily activities. In addition, medication and neurosurgery, including deep brain stimulation, are traditional treatments (Véron-Delor et al., 2018; Mainka et al., 2021). However, these therapies have apparent constraints, and alternative methods are needed. Music is an all-encompassing cognitive stimulator that simultaneously presents an external auditory cue to help control movements. Perception precedes action, and they share resources in functional brain areas, efficiently activated by music (Hommel et al., 2001).

When Dotov and colleagues (2019) discussed dynamic system theories, particularly perception-action-based interaction, they noted that while action spontaneously entrains some perceptual information, successful synchronization requires saliency factors such as predictability and consistent variation, but also interactivity. While they compared the gait entrainment between two predictable and two interactive auditory stimuli, the mutually interactive condition showed the best results. Thus, interactive musical sounds complying with movements improve auditory-motor coupling. Effenberg and colleagues (2016) claim that supporting multisensory integration in motor learning by musical sounds works even subconsciously. Therefore, as they state, despite some restrictions in cognitive processing, music is still impactful. The intermodal real-time movement sonification method is adaptable in several motor rehabilitation contexts, such as post-stroke or orthopedic gait rehabilitation.

Adjustability and interaction stand out as critical issues in several studies. Individualized and interactive music stimulation enabling more spontaneous entrainment seems most promising for enhancing Parkinsonian gait (Hove et al., 2012; Dotov et al., 2019). Also, according to Ready and colleagues (2019), a flexible real-time modification that adapts to steps appears more beneficial than a fixed tempo. As generally observed, live music is more effective than recorded music in a therapeutic setting, conceivably for being strongly present and interacting. Live music performers set the tempo to the patient's movements and take rubato, stretch measures, or phrases.

Some semi-personalized music-based locomotion rehabilitation applications exploit the interactive tempo adaption idea. Mainka and colleagues (2021) started pursuing bilateral, symmetric arm swings by tracking and accelerating human locomotion. The solution Cochen De Cock and colleagues represent (2021) adjusts the musical features to individual gait dynamics modeled and measured with coupled oscillators and inertial sensors on the phone. The application first detects the natural walking pace and phase, generates synchronized music, and gradually accelerates the tempo by ten percent. Here, a musical genre assortment is another step toward personalization. While walking outdoors, Parkinsonian patients get step-synchronized performance feedback. By measuring usability, observance, tolerance, safety, and enjoyment, the study verified the hypothesis that the benefits overcome the risks of use, such as random gait disturbances or fear of falling in the woods or among crowds.

Hip or knee arthrosis patients often develop a faulty gait pattern too. While replacing the articular surface in an arthroplasty operation helps with pain, a symmetric and steady gait is hard to regain, weakening the quality of life (Reh et al., 2019). Reh and colleagues (2019) presented a twofold gait sonification method combining real-time feedback and instructive model sequences for relearning a symmetric gait. The motion-sound interconnection loop activated patterns between the auditory and motor networks, perception, and action. Thus, inertial sensors measured gait parameters such as ground contact and angular velocity of the knee joint, and each marker point triggered a sound. The ground contact resembled walking in heavy snow, whereas a sequence of xylophone strokes, quickly ascending, represented knee extension. The sound of the left leg was a major third lower than the sound of the right leg, and both sides panned to their channels. The instruction mode represented the model for the trajectory, the external goal, same sounds at a fixed tempo, demonstrating concatenating cyclic movements.

Step lengths of the affected and unaffected leg converged over time with sonification, making the gait more symmetric than without feedback. Stride length and time had a higher variability during the real-time feedback training compared to the instructional model sequence mode. Reh and colleagues (2019) regard the twofold method as suitable for supporting gait rehabilitation and home-based training for orthopedic patients. They note that implementation enables using multiple motion sounds and varying mappings, but different sonification types and their effects on the gait pattern require further empirical testing.

5.3 Fine motor skills through a writing exercise

Fine motor skills required for handwriting are often affected by Parkinson's disease, and half of the patients start writing small letters, which results from the inability to preserve constant writing force (Van Gemmert et al., 1999). In addition, it is challenging to synchronize wrist and finger movements when velocity, fluency, and fluctuations alter along penmanship. Therefore, Véron-Delor and colleagues (2018) examined graphomotor response to music and musical sonification. As a result, the writing speed increased significantly with musical sonification, and the improvement prevailed in the short term.

Although without neuroimaging, Véron-Delor and colleagues (2018) state that musical cues activate compensatory brain functions reducing strain on the impaired neural pathway. Accordingly, reorganization facilitates motor relearning. The sonification model turns writing into music practice, where the writer figuratively conducts music with a pen. The musical sonification lives to pen strokes in real-time, linking changes to kinematic thresholds. For instance, music distorts when the motion is dysfluent or too slow, and the aim is to show movement irregularities and provide auditory guidance based on rhythm. Thus, audio feedback expressed movement correctness and synchronized writing with the musical rhythm with a pleasant, motivating melody. Making music was an external, intentional goal. The positive results align with other studies concerning playful musical agency, even though the motion is in miniature scale (Fritz, 2017).

Handwriting per se may seem secondary in the digital world, but the benefits of fine-motor improvement are apparent. Clumsy or poorly functioning hands impact daily tasks such as eating, shaving, and dressing up, and thus, the quality of life. However, sonification-aided handwriting exercise benefits the visually impaired too. Their hands are functioning, but writing motor skills are challenging to develop, as Reid and Plimmer (2008) note. Regardless, we all must sign documents, contracts, and agreements, and the signature should be preferably repeatable and esthetically acceptable. Reid and Plimmer (2008) presented a multimodal system integrating sonification, haptic guidance, and tactile feedback to form letters and a signature without vision. Even a minor change in the pitch is discernible and illustrative, and combining that with panning simplifies the idea of position into two dimensions, creating an abstraction. The vertical pen stroke links to the pitch, and horizontal motion creates a stereo-panning effect. Spada and Bigand (2017: 262) state that for the visually impaired, stimulation to enhance motor skills, motivation, interaction, and cognitive competence is not a matter of rehabilitation or therapy. Adaptations of education are required to develop knowledge and skills, and music has multi-faceted efficacy in the field.

5.4 Visual impairment and mental constructions

Smartphones have enabled many new solutions to help our daily lives. They have also enhanced indoor navigation systems promoting the independence of the visually impaired. Therefore, representing quantitative information with non-visual and non-verbal instructions is essential, and musical sounds have assets in the role. Indoor navigation systems generally use beacons, simple gadgets sending an ultrasound signal that allows precise localization inside buildings, where satellite tracking does not work adequately (Ahmetovic et al., 2019). Subsequently, we can link the changing location to various rhythmic impulses, alternating pitch or melodic progressions, or utilize stereo-panning, for instance (Dubus & Bresin, 2013; Spagnol et al., 2018; Ahmetovic et al., 2019).

The visually impaired move through and explore spaces to enhance the connection between proprioception, perception, and action, all crucial for pedestrian safety. Assistive technology, sonification applications, and sensory substitution devices (SSDs) convert colors, dimensions, and contrasts to sounds according to perceptual and semantic schemes, often with music. These devices help the visually impaired detect things, explore and understand the surrounding world, and improve interaction with it (Banf & Blanz, 2013; Banf et al., 2016; Hamilton-Fletcher et al., 2022). Interpreting visual stimuli from sounds may be more challenging than seeing them in complex natural settings. However, with SSDs, the visually impaired can navigate crowded corridors while avoiding obstacles and even identify emotional facial expressions from a few meters away (Striem-Amit et al., 2012).

Sounds, conveying visual information, help the brain construct conscious three-dimensional models by activating the visual cortex (Merabet et al., 2009; Ward & Meijer, 2010). Similarly to visual perception, processing mental imagery activates several brain regions (Farah, 2000; Ganis et al., 2004). Striem-Amit and colleagues (2012) suggest that with auditory SSDs, blind people achieve much more detailed visual information than with other sight rehabilitation approaches. They showed that the congenitally blind could even pass the WHO blindness threshold with an SSD in the Snellen letter chart test. Ward and Meijer (2010) reported a study with two blind users of the vOICe SSD, although not musical in a traditional sense, describing detailed, conscious imagery that developed within months of intense audio visualization and continued to evolve over the years. The sound signals arouse imagination concerning the space and scenery. Eventually, the sensory substitution mapping between the auditory and visual domains was not limited to using the device, and therefore, Ward and Meijer (2010) talk about acquired synaesthesia.

Generally, SSD users have considered spatial information the most important source of information, and the devices were easier to use when the auditory feedback to the motion was instant (Hamilton-Fletcher et al., 2022). There is a reference to enactivism that involves ongoing interaction with the environment with a central assumption that cognition is not providing models but serves action and sensorimotor coupling (De Jaegher & Di Paolo, 2007). Thus, we construct the cognitive experience in dynamic interactions within a given situation (Varela et al., 1991). Music has great potential to convey information about spaces, scenes, materials, atmospheres, emotions, events, and motion. Presenting events in an auditory modality improves accessibility and helps move, understand changing situations, and participate. We can strengthen awareness by augmenting sounds in virtually any environment (e.g., Cohen, 1994 a & b; Walker et al., 2006), and musical soundscapes can deepen the cross-modal experience for everyone (Shams & Kim, 2010).

Banf and Blanz (2013) represented a sonification model where the counterparts of the visual elements map to perceptual and semantic schemes. The user explores the scenery on a touch screen and receives auditory feedback about the content at each position, similar to reading a Braille text. Since analyzing and understanding images depend on the user, Banf and Blanz call the technique auditory image understanding. The system combines low-level information, such as colors, with high-level features produced by algorithms. Direct audio icons represent recognizable objects as such (dogs on the street), and synthesizers create colors with musical sounds. For instance, two adjacent sine waves create an intense tremolo for red, whereas a soft rhythm of harmonic sine waves generates a calm green. Rhythmic patterns represent built structures, a typical solution in similar applications, and rain-like brown noise conveys the natural roughness. In addition, stereo panning, projection, and fading of the sound exhibit spatial information. That is how landscapes transform into soundscape impressions.

Pattern recognition as a human cognitive task relies on contours and shapes that we compare to images saved in our memory (Braisby et al., 2012: 105–106). The same principles apply to machine vision with pattern recognition algorithms. Even though we process sounds fundamentally differently from visual stimuli, Kramer (1994: 15) described follow-up tasks similarly by template matching. Once we know the sound and its meaning, we can match the acoustic pattern to the catalog of familiar sounds. According to Kramer (1994), the difference between the explorative and follow-up tasks is that when exploring a strange environment, the data does not enable presumptions and matching, and we need context. Banf and Blanz (2013) showed that with context and musical sounds, the visually impaired could understand the general scenery remarkably well and recognize objects quickly and meticulously. Later, Banf and colleagues (2016) developed the system further regarding navigation and mobile use. In this edition, pre-sampled tone arch types expressed the opponent colors, and mixed samples represented color mixtures. The contrast value from white to black was attached to hues and represented with musical scales. Subsequently, verbal descriptions of the images became even more precise, and the users considered the application intuitive. Contrary to Noordzij and colleagues' (2006) findings on the continuous route model, the visually impaired could generate survey-like representations, probably due to the mixed method with a tactile map (Cattaneo et al., 2008).

Reich and colleagues (2012) point out that our brain is remarkably flexible and eventually more task-oriented than sensory-based. The statement holds chances for visual neuro-rehabilitation long thought unachievable. Replacing the visual sense with other modalities in different systems creates valuable information on the effect of blindness on the organization of the brain (Striem-Amit et al., 2012; Banf et al., 2016). The results imply that cognitive stimulation enhances plasticity and enables restoring visual acuity for early-onset and congenitally blind (Striem-Amit et al., 2012). Cross-modal training promotes brain plasticity (Ward & Meijer, 2010), and therefore, it can be beneficial before and after invasive procedures, during temporary sight loss, or visual field defects. As the saying goes, "our eyes look, but the brain sees."

5.5 Chronic pain, self-awareness and pacing

Incurable and debilitating chronic pain affects about a fifth of the population (Breivik, 2006). It is often self-managed, even though physiotherapists recommend physical activities with everyday tasks. Therefore, Singh and colleagues (2017) examined the impact of sonifying motion in mundane domestic chores, such as loading the dishwasher, to support pacing and other pain management techniques. While preparing, the users recorded three individual marker points for changing the sound: an upright position, stretching confidently despite the pain, and the goal beyond. The smartphone gyroscope tracked the motion, and the implementation included three alternative sounds.

Firstly, ascending tones led from standing up to the comfortable stretching boundary, and descending tones designated approaching the goal maximum point. After that, the sound flattened out and kept repeating. While moving backward, the sonification reversed. In the water sound condition, crossing the comfortable point played a splash, and other movements generated the sound of running water. The third version did not read the markers but transformed the motion into windchime sounds. On their part, Newbold and colleagues (2016) examined how embodied, musically-informed movement sonification helps avoid excess strain and facilitates stretching exercises to manage and alleviate chronic pain. They sonified a target point in a stretch exercise with a stable, musically resolved cadence to indicate movement ending and an unresolved sound to motivate continuation.

Singh and colleagues (2017) concluded that real-time sonification increases the feeling of control during domestic tasks with chronic pain. Newbold and others (2016) underline that with chronic pain, it is crucial to be aware of the balance between physical capacity and safe boundaries in necessary exercises and activities since overdoing leads to setbacks. System calibration to individual needs and strengthening self-awareness with music enables discovering the fine line between physical capabilities and overdoing, otherwise blurred by pain or a dysfunctional proprioceptive system.

5.6 Affective computing

Traditionally, human-computer interaction is more unidirectional information processing than genuine interaction between the computer and the user. The next generation of computer interfaces with affective computing aims to create ostensibly balanced interactive environments supporting the motivational and affective goals of the user. Affective computing relates to, arises from, or deliberately influences our affective states (Picard, 1997) by expressing feelings or targeting the underlying mechanisms. Thus, these computing systems can recognize, interpret and simulate emotions.

Winters and Wanderley (2013) present musical sonification based on affective computing as a trigger and a display of emotions. When discussing sonification strategies for continuous representation of arousal and valence (Russell, 1980), they nominate the brainstem reflex, the primitive rhythmic appeal, and contagion, transferable emotions, as the most convenient frameworks. Diverse technologies have enabled real-time recognition and sonification of motion and emotion, and advanced systems combine affective computing with algorithmic composing (Giomi, 2020; Landry & Jeon, 2020; Zhang, 2015). Therefore, active, expressive therapy with artistic features can employ musical sonification as a creative, interactive tool (Giomi 2020).

Bläsing and Zimmermann (2021) addressed multiple issues on sonifying expressive motion. They state that sonification can reach , the core of the dance art form and provide explicit choreographic information for the blind. Dancing as an embodied musical experience and training method improves body awareness, balance, gait speed, and the ability to reach forward (Larsson & Frändin, 2006). is recognized and accordingly integrated into training methods. When the body is an artistic medium conveying emotion (e.g., Orgs et al., 2018), motion is more than mechanics. Dance can be light, airy, fragile, grounded, or strong, and sonification needs to support the perceptual quality of the motion. How performers encode and listeners decode emotional cues in music and dance are relevant questions in dance sonification research (Camurri et al., 2003).

Niewiadomski and colleagues (2019) based their dance movement sonification model on the assumption that certain spectral features of a sound can contribute to the cross-modal perception of the movement quality. They followed the central idea that observers do not give equal importance to all perceived movements, and some features are predominant. The computational model follows the same principle, detecting low-level features first, then evaluating saliency, and subsequently detecting mid-level features and nuances. In their case study, Niewiadomski and colleagues (2019) created sonification models for lightness and fragility, two distinct movement types. Specifications for lightness include spectral smoothness and polarity between light and heavy, whereas fragility lacks both, representing sudden and non-periodic alterations and discontinuities with frequent silence breaks. Reybrouck (2017: 58) presented a similar distinction between discrete and continuous models, where structural knowledge of music can rely on pre-existing concepts of the unfolding or ephemeral experience. IMU sensors on wrists and ankles produced the source data, fifty frames per second with an accelerometer, gyroscope, and magnetometer, each with three points in space (x, y, z). The prevalence of one movement type component produced the correlated sound with a granulator running on Max/MSP. Audio extension Max Signal Processing MSP enables advanced real-time sound manipulation, simultaneously processing several data lists.

Even our everyday movements reflect our emotions and mental states (Roether et al., 2009; Saarikallio et al., 2013). For instance, depression causes problems in identifying, expressing, and regulating emotions and affects movement expression, resulting in a slow gait and collapsed postures that worsen helplessness (Punkanen et al., 2017). Body motion is essential for perceiving and producing emotion and, therefore, useful in depression treatment. The statistics show that depression affects over 280 million people globally (WHO, Fact Sheets 28.11.2022) and 8.8 percent of the Finnish population (Eurostat, EU Statistics 28.11.2022). It is a prominent public economy issue. Movement therapy is a cost-efficient alternative for managing emotions. Generally, dancing enhances the interaction between musical flow, the self, and the environment, while group activities enhance social cohesion and positive moods. Music and dance are both considered non-verbal languages of emotional communication, and not everybody can verbalize feelings or express them by playing an instrument. According to Reybrouck (2017: 58), music's meaning might not be verbalizable or reducible structural knowledge. Therefore, we should process expression with musical terms.

Lacking emotional communication and social interaction skills makes many situations difficult for people with autism spectrum disorders. Recognizing facial emotions may also be impaired in Alzheimer's disease (Hargrave et al., 2002). To support interpreting situations and help communication, Zhang and colleagues (2015) developed an emotion orchestration robot that generates real-time sonification based on facial expression detection software and interaction models. The method derives from the familiar idea that music induces, conveys, and regulates emotions. Thus, the robot fosters social interaction and promotes expressing and understanding emotions with music. In addition to facial expressions, even simple involuntary motion cues are essential in communication (Koppensteiner, 2013). Therefore, framing short cycles of motion may suffice for the grounding dataset. In addition, Niewiadomski and colleagues (2019) studied embodied sonic training methods of experiencing own body movements by interactive sonification. As they state, the cross-correlation, non-verbal whole-body movement expression bound to sound can also serve communication and social interaction in multimodal interfaces.

Landry and Jeon (2020) discussed the potential of musical sonification in communicating cognitive information, motion, emotions, and aesthetics. When affective computing combines with algorithmic composing, real-time sonification is already quite complex, as are specifications. However, technologies evolve, and with enough data, intelligent algorithms can deep-learn rules and regularities and eventually grasp a language. Compared to the language syntax, our body language, the natural movement, is multidimensional with individual entropy, a degree of chaos. However, reoccurring principal components representing prevailing motion features can be detected and extracted from the kinematic data.

Niewiadomski and others (2019) implemented their case studies with perceptually apparent sounds, more environmental than musical in a traditional sense. However, Landry and Jeon (2020) assume the same elements that make sonifications more musical, such as discrete pitches, quantized rhythms, and multiple instruments, increase emotional expressivity ratings. In addition, compared to a plain melody, arrangement with accompanying instruments such as drums and bass increased the emotional expressivity of the music. Contagion, and salient rhythms, as Winters and Wanderley (2013) said. Landry and Jeon (2020) positioned discrete emotions on the continuum of two dimensions of arousal and valence, similar to Russel's (1980) model. Yet, generalizing the results requires further studies. Here, the dancer did not have genuinely interactive control over the sound, and an objective evaluation of the sonification is needed, the issue addressed in several studies (Kramer et al., 1994; Pirhonen et al., 2006). However, several musical sonification models clarified and deepened the emotional content of the movement, with similar results to other cross-modal affect studies.

6 DISCUSSION

Music is a powerful and flexible tool in rehabilitation. It alters mood, motivates, and includes rhythmic components for accentuating motion while strengthening self-awareness and the connection between perception and action. The continuous process of perception and action encompasses introspection and interaction with the external world, connecting the self with our environment. Here, by music. This action-related cognition has clear functional relevance.

Music perception and production entail embodied movements, from tapping to rhythmic gait, expressive gestures, and skilled instrumental performances. Making music generally represents a motor behavior area with a detailed output based on the quality of the input, whether it is pressing a key, hitting a drum strike, or any other motor control. For instance, Effenberg and colleagues (2016) turned the rowing ergometer into a musical instrument to refine techniques for rowing. The sonification output can be very enlightening. Furthermore, sonified body motion that enables a straightforward musical expression for instrument-illiterate or -disabled is a notable addition to the therapeutic repertoire.

Based on psychoacoustics, musical signals can be audible yet enjoyable, with psychological effects on understanding the message, successful interaction, motivation, and usability. Music evolves in time, so it is appropriate for representing dynamic events, motion with emotion, and performance quality. Transformability creates an intuitive sense of direction with metric information. Generally, understanding alteration with music is relatively easy because we perceive notes in the continuum related to each other, which makes comparing and remembering the values effortless. These values can represent kinematic information.

In addition, cyclic musical time based on repetition results in entrainment and predictive timing in action plan schemas (Huron, 2006; De Lucia et al., 2009). These structural benchmarks create external goals that help accentuate and synchronize the motion, simultaneously activating several brain areas. Therefore, music is a promising method with motor and sensory impairments, enhancing exercise and therapy effects in rehabilitation. Multimodal stimuli improve precision in motor perception, motor control, and learning (Effenberg et al., 2016). To illustrate all this (in figure 1), I present a summation of musical sonification according to Maes, Buhmann, and Leman (2016). It is a three 3Mo model where mos stand for motivation, monitoring, and modification.

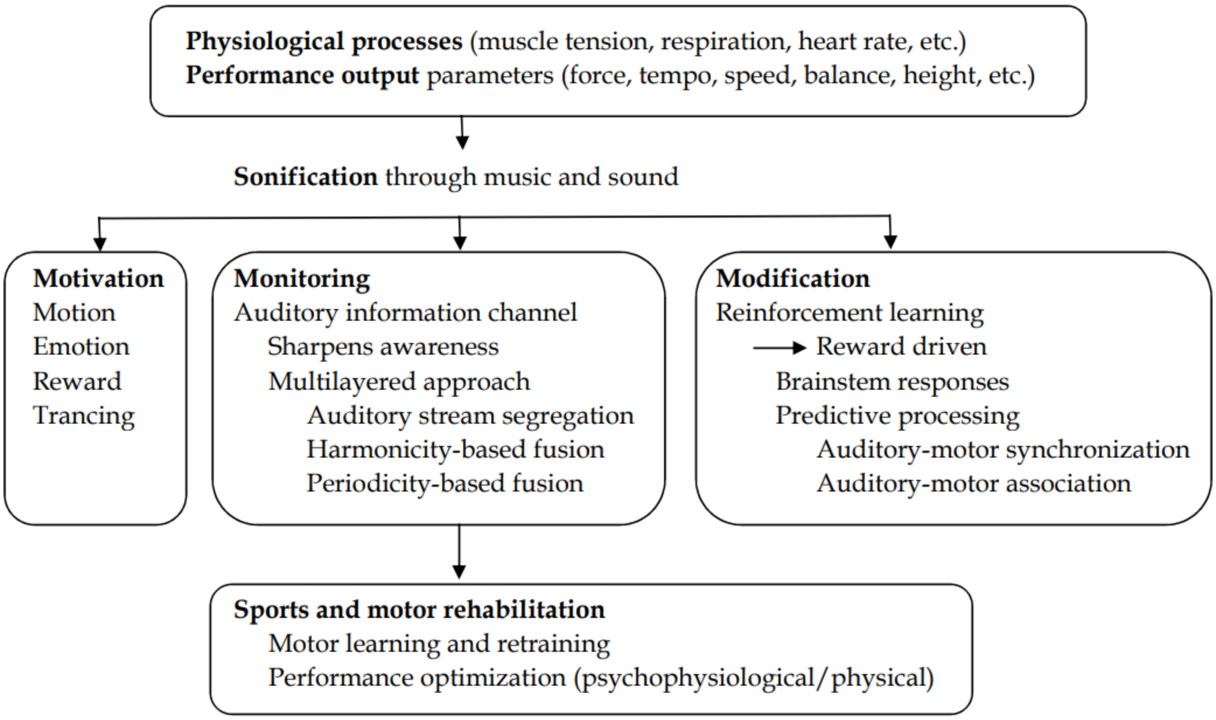

FIGURE 1 3Mo model for motivation, monitoring, and modification (Maes et al., 2016).

After this overview, I will return to my first research question on taking real-time musical feedback applications home to support daily exercises that rehabilitative programs generally require. Since the supervised therapy sessions are often weekly or less frequent, facilitating home-based workouts is essential. In addition, feeling more functional at home, in a meaningful environment, contributes to all-around motivation. There are several requirements for successful implementation, but convenient theoretical tools for addressing them too. I will start with the use scenario specification.

According to a semiotic approach, auditory displays should match the conceptual definition of the information they represent, or auditory interfaces start to reflect empirical knowledge and subjective preferences with random sounds (Pirhonen et al., 2006). Therefore, Pirhonen and colleagues (2006) developed a theoretical framework based on creating a detailed use scenario that includes the specifications of the user, the task, and the goal. Professionals and end-users should participate in and comment on the outline to produce the most convenient way to use a sound in a specific context. When designing sound interaction, we need to identify the roles sounds have between users and products, services, and the environment. The aim is to support the user in reaching optimal performance. Thus, the sound type, manipulation methods, etcetera, need to be defined. This method applies to virtually any technical specification project, but first and foremost, it underlines the importance of regarding the user group.

The variety of interaction models between human and musical sounds in literature provides suitable hypotheses for the computational models of auditory displays. Understanding embodied music interaction, how we process music, and the psychoacoustic principles are the basis for sound design. However, considering specific situations and individual needs is necessary. Still, arbitrary health issues and neurological disorders can interfere with intended interaction resulting in discrepancies with generally impactful models. For a researcher, case-specificity makes it challenging to organize an experimental study with the rigor the scientific method requires (Spada & Bigand, 2017: 264). Therefore, the literature exhibits few studies that can conclusively show the effectiveness of the interventions. Thus, Nikmaram and colleagues (2019) acknowledge the supplementary role in neurorehabilitation and the benefits of motivational factors but are reserved about the clinical benefits.

Difficulties with rhythm perception and synchronization, common in Parkinson's disease, could be defeated with an adjustable tempo, starting by analyzing the individual locomotion instead of a given tempo (Cochen de Cock et al., 2021; Mainka et al., 2021). Perhaps unexpectedly, the prevalence of another type of inability to follow the music, amusia, is also relatively high, with half of the patients after acute cerebral stroke (Sihvonen et al., 2021). As a result, detecting rhythm or changes in musical succession, remembering music, or producing emotional reactions to it might be unattainable. Therefore, sometimes more ambient environmental sounds may serve better than musical scaffolding. It is essential to examine how different end-users perceive and act to sonifications while acknowledging that we can define the user group only to a certain extent. Varying health conditions, subjective evaluations, or reactions to music, do not make a homogenous group. In addition, relatively common brain injury-related aphasia, one-handedness, and clumsy or clenched hands challenge designing convenient user interfaces and controllers. Considering specific situations and individual needs is essential.

Subtleness and appropriate expediency are salient themes in designing musical interaction and equipment in rehabilitation and assistive technology. Reports on usability issues concerning controllers were rare in the literature. Nowadays, IMU sensors, for instance, are compact and easy to slip into a wristband, and in some cases, a phone in a custom pocket sufficed for measurements. Earlier, robust, clumsy devices have hindered sound-aided technology from going commercial by being expensive, impractical, embarrassing in public, or the soundscape was considered annoying (e.g., Elli et al., 2014; Hamilton-Fletcher et al., 2022). In addition, heavy equipment attached to extremities would slide down in motion, disturb, and be challenging to readjust, especially with clumsy hands or one-handedly. Saluting the technical development, conveniently tiny and yet affordable equipment is obtainable. Furthermore, according to user experience requests, many of the musically informed technical solutions are pleasant, motivational, and fun (e.g., Fritz et al., 2013; Scholz et al., 2016; Ahmetovic et al., 2019). That is promising for deploying supplementary means for consistent home-based and goal-directed rehabilitation exercises providing better chances for improving functionality.

There are guidelines and estimations for musical features to prompt desired outcomes, but it would be all too easy to produce systematically identical motion output with specific musical input components. Yes, the low-voice superiority effect carries in rhythmic information efficiently (Hove et al., 2014), regularity transfers to sensory-motor behavior (Senn et al., 2018), and vertical and lateral gross and fine body motions correlate to certain musical metric levels (Toiviainen et al., 2010). However, our dynamic system is more complicated than that. Personality characteristics, individual entropy, and musical experience, not to mention life experience, impact how sound embodies, which makes the equation rather challenging. Yet, in rehabilitation, empirical studies do not just make mathematical models alive but involve real-life situations and sometimes tragedies. Therapy depends on the music but also on how the client is experiencing it. Music relaxing or motivating to one might not be that to another. The response is situational, a matter of taste, and a sum of our past experiences, forming a substantial motivational factor we need to regard in planning an independent exercise.

Hunt (2013) notes that identifying preferences and personalizing intervention helps optimize effectiveness. Yet he stresses the importance of constant practice in reprogramming motor functions. Thus, healthcare professionals could help find and configure individual settings and objectives for workout routines between supervised sessions, determine the plan and ensure engagement with it. Developing efficient exercises with new technologies requires candid patients and professionals, both with commitment. Hunt (2013) describes a practical cooperation protocol for starting sound-assisted motor relearning with the first steps of explaining and setting the goal for movement modification and taking enough time to rehearse the new movement with real-time feedback.

Historical circumstances have given rise to numerous disconnected experiments with audio-aided solutions. So far, technical limitations and consequent design choices have constrained their potential. However, the recent exponential development in computing efficiency has enabled new solutions. Yet, taking the algorithms to clinical use or home-based training does not happen solely between the patient and a therapist or an engineer. The system requires multidisciplinary cooperation with different professionals and clients, which was a recurrent theme in the literature. Supervised exercises in clinical environments probably require adaptation to conditions at home. Also, occasionally empirical studies presented rough participant exclusions for generalizations, which can affect feasibility. However, inconsistencies in empirical studies lead to valuable test scenarios and adjusting variants for further studies. Many of the described solutions had the underlying agenda of being eligible for clinical settings (e.g., Spada & Bigand, 2017; Véron-Delor et al., 2018; Bevilacqua et al., 2018) and home exercises (Singh et al., 2017; Cochen de Cock et al., 2021; Nikmaram, 2021; Mainka, 2021) or developing standardization for people with special needs (Ahmetovic et al., 2019).

Identifying reasons behind the negligible diffusion of sensory substitution devices in the blind community, Elli and colleagues (2014) examined neurocognitive, psychosocial, and ergonomic issues associated with use. They underlined the relevance of addressing factors on a broader scope in developing solutions. Suggesting a multidisciplinary and participatory approach, they remark that cooperation leads to fundamental theoretical research questions and an understanding of customers' everyday needs, eventually promoting new technologies. Combining different techniques to deliver advanced models for meeting patients' individual needs and preferences is a future challenge. Complicated, but by tightening interdisciplinary cooperation to get an idea to practice with adequate knowledge and proper specifications, it could be feasible. But how? That happens at the crossroads of theoretical frameworks, applied sciences, and practice. Music therapy integrates several branches of science to serve many situations and needs. Yet combined with new technologies and the sonification field, the variety of overlapping potential theoretical frameworks is massive. Hypotheses derive from psychology, medicine, cognitive sciences, and psychoacoustics, whereas applied sciences and practice validate them. Occupational therapy, audio engineering, computer music, and product design are all there, with the client at the center.

Thus, getting to the second research question, we can tighten interdisciplinary cooperation to get an idea to practice with open discussion and bold discipline crossover by taking inventions in one niche to another. However, that requires systematic work. First, even though available solutions and applied science projects utilizing sonification are numerous, scattered literature reflects the core challenges of the vast field. The spectrum of sound-aided and musically informed technical solutions in sports, rehabilitation, and adaptive learning is extensive but siloed. Therefore, the lack of synergy for combining methods for the optimal outcome or adopting single strong ideas from one use to another was apparent. Had I chosen one diagnosis or one technique for the scope, this study would not be such an eclectic idea collection. However, at the same time, I would have supported the prevailing structural segregation instead of getting acquainted with functional, musically informed practices by crisscrossing. That is how hybrid solutions refine.

Second, there is a contrasting difference in regulation between the disciplines that should cooperate here. In laboratory-based research, a single researcher performs the study within one area, while applied research has a more multidisciplinary touch but different monetary mechanisms and agendas. Healthcare is a heavily regulated domain with many conventions. If a study aims to enhance the information on health, reasons or symptoms of disease, diagnostics, or prevention, the law of medical research (488/1999, 295/2004, 794/2010) applies. The procedures of registering for clinical trials, getting approval from the local ethics committee, and acquiring the written consent from the study subjects can be arduous. Developing and refining an interdisciplinary clinical protocol requires broad research and multiple case studies to gather the necessary information to validate large-scale trials and, eventually, define elements of clinical assessment, interventions, and practice.

On the other hand, the legislation often follows agile computer science with a delay. The General Data Protection Regulation (2016/679), GDPR, and Data Protection Act (1050/2018), for instance, are recent developments that address questions digitalization has brought. The aim is to enhance individuals' control and rights over personal data while our lives are in databases and online. Also, in audio design, apart from some OpenSource standardization attempts (Ben-Tal et al., 2002), regulation seemed weak till the recent accessibility directives and smartphone-affiliated audio navigation standard (ITU-T F.921/2018). Eventually, technology-neutral solutions are essential to implementation, usability, and compatibility in commercial use.

While the semiotic approach covers sound design and technical implementation, we cannot ignore the ecosystem around it. Therefore, my second research question links to the first one, and by answering it, I will describe the preceding steps for the actual implementation. When surveying the dispersed field, the activity theory approach (e.g., Engeström, 1999) is convenient for depicting prevailing regulations, interactions, and expectations. It recognizes cultural norms, rules, and regulations too. Thus, the theory promotes dialogue between theory and practice. It acknowledges the past and the present to let us learn for the future. To develop using tools and methods to solve a problem or perform a task, taking hold of the current state through a literature review is one of the initial steps. Subsequently, research questions and study designs arise, including methods, systems, materials, and approvals. We need to make observations and interviews and collect qualitative and quantitative data. Eventually, statistical models and valid methodology help analyze and conclude results and reflect on practice. The impacts are on several levels, creating knowledge with practical relevance, generalizing findings, and sharing them with the community.

Conveniently, despite the current wide application area, the inventors of the activity theory have a background in rehabilitation work. The academic work of Alexander Luria (1902–1977) intertwines with his profession as a medical doctor as he developed neuropsychological examination methods for patients with brain damage moreover treatments for restoring speech in the case of trauma or aphasia. On his part, Alexei Leontiev (1903–1979) worked with injured soldiers, rehabilitating movement functions, which led to theoretical results and practice-based innovations. Alexander Meshcheryakov (1923–1974) developed adaptational education methods for children with multisensory impairments. (Sannino et al., 2009: 5.) The world was very different a hundred years ago, but it was apparent, already then, that a deep understanding of the symptoms is paramount in rehabilitation practice and that patients' activity, means, motives, and goals also play a substantial role.

Then, to address my third research question, there is evidence that combined with professional supervised therapy, independent exercises with augmented sensory feedback accelerate the process of improving functionality (e.g., Molier et al., 2010; Hunt, 2013; Reh et al., 2019). With a more extensive scope, Molier and colleagues (2010) note that while augmented feedback generally is beneficial, multiple variants and feedback types in studies make it impossible to unveil the most efficient combinations or underlying mechanisms. Embodied music cognition explains the effectiveness of musical sounds where the successful interaction results from music's inherent properties, such as contagious layered pulsations, perceivable scaffolding and continuity, the connection between perception and action, and engaging emotional and cognitive processing. Some studies suggest that musical sounds can even work subconsciously, below cognitive processing, conveniently overlooking neurological dysfunctions (Effenberg et al., 2016).

Looking at the Kela statistics, perhaps surprisingly, the mean age of the new rehabilitants was relatively low, at thirty-three years (Statistics, 26.9.2022). Therefore, considering new, often smartphone-based solutions and the playful nature of applications, technology acceptance is likely. Studies in this review reported that rehabilitants thought the methods were frequently enjoyable and motivational. That is substantial in implementing solutions to daily domestic exercises. Different hybrid techniques have taken steps forward, and the relatively recent smartphone coverage and other obtainable hardware have enabled many new solutions. Finding hope and drive in new technology in a long-term situation requiring absolute persistence, music-aided, emotionally appealing motion practice has unemployed potential.

In 2021, the largest rehabilitation group at Kela, with over a hundred thousand customers, was mental and behavioral disorders. Over sixty thousand clients were in rehabilitative psychotherapy, forming a prominent public economy issue worth over a hundred million euros. (Statistics, Kela 26.9.2022). Depression is part of the concern, bringing associative problems in identifying and expressing emotions and impacting movements (Punkanen et al., 2017). Accordingly, body motion is essential for perceiving and expressing affective states, and therefore, systems that recognize and simulate emotions with music can provide tools for expressive therapy (Giomi, 2020; Landry & Jeon, 2020). Advanced software transforms functions and environments into musical sounds with an intuitive outcome improving accessibility, the possibility of participation, and supporting independent life despite sensory or motor deficiencies. However, simple implementations, such as the commonly used C major scale, were influential too. The literature presented several different sonification methods with two main approaches. Either music induced, entrained, and gradually modified the movement or moving produced musical (bio)feedback from scratch. Sometimes methods involving musical entrainment and feedback were seen as separate phenomena (e.g., Mainka, 2021), but usually, they were just different aspects of augmented musical feedback and both effective.

The second-largest Kela rehabilitation group is musculoskeletal disorders, with around ten percent of the rehabilitation clients, followed by a neurological disorder group of almost the same size. (Statistics, Kela 26.9.2022). Music and dance therapies are effective with motor and cognitive deficits, encouraging movement activities and social participation. Dancing facilitates interaction, and task-oriented musical and physical activity induces hormones that dispel the exertion and work as a reward speeding the learning process (Fritz, 2013; Turner & Desmurget, 2010; Foerde & Shohamy, 2011). All of this leads to better well-being.

In addition to measuring trajectories or evaluating the quality of performance in physical activities, rehabilitation often includes verbal consultation. For instance, during COVID-19 general restrictions, Kela dismantled some regulations, and neuropsychological rehabilitation went online. Even though it is primarily discussion, the rationale for the one-to-one live meeting requirement has been that therapists want to see and evaluate the client's body language and alertness. Examining body language musical sonification as a supplementary status display in between consultations or during sessions would be interesting. Thus, the client could be more aware of the mood and energy levels and consequently concentrate on the regulation, while the application could collect and display the dataset. Thought experiment, maybe, but it is not that far-fetched in this biohacking era.

We give involuntary motion cues (Koppensteiner, 2013), and our autonomic nervous system reacts to affective states, such as anxiety. Some auditory interfaces already map corresponding physiological signals, such as electrodermal activity, temperature, heart rate, and respiration, to musical components (Cheung et al., 2016). The low processing costs, improved science literacy, self-reflection, and velocity of hypotheses are recognized advantages of self-measuring experimentations compared to conventional health studies (Dolejsova et al., 2017). However, the potential is justifiably tailed by the legislation and shadowed by privacy-related concerns, and the scientific validity can be limited.

Nevertheless, already evidently, music strengthens interconnectivity by activating several brain areas and enhances brain plasticity, providing remarkable results with various types of injuries and illnesses (Ward & Meijer, 2010; Striem-Amit et al., 2012; Banf et al., 2016; Sihvonen et al., 2021). Music is a non-invasive and non-pharmacological method for brain and motor function recovery, a cognitive stimulator that enables alternative ways to improve well-being. Musical sounds can compensate for sensory impairment or lost proprioception, help relearn motor functions, and optimize pacing. In addition, sensory substitution solutions provide affordable cross-modal training that is beneficial as supplementing therapy, before and after invasive procedures, and during temporary sight loss or visual field loss. As Spada and Bigand (2017: 261) state, understanding the cognitive and neural mechanisms that facilitate neural plasticity has clear significance for society in healthcare, education, and technology. That is what we can learn and do with music.

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