Movement Sonification of Familiar Music to Support the Agency of People with Chronic Pain

Kyrill Potapov
UCL Interaction Centre, University College London
London, United Kingdom
kyrill.potapov@ucl.ac.uk

Nicolas Gold
UCL Computer Science, University College London
London, United Kingdom
n.gold@ucl.ac.uk

Temitayo Olugbade
School of Engineering and Informatics, University of Sussex
Brighton, United Kingdom
t.olugbade@sussex.ac.uk

Amanda C de C Williams
Department of Clinical, Educational & Health Psychology, University College London
London, United Kingdom
amanda.williams@ucl.ac.uk

Christopher Dieter Overbeck
UCL Computer Science, University College London
London, United Kingdom
chris@overbeckmusic.com

Danielle Lynch
His Majesty's Civil Service
London, United Kingdom

Minna Nygren
UCL Interaction Centre, University College London
London, United Kingdom
minna.nygren@ucl.ac.uk

Nadia Berthouze
UCL Interaction Centre, University College London
London, United Kingdom
n.berthouze@ucl.ac.uk

Abstract

FFAME (Filtering Familiar Audio for Movement Exploration) is a novel sonification framework aiming to facilitate movement in individuals with chronic back pain. Our personalised, music-based approach contrasts and extends prior work with predetermined tonal sonification. FFAME progressively filters selected music based on angles of the trunk. Through a qualitative analysis of reported experience of 15 participants with chronic pain and 5 physiotherapists, we identify how sonification parameters and musical characteristics affect movement and meaning-making. Music-based movement sonification proved impactful across multiple dimensions: (1) encouraging movement, (2) escaping pain-related rumination, (3) externalizing pain experiences, and (4) scaffolding physical activities. Drawing on enactivism and related philosophies, the study highlights how the semantic indeterminacy of music, combined with real-time movement sonification, created a rich, open-ended environment that supported user agency and exploration. Sonification for pain management can be creative and expressive, enabling people with pain to extend challenging movements and build movement confidence.

CCS Concepts

• **Human-centered computing → Auditory feedback**; **HCI theory, concepts and models**; **Empirical studies in HCI**.

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movement sonification, chronic pain, agency, sensors, music, enactivism

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1 Introduction

Chronic musculoskeletal pain is a debilitating condition that affects millions of people worldwide. While physical activity is crucial for maintaining general health and performing everyday activities, people with chronic pain often avoid movement due to fears of causing further damage or exacerbating their pain. This fear-avoidance behaviour can lead to a vicious cycle of decreased physical function, increased pain, and reduced quality of life [58]. Recent research suggests that supportive approaches focused on enhancing patients' understanding of their condition and promoting a sense of agency in everyday life may be effective in managing chronic pain [29, 59]. In this context, the use of sonification, a technique that translates real-time movement data into sound, has shown promise as a means of encouraging physical activity and providing meaningful feedback to people with chronic pain [41].

This study explores the potential of a novel sonification framework, Filtering Familiar Audio for Movement Exploration (FFAME), to support agency and movement in people with chronic back pain. The FFAME system uses familiar music chosen by its user and alters its playback based on the user's body movements, creating a personalised and engaging experience. Through a qualitative approach, we aim to understand participants' experiences with the FFAME system and its impact on their movement, pain perception, and sense of agency. We consider how FFAME is implicated in participants' *meaning-making* as they engage in movements perceived as challenging: how the experience of the sonification is interpreted as personally relevant to the user's goals, values, knowledge and emotions. By providing an open-ended and exploratory setting, we explore benefits and limitations of this novel sonification technique in the context of chronic pain management. The findings contribute to the design of innovative strategies for supporting physical activity and meaning-making for people living with chronic pain.

2 Related Work

2.1 Chronic pain and movement avoidance

Chronic musculoskeletal pain is a prevalent health issue affecting a significant portion of the global population. It is characterised by persistent pain in the muscles, joints, and bones, lasting for more than three months, and often for many years [44]. The impact of chronic musculoskeletal pain is multifaceted, influencing not only physical health but also mental well-being and quality of life. It can lead to reduced mobility, impaired physical function, and increased engagement with healthcare [58]. It is associated with psychological distress, including depression and anxiety, exacerbating the overall burden of the condition [19].

Fear and avoidance are common responses to chronic musculoskeletal pain. Individuals with chronic pain may hold the belief that movement is the cause of pain or risks causing damage [37]. As result, they may limit or constrain movement or desist from initiating movement. While these behaviours may initially protect a healing injury, over time, they can lead to physical deconditioning, increased pain, and further functional impairment [36]. Fear and avoidance can also contribute to the development of chronic pain, as it promotes a sedentary lifestyle and undermines recovery [69].

Finding strategies to remain physically active is a critical and challenging part of self-directed chronic pain management [3, 56]. A common strategy in managing conditions with an identifiable biomechanical basis involves assessing and correcting movement patterns [45]. However, in the case of chronic pain with no underlying tissue damage, the benefits of such an approach will be very limited [35]. It is instead recommended to take a more holistic approach, helping people with chronic pain to build confidence for movement [6, 20].

2.2 Supporting agency

Research increasingly recommends psychological interventions in chronic pain management focused on supporting patients' agency in everyday life [29, 59]. Agency can be said to depend on our possibilities for action or affordances [68]. Croninx & Stilwell [7] argue that chronic pain involves the limiting or transformation of affordances. For instance, climbing the stairs may be perceived as having a negative valence and thus may not be a salient possibility for action.

Following Vygotsky, we can think of agency in terms of two interconnected levels: the affective-volitional (or sensorimotor), and the semantic-normative [47]. On the affective-volitional plane, agency involves the modulation of an aspect of the environment to which we are dynamically coupled; for instance, as we habitually use a steering wheel to modulate the direction of a car [11]. On the semantic plane, agency involves the interpretation of our activity in light of our goals, needs and identity. Agency involves complex dynamic relations between normative interpretation and other determinants of our activity [18].

Be it a handkerchief knot orienting us to buy milk or a personal journal orienting our emotional experiences, we appropriate aspects of our environment to structure our activity in ways that support our agency [67] i.e., as scaffolding [13]. Schyff, Schiavio & Elliott [51] discuss music as "involve[ing] extended interactions with the material environment (technologies and spaces) as the experiencer offloads various self-regulative and relational dimensions to the sonic world they enact." (ibid., p.122). Externalizing our affective states in music can "afford increased epistemic access to [them]" by making them tangible to us (ibid., p.108). Engaging with music can offer direct ways to transform our environment: it can create affective scaffolding i.e. ways to regulate our affective states [8, 33]. The ability to select music appropriate to my affective state could itself support pain management [26, 52]. Music sonification is particularly interesting in this context as it can offer additional ways to transform or modulate the experienced environment [57].

2.3 Sonification and Physical Activity

Movement sonification involves the mapping of sound on to an aspect of the user's movement (such as angle or speed) so that changes in the movement cause changes in the sound (such as pitch or start-stop of a tone). The sonification is an auditory representation of the movement, in the same way that a visualisation can be a visual representation [23]. Movement sonification has been used in sports and therapeutic contexts to support and encourage movement. In the sport context, sonification could help the user practice a golf swing [32] or rowing technique [12]. Sonification has an advantage over visualisation here in not needing to interrupt or draw focus away from the activity. Sonification has also been employed to encourage participants who do not engage in regular physical activity; for example, by leading them to appreciate bodily feelings during exercise [34] or by creating a sense of fulfilment as they complete a chord sequence in the sonification when they fully execute a squat [40].

Sonification has been widely used in therapeutic contexts, often as part of a motor rehabilitation intervention e.g., for arm movement after stroke [49, 50], shoulder mobility [66], or gait [30]. Here, the sonification provides biofeedback to guide repetition of a specific range of movements predetermined by a physiotherapist. A similar approach has proven effective for forward reach stretches with chronic pain [54], though the emphasis in this work is not on rehabilitation (interpreted as ensuring correct execution of movement) but challenging movement avoidance as a critical aspect of chronic pain management. A few studies have explored the use of sonification as cognitive prosthesis or scaffolding, for example in supporting functional activity in Alzheimer's disease [57] or supporting learning among proprioceptively deafferented individuals [9]. These latter studies indicate the potential affordances in interacting with sonification beyond offering the user information about their bodily position and movement. Work by Ley-Flores et al.

[34] with healthy participants found that different types of sonification could enhance a sense of agency while performing movement. The authors argue that this is due not only to the indexical mapping of the sound to movement, but also symbolic qualities such as participants' associations of the wind or water sounds used in the sonification with personal meanings such as feeling "light", "heavy", "like a bird". This semantic dimension remains underexplored in the literature, perhaps partly because prior work has tended to use simple tonal sonification paradigms – these may lack the rich texture necessary for meaning-making i.e. music could better support qualitative differentiation within the interaction which the user can interpret as personally relevant.

As discussed in 2.2, music can be effective in the management of conditions including chronic pain, in part due to its ability to hold personal significance and convey affective qualities [21][26]. To date, few studies have explored musical sonification in therapeutic contexts. In a study by Kantan et al. [30], participants chose a song for sonification to support walking gait after stroke. However, the motivation was to enhance participant engagement with the intervention and the authors do not report on participant experience of selecting and hearing their body in the form of music. A particularly relevant set of studies was conducted by Singh et al. In their study [55], fifteen participants with chronic lower back pain performed exercises with three types of sonification: tonal, nature sounds, and music. All participants found the sonification frameworks useful in supporting their movement. The authors discuss the positive impact of the interaction on psychological factors like self-efficacy. For example, participants appreciated the ability to identify their own comfortable and maximum movement point in a particular session. While music was found helpful, it was deemed less helpful than other less "complex" sounds, ie. tones. However, this negative experience of complexity may relate to limitations of the study - specifically, the use of non-wearable Kinect sensors that were insensitive to small trunk movements, combined with participants' unfamiliarity with the available music. There is a gap in the literature on how familiar music chosen by the participant could support better calibrated sonification e.g., through wearable movement sensors.

In a follow-up study, Singh et al. [53], working only on tonal wave sound and not music, demonstrate that movement sonification can support people with chronic back pain in performing not just exercises but also everyday activities as well as exercises in a domestic setting. Moreover, the authors report that the positive effects of the sonification on functional movement transfer to times when the device is not worn. These studies point to the potential of sonification to support the movement and agency of people with chronic pain for complex everyday functional activities: a critical aspect of chronic pain management [43] that goes beyond typical rehabilitation exercises.

Building on this body of work, the present study explores whether and how the sonification of familiar music facilitates movement and supports agency of people with chronic back pain.

3 FFAME - Filtering Familiar Audio for Movement Exploration

This study utilised the FFAME sonification system (Filtering Familiar Audio for Movement Exploration) developed to help participants understand their body movements through sound. FFAME is a research prototype designed for the present study. The study focus goes beyond evaluation of the FFAME system [1] itself, to consider its potential role in affective and normative dimensions of participants' activity.

The movement sonification operates using a series of loosely-coupled applications. Low-cost wearable inertia Notch sensors [2] worn on the body sample the body-position at 40Hz and communicate this over Bluetooth to an Android phone running a custom app. We wrote the phone app in Java and used Notch's libraries to respond to sensor data. The custom app logs movement data locally and further transmits it in real time to a desktop app, using Open Sound Control (OSC) protocol over User Datagram Protocol (UDP). The sonification app (written in Pure Data) then processes the data appropriately to create and modify sound. The app (see Figure 1) allows for the selection of the type of filter, the music file to be played, the scaling of the range of sensor input values to the filter frequency range, the use of log or linear scaling for the frequency, and controls for the sound itself.

The FFAME sonification models the sense of the body being 'open' or 'closed' and uses familiar music as its canvas. The use of familiar music draws on the previously recognised importance of self-selection of music [21]. The FFAME model adopts a music-orthogonal approach to avoid implying a need for extended entrainment. FFAME functions across one plane of movement: trunk flexion in our study. The simplicity of the sonification reflects study objectives of enabling participants to grasp and reflect on their experience. The 'open' and 'closed' effect with trunk flexion was chosen as fear of bending is prevalent among people with chronic low back pain and can affect a wide range of functional activities (e.g. bending to load the washing machine, or stretching forward to clean the back of the car) [5].

The sonification requires only one sensor unit worn on the chest (Figure 2) and responds to the position of that sensor as the trunk flexes forward and then extends backward during bending and return movements. A low (or alternatively high) pass filter is used to process the playback of a participant-selected commercially available music recording. The participant hears the music 'close' (high frequencies become gradually muted) as the body bends forward and 'open' (the high frequencies are gradually restored) as the body returns to an upright position. We also explored the opposite approach, i.e. having the music 'gradually open' with trunk flexion and 'gradually close' with extension. The range of flexion that the sonification is sensitive to could be adapted in the sonification app (Figure 1). The full spectrum of filtering could for example be delivered within a narrower range of movement, increasing the rate of change in the music over the same distance moved.

[1] We use the term "system" to refer to the technological components and "framework" to refer to the type of sonification and its emergent affordances.
[2] https://animation.wearnotch.com/

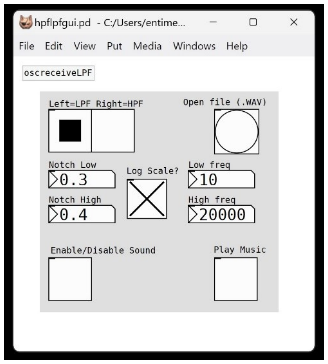

Figure 1: Desktop app interface to adjust sonification parameters. "Left/Right": toggles low-pass to high-pass filter. "Notch Low / High": sets range of sensor values across which sonification acts. "Low/High freq": range of music frequencies filtered. The Notch value in the Notch Low to High range is mapped to the corresponding proportional point in the frequency low to high range, either linearly or on a log scale depending on the setting.

4 Methodology

4.1 Participants

15 participants with chronic musculoskeletal lower back pain took part in this study (5 male, 9 female, 1 non-binary; 27-82 years old). The study was carried out at our lab as it was an early exploration of the sonification framework. In one case, the procedure was carried out in the participant's home to support their mobility needs. After the participant explored the sonifications (the exploration procedure is described in Section 4.2 below), we used a semi-structured interview to capture the participant's experience and the possible role or value of the sonifications in everyday physical functioning. We additionally recruited 5 physiotherapists specializing in chronic pain [3]. After a demonstration of the FFAME system, we interviewed them about the technology and its use by people with chronic pain, as well as possible applications in clinical contexts, such as chronic pain rehabilitation programmes and self-management. Participants were offered £15 and reimbursement of travel as a token of appreciation for their involvement.

[3]We use "P#" to refer to participants with chronic pain and "PT#" to refer to physiotherapists throughout.

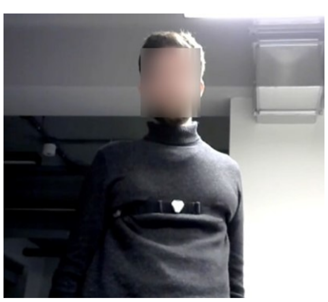

Figure 2: A Notch movement sensor worn around the chest to detect trunk flexion

This study was conducted in accordance with ethical guidelines and received approval from the institutional research ethics committee (ref. 5095/001). Participants were recruited through snowball sampling and social media channels. Prior to the study, all participants returned signed consent forms. At the beginning of each session, the consent form and information sheet were reviewed again with the participant to ensure full understanding. All study data was stored securely in a dedicated data haven to protect participant privacy and confidentiality. Study protocols were developed in collaboration with a clinical psychologist on the research team with extensive relevant experience, and piloted with multiple healthy participants.

4.2 Procedure

4.2.1 Pre-exploration: Before coming to the lab to explore the sonification, each participant was asked to send us details of three songs they were familiar with and enjoyed listening to. One of the three songs was then chosen by the experimenter and used in the FFAME sonification for the participant, with preference for songs with a variety of both high and low notes and a clear melody.

4.2.2 Exploration in Exercise Movements & Parameters Setting: On the sonification exploration day, the participant arrived at our lab and was welcomed by two members of the research team: one leading the session and one acting as demonstrator. They were briefed about the study, with clear information that they could take breaks or stop at any time and should only perform movements they were comfortable with. Adjustments were made to the protocol based on the participant's pain level and mobility needs; for instance, by performing activities sitting instead of standing.

The participant first explored the FFAME sonification (based on the self-selected music described above) with a trunk flexion movement, bending forward until they notice the effect of leaning forward. Trunk flexion was chosen as a focus because people with chronic low back pain typically experience hesitancy about this type of movement [5]. Following prior work [2, 55], they were then asked to do sit-to-stand-to-sit movements paying attention to how their movements affected the music.

After this, the two FFAME sonification parameters were calibrated to the participant's preference. The first parameter explored was the sonification sensitivity, i.e. the range of movement that the full spectrum of the filter transformation mapped to. For this, the participant either did a trunk flexion-extension or a stand-to-sit movement depending on their preference. Next, the participant explored the alternate filter direction, i.e. the sonification with the filter inverted so that it 'opened' rather than 'closed' with trunk flexion. This was done during trunk flexion. The participant could also adjust the volume to suit their preference.

4.2.3 Exploration in Enacted Functional Activities: For exploration of this sonification, we asked the participant to enact simple activities representative of everyday activities performed at home. Four sets of activities were done by each participant. After each activity, they were reminded that they were exploring how their movement and pain related to the music.

(1) *Enacted everyday activity:* Here, the participant was asked to imagine that they were carrying out a household chore and in particular had to pick up a real bag of washing (with four or five clean items of clothing in it) from the floor and carry it over to a proxy washing machine (a chair) and load the clothes into the machine drum (in between the legs of the chair). A healthy actor demonstrated the task. This activity was chosen as survey data in prior work suggests it is likely to cause worry for people with chronic low back pain [38].
(2) *Stretch exercise:* Stretches are sometimes incorporated as a break between actions or activities in functional activity by people with chronic pain [53]. Thus, the healthy actor also led the participant through a Pilates stretch. In the stretch exercise, the participant was asked to reach their arms up, then gradually bring them down, bending their neck and back as far as they were comfortable, then rolling slowly back up from the bottom of their back to their head. If they chose to perform the stretch from a neutral standing position, they were encouraged to keep their knees slightly bent. They could also keep their hands on their leg, slowly sliding them towards their knees for support. This stretch was performed twice.
(3) *Unfamiliar activity:* The purpose here was for the participant to perform a series of unfamiliar movements which require slower, deliberate execution while pursuing a real goal. The healthy actor demonstrated a 'challenge' which the participant then attempted. The challenge was to pick up a wrapped sweet from a box on the floor or a chair (depending on level of comfort) and balance it on a magnetic board rubber on a whiteboard on the wall of the lab. The participant then had to move the board rubber from the top left of the board to a cross in the bottom right without the sweet falling off. They could eat the sweet when they completed the challenge.

They could stop and take a break at any time. We also emphasised to them that they should only do movements that they would normally do and to the extent that they were comfortable with. This information was provided to the participant before and during the sonification exploration day, together with a general description of the activities that they would perform. Where necessary, activities were adjusted based on participant feedback prior to the day or during the day itself, e.g. performing a stretch activity while sitting (instead from standing), or enacting a loading the washing machine activity with the bag of laundry beside the proxy machine (instead of having to lift and carry the bag across the room).

4.2.4 Free Exploration: After these guided activities, the participant was given the space to explore the sonification freely, trying whatever movements they wanted. At this stage, they could also request changes to the sensitivity of the sonification and the direction of the filter. They could also try the sonification with an unfamiliar song ("Above the Clouds" by DJ Wave - a stock dance/electronic song well suited to the sonification). This exposure to an unfamiliar song was to trigger further reflection on the influence of song familiarity.

4.2.5 Interview: When the participant had explored the system as much as they wanted, we proceeded to the interview. The interview lasted 15 minutes and was audio recorded and transcribed. It was composed of 4 main parts:

(1) A brief introduction for insight into the participant's chronic pain condition, typical daily practice, and their management of the condition;
(2) Their experience of the FFAME sonification, what they thought its purpose was, and situations where it might be helpful or interesting for them;
(3) The impact of FFAME sonification parameters, i.e. the influence of music choice, sonification sensitivity, or open-vs-closed filter option on their experience;
(4) Any changes they would like to the FFAME sonification to make it valuable for them, and in comparison with commercially available health/movement technology that they have previously used.

4.2.6 Consulting physiotherapists: Three physiotherapists followed the same procedure to explore FFAME. Two physiotherapist sessions were conducted via Microsoft Teams, with the researcher demonstrating FFAME on video, due to Covid-19 restrictions. In the interview, physiotherapists were initially asked about their general impression of FFAME and whether they would use it in their practice. Following this, the researcher shared selected quotations from participant interviews that illustrated emerging themes in the analysis. These quotations served as prompts for further open-ended discussion. Interviews lasted 30 minutes. This approach helped to draw out the differences and similarities in patient and healthcare professional perspectives on self-management [48].

4.2.7 Analysis: Interview transcripts and researcher's handwritten notes were thematically analysed through stepwise inductive-deductive analysis [62]. Bottom-up coding in NVivo led to eight initial themes focused on participant experience and evaluation of the system. Concepts of agency and scaffolding emerged as salient in a number of data excerpts. Codes were subsequently reorganised into six themes, with a greater emphasis on agency, loosely oriented by an enactivist theoretical framework.

5 Findings

We present findings from interviews with participants with chronic pain, and with physiotherapists. Thematic analysis of participant reflections on their experience suggests the sonification could help to:

- **Encourage movement:** The sonification could help participants to initiate and extend movements.
- **Escape rationalization:** The sonification could help participants to quiet their thoughts about their pain and movement, allowing them to focus on the present moment.
- **Embody and externalise pain:** The sonification could help participants to better understand and express their pain.
- **Scaffold activity:** The sonification could help participants to direct and organise their activity.

These themes are discussed in more detail below. We also report on the impact of aspects of the design of the sonification such as the ability to choose familiar songs and to change filter sensitivity. The final section of the analysis focuses on the perspectives of the physiotherapists to consider the potential of the technology in a clinical context.

5.1 Responses to the sonification

Most participants (N = 12) reported positive experiences with the FFAME technology (in contrast to prior work in which music was not appreciated) [55]. The few negative evaluations (N = 3) related to finding the sonification "weird" (P3) or confusing. For some, it took some learning or entrainment before they could see any value in the sonification: "It took me a little while to get it" (P10); they needed to experiment through a range of movements before it "clicked how I was controlling it" (P14). The need for entrainment or learning was not reported in prior work using tonal or other simple sonification frameworks [29, 55]. Once participants understood the technology, they identified different values in using it. Some of these are described in the rest of this section.

5.1.1 Encouraging movement. Asked what they found interesting or useful about the sonification, most participants suggested that it could support their movement. Many participants suggested that the sonification could encourage movement they were avoiding but which they thought they ought to perform, either for therapeutic reasons (such as performing squats recommended by a physiotherapist (P4)) or out of necessity:

> [With tasks] such as hanging up clothes, if there's 20 or 30 rounds of it, the repetition can get overwhelming for me. If I knew there was going to be feedback [the music changing] every time it happened I would really like that (P6).

For this participant, the system could give feedback as changes in the music created qualitative changes in how the physical activity is experienced (giving it a more positive valence). This echoes work suggesting music can reduce perceived exertion during physical activity [17]. This was also described as the system valuing or affirming their movement. Participants appreciated support with activities they were avoiding either because of direct anticipation of pain, or more global factors such as boredom or laziness:

> I've got quite lazy… so if I'm at home and it can tell me to move and you've got the music telling you, I think I might do it more. That could be quite useful. (P2)

Participants suggested they could integrate FFAME into existing practices to motivate themselves to move. While for some sonification helped initiate movement, for others it was helpful in extending movements they were already enacting:

> [While stretching down] I found myself sort of wiggling, just moving to try to find the sweet spot for that perfect sound (P12).

> I probably moved a bit further there just with the music with me (P3).

However, one participant also worried that they could "overexert myself because I'm chasing the music" (P6). While overexertion should be acknowledged as a potential risk, it was not reported to have been experienced during the study. Most participants characterised the music as something they moved or "collaborated" (P2) with; they did not feel pressured to move in ways they were not comfortable with. Though many participants felt the sonification "covered a lot" (P1) in terms of their range of activities, several suggested it could be improved if it was more responsive to their movement. This could be because it did not respond to movements which they valued support with (i.e. movements other than trunk flexion), because they felt like it lagged with quicker movements, or because they wanted the change in music to be more obvious (though recognising that this could improve as they became more familiar with the filter).

5.1.2 Escaping rationalisation. Many participants suggested that the most beneficial aspect of the sonification was the "distraction" it offered from their pain. More specifically, the experience of the technology helped participants to "[get] out of your own head" (P4), quieting thoughts about their pain and movement:

> Very briefly, you're not second guessing yourself, you're going along with [the music] (P10).

Participants could pause familiar thought patterns by becoming immersed in the flow of the music: "I shifted my focus… I merged with the song" (P12). As one physiotherapist (PT1) suggested, this effect is potentially valuable as people with chronic pain tend to overthink movements in ways that can stifle their flow. As in prior work [34], the "flowing" quality of the sonification was often emphasised by participants. The sonification was least helpful when it made participants "more conscious" of their activity because it did not "flow with it" (P1). This could be due to the composition of the music or because the sonification did not seem well calibrated to their movement:

> I'm trying to hear what my body is doing… I'm not doing it too fast because I would probably get sick because of the out-of-sync-ness with the sound (P2).

For this participant, latency in sonification that started to appear due to what appeared to be a sensor calibration or sensing issue had a severe effect on their sense of agency and embodiment. Participants were not on the whole distracted from their sense of their own bodies, but from rumination about these experiences. As P11 explained, while her pain is "always there", the constant feedback of the sonification forced her attention to the present moment and the activity she was engaged in:

> You can't cheat the sound… you just have whatever you're doing, the real movement. You can't ignore it. (P11)

Participants rejected framings of the sonification as "data" or "information" which they could reflect on and analyse, but saw it as something that could develop how "tuned" (P10) they were to their own bodies in the present moment. Prior work [53] suggests such apparently unreflective movement awareness could lead to later reflection.

5.1.3 Embodiment and Externalisation. For some participants FFAME "corroborated" (P9) what they were feeling by serving as an embodiment of their pain:

> There's an element of validation. You know I'm feeling my pain and it's so subjective. Nobody else really gets it. But if you can actually hear when you are doing something... associated with the pain... having that

> externalised is quite pleasing. Reassuring in some way. It makes you feel like it's not just you. Something else can hear, can react to it (P7).

By mediating their activity, the sonification could make participants' experiences more tangible and potentially more intersubjective. It could offer a "new angle" (P2) or vantage point on familiar experiences.

As proposed by Newbold et al. [39], the participant's sensorimotor activity could become coupled to structural features of the music. Several participants reported the music "synchronising" (P10) with their pain:

> Points of pain were in tune with the music. It was a lot of the beat where you could sort of feel it mimicking my pain… (P8).

Moving with the music could lead participants to perceive covariance between it and personally significant aspects of their experience. Extending prior work [34], the synchronisation here could incorporate participants' semantic-normative schemes. Some participants described complex effects arising from use of the system:

> It could detect the stress, difficulty or discomfort... with things that caused quite a lot of discomfort it got quite loud... it was sensitive enough to detect what I was feeling and reflect it in the effect, the volume (P9).

During the free exploration phase of the study, P9 spent an extended period of time experimenting with movements – making use of the space, chairs, boxes, and the low-pass and high-pass filter. He recognised stress and discomfort during some of these movements and interpreted these feelings as covariant with the music. The functions P9 attributes to the tool (such as detecting stress) were not part of its design but emerged through his active exploration. The sonification mediated complex dynamics between affective-volitional and semantic-normative schemes of activity. Though the participant has arguably misunderstood the function of the technology, the meaning-making here could still support him in expressing and grasping his experiences. The sonification led P9 to "explore" and could "corroborate" experiences of living with chronic pain which he typically "masked", in part due to perceived gender norms.

Several participants described the sonification as expressing or emphasising their experience of their own body. One participant connected their sonification experience to the sonification in a dance performance they had attended:

> It seemed a lot like liberating, using their body to control ephemeral music... the movement becomes more important because it is… music coming straight from the body in a way (P2).

The dynamic coupling of the music with bodily movement could support participants' sense of agency. It could be associated with creative activity, in contrast to the "mechanical" (P10) or "stressful" (P9) exercises typically recommended by a physiotherapist. This emergent creative or playful dimension of the FFAME sonification could encourage movement and support agency:

> When it clicked how I was controlling it, it was much more interesting... You play around with your body more when you realise that your body is affecting the music. So I was doing things [rhythmically reaching down] that I wouldn't have done if I hadn't been wearing that. So I was in control with the music. (P14)

However, one participant (a professional musician) suggested that the sonification was limited because it did not offer enough affordances "to be more creative… to manipulate the music more to see how that feels" (P15).

Sharing the experience of the sonification with the researchers in the same space was likely an important factor in its expressive power. In imagining applications of FFAME in contexts outside the study setting, participants described scenarios in which the tool became implicated in existing practices and relations, e.g. in coordinating household chores or receiving encouragement from a family member. A few imagined using the technology with their physiotherapist.

5.1.4 *Scaffolding activity.*

While some reported effects which arose serendipitously while experiencing FFAME, others also saw it as a tool they could use to pursue their own goals and concerns: "It made me think of the blind guy who uses sound to guide his movements. It's a little bit like that. You're creating an extra sense that you can then use" (P7).

Some participants intentionally offloaded an aspect of the sense-making in their activity onto the tool:

> I was using it so as it got low you're sort of leaving the comfort zone. (P12)

The dynamic coupling here was connected with a concept of a "comfort zone" which P12 could rely on to judge her movement, as well as helping her challenge this judgement by hearing when she is going further. Similarly, P7 saw the sonification as a "warning system" to alert him when he should slow down (as reported in [55]). Features of the music, like its rhythm, pitch, or chorus structure could help participants direct and organise their own activity:

> It repeats like a chorus, so you know I'm going to stretch and then as you go, it gets louder. (P6)

However, structure and organisation could also be something participants reacted against in their movement. P4 herself did not think she would use the sonification to build up exercise habits because she did not like feeling a "pressure" to move. A number of participants described avoiding organised activities in their daily lives because external expectations and a lack of sensitivity to their pain from others prevented them from feeling they could determine their own engagement in the situation that arose, e.g. based on their pain level. However, some participants contrasted these kinds of organised experiences from the experience of the sonification, in which "you're in control" (P11). FFAME could give them the freedom to find structure through their exploration rather than by adopting structure that was fixed, prescriptive, or externally imposed. The significance of the sonification was open for them to discover and integrate with their personal goals and experiences.

5.2 Evaluation of features and functions of FFAME

Echoing prior work [52] , participants reported that selecting and listening to familiar music contributed to agency in their movements. However, our findings suggest that it was not the music alone that mattered - the specific parameters of the FFAME system played an important role, with participants expressing clear preferences for settings that they experienced as aligned with their goals.

5.2.1 The impact of song choice. Several participants were already using music to manage their pain and reported that hearing the familiar song in the sonification had a "soothing effect" (P1). This could be because of positive personal associations with the song or simply because they had chosen music which they enjoyed. Participants picked a range of musical styles including pop, rock, and jazz according to their individual tastes. Though participants preferred the music they themselves selected to the unfamiliar music played by the experimenter, many suggested that they would change their music choice having tried the technology. One participant would have preferred "something with less structure and more fluid" (P1). A few felt the music was too fast to support their movement, while P14 suggested "If I moved quickly, it [the sonification] didn't like that" because fast movements did not fit well with the slow music. Therefore, it was not just affinity for the song, but also its structural features that were important in the selection. A few reflected that their song choice may be "too distracting", for instance, because they wanted to sing or dance to the song instead of engaging with the activity (P13). Participants also valued familiar music because they knew what to expect:

> If it's a track I knew, I knew I could move to it quite slowly (P8).

An unfamiliar track could introduce uncertainty around their movement and prompt anxiety that it would make them move in uncomfortable or unexpected ways. One participant suggested she was "more sure" (P6) in her movements with a familiar song because she could anticipate when there would be a chorus. Participants felt "connected" (P5) with the music they had chosen in ways that could support its appropriation in their activity. This extends prior work in which unfamiliar music and soundscapes were found too "complex" and thus worrying or distracting to participants [55]: familiarity could mediate complexity.

5.2.2 The preferred parameter settings. Many participants felt that the choice of sensitivity of the sonification should match their level of comfort and perceived ability to move. Participants with more restricted movement and higher pain levels tended to prefer a higher sensitivity i.e. for less movement to be necessary to fully filter the music. This finding supports previous approaches [53], where the sensitivity of the sonification system is calibrated to the comfort level of the user. P12 wanted to test out how she could move while sustaining some level of "suffering" but, still had a comfort zone she wanted the sonification to reflect. Participants liked the "gradual" (P5) quality of the filter and some connected this to a lower sensitivity. When experimenting with an unfamiliar track at the start of the study, P11 worried that the transition would be "too sudden" but found that it was "smooth". It was important for the sonification to support an experience of "smoothness" along a gradient, but this could be achieved at different levels of sensitivity. This contrasts with sonification frameworks using fixed start-stop thresholds [30].

Most participants preferred the high-pass filter, that 'opens' with trunk flexion. This was because it "rewarded" (P7) movement or felt "more meaningful... easier to understand what I was trying to achieve" (P3). However, a few participants preferred the low-pass filter, describing it as "more natural" (P1). P1 noticed the effect of the high-pass filter more but found that this made her "more conscious" of what she was doing, disturbing the flow of the movements. This preference related not only to how movement activated the filter, but also to the frequency ranges filtered:

> [With the high-pass filter] it disappears into fizz whereas with the other one, it goes so low and those low [notes] can be felt in your body (P2).

Interestingly, P2 felt the low-pass filter was more closely connected with their body. The experience of lower frequencies could itself encourage movement by creating a more enjoyable or immersive experience:

> I noticed that when the bass increased, I was maybe more willing to stay in uncomfortable positions for longer (P12).

Future work could explore other parameter configurations, such as a low-pass filter where bending increases the cutoff frequency.

5.3 Potential clinical uses

While the preceding findings concern the experiences of participants with chronic pain, this section turns to the views of physiotherapists specialising in chronic pain management. There were sometimes tensions between physiotherapist and participant perspectives on using FFAME, though both viewpoints offer valuable insights for implementation in chronic pain management [27, 48] . Physiotherapists shared both opportunities and concerns about integrating the technology into their practice, while recognizing its potential benefits for certain patient populations.

As well as offering general responses on their thoughts about the technology, physiotherapists were asked to consider how and if FFAME might be used in their own clinical practice. Each of the five physiotherapists could see a role for the sonification system for patients with musculoskeletal chronic pain as well as risks and uncertainties around such uses. Most were already using technology as part of their practice, primarily to create a programme for their clients through an app-based database of videos demonstrating specific exercises. All emphasised that the suitability of a technology like FFAME would depend on the needs, goals, and profile of the client, and that certain populations, such as elderly clients with limited mobility, were unlikely to benefit. This was not reflected in the study data or prior work [53]: elderly and less mobile participants did benefit, but adequate calibration was important here.

Three physiotherapists (and some participants with chronic pain) offered graded-activity therapy as a context in which they could envision FFAME being used. This could involve continually challenging the perception that movement is threatening (PT2) by gradually increasing the range or complexity of movement (PT4). As a participant described it:

> If they could just do a very small movement [with a song they enjoy] they could think 'oh my god it didn't hurt, why didn't that hurt? Let's try that again.' Then you could make the sensitivity a bit less [and try again] (P13).

In this context, PT1 worried that the limit of the study design to one plane (of trunk flexion) would encourage overly narrow focus on particular movements rather than encouraging more "global" activity, while PT5 suggested it could be helpful to start with isolated movements and work up to greater complexity, perhaps introducing new sonifications along the way. Meanwhile, PT2 questioned whether exercises performed with music would transfer to everyday contexts without it. Prior work suggests sound sonification can transfer in this way [53].

There were worries that the sonification would give people with chronic pain the message that their movement was wrong or inadequate, or that they were failing to make progress. Parallels were made to physical activity trackers like the Fitbit. While some participants, and clients of physiotherapists, were using such devices to set daily movement goals (P4) or for a sense of validation (P7), it was noted that this was not always helpful for those living with chronic pain. People with chronic conditions may not make progress and setting up such expectations could be problematic. However, PT3 also recognised that FFAME could avoid this limitation because it did not accumulate data, but was relative to each session and to the choice of music.

Many of the concerns about the use of the sonification related to whether clients would overthink their movements or label certain movements as bad. While participants found it helpful to use the sonification as a "warning system" or to learn about their "limits", physiotherapists found such affordances problematic. However, PT5 suggested that working with a client using FFAME to recognise perceived limits could be a way to challenge them. As PT4 suggested, instead of posing hard limits, the sonification was something more open which could change how a client perceived their own movement.

A contrasting potential use for FFAME identified by physiotherapists related to the perception that it was something casual, free, and self-determined. One physiotherapist described clients who were "not buying into" clinical approaches:

> [For some] pain science, different programmes, CBT just feels unmanageable, and they just need something to get them moving (PT4)

These were clients to whom PT4 would recommend FFAME because it was less prescriptive and potentially more personally motivating. The sonification system was amenable to recommendations from the physiotherapist to a client that are less direct and more explorative:

> It's 'Try that out, see how you feel' which feels less threatening than 'Could you please bend?' (PT1)

PT5 suggested the sonification could also potentially support communication between physiotherapist and client, noting that with some clients, "you get a slightly exaggeration version" of certain movements because they want to communicate how much pain they are in. The sonification could perhaps mediate this in some ways.

6 Discussion

The findings of this study suggest that the FFAME sonification framework has potential as a tool for supporting movement and agency in people with chronic musculoskeletal pain. While a broad range of prior work has demonstrated how selecting and listening to music can be effective in self-directed chronic pain management [15, 21, 26], the findings of the present study suggest ways in which such effects may be enhanced and expanded through movement sonification. The themes that emerged from participant interviews - encouraging movement, escaping rationalization, embodying and externalizing pain, and scaffolding activity - highlight the multifaceted ways in which this technology might be beneficial.

6.1 Facilitating movement confidence through music sonification

One of the primary benefits of the FFAME system was its ability to encourage movement, both in initiating activities and extending ongoing movements. This aligns with previous research on the use of technology to promote physical activity in chronic pain management [54]. However, our findings suggest that experiences with the FFAME system go beyond simple encouragement. By creating dynamic coupling between movement and music, it fostered what participants described as a collaborative relationship with the technology. This resonates with theories of affective niche construction, where music and other aspects of the environment can be appropriated for self-regulation [33, 51]. As in prior work [40, 53], the sonification could provide scaffolding for participants to explore comfort zones, experiment, and set targets in their movements. While prior work has focused on tones and continuous sounds, the use of music in the present study made the determination of such zones and targets more ambiguous and fluid. Arguably, this encouraged greater exploration, and less judgement of movements as "bad" or "not enough". These findings address concerns of physiotherapists that movement sonification could reinforce imagined limits or prompt negative self-judgement. Instead of repeating a movement towards a set point, participants needed to work with the dynamic structure of the music. This discouraged views of the sonification as an objective judge or a passive source of information, as it is widely positioned in prior work [30, 39]. The choice of familiar music and the ability to adjust sensitivity settings allowed participants to tailor the experience to their comfort levels, supporting a sense of agency. This personalization is crucial in chronic pain management, where individual experiences and capabilities can vary widely [65]. Choosing music could not only offer familiar structure but could also introduce an element of creative expression. This contrasts with prior more homogenised approaches to sonification for chronic pain [40]. The potential for creative exploration could itself encourage movement or ways to make sense of it. Future work could design explicitly for creative expression for people with chronic pain, perhaps by drawing from more artistic approaches to sonification [4]. The FFAME system helped participants move away from overthinking their pain and movement. By immersing participants in the present moment through the dynamic music feedback, the system may help interrupt the cycle of pain catastrophizing often seen in chronic pain [60]. Interestingly, this effect was not about distraction from bodily sensations, but rather a shift in attention from rumination to present-moment awareness. This suggests that the FFAME system could complement mindfulness-based interventions for chronic pain [64], offering a novel, client-led, technology-mediated approach to cultivating present-moment awareness. At the same time, our findings raise the risk of overactivity [1]: music sonification could encourage users to "chase the music" and to move too much or without taking adequate breaks. Future research could examine how choice of music contributes to or helps avoid overactivity. Design could consider how a sonification system can encourage users to take breaks or slow down their movements.

6.2 Embodiment and externalisation: new perspectives on pain

The capacity of interactions with the FFAME system to embody and externalise pain experiences is a particularly intriguing finding. It echoes findings by Tajadura-Jiménez et al. [61] and Singh et al. [53, 54] that sonification can aid bodily awareness in chronic pain. By providing an auditory representation of movement, the FFAME system offered participants a new way to understand and express their experience. While these prior studies suggests participants value simple tonal sounds in sonification, our findings indicate that music can enhance embodiment if it is familiar and following a period of entrainment.

The perception of music "synchronizing" with pain points to the potential of the FFAME system to create what DeNora [10] calls "musical affordances" - opportunities for action and meaning-making through music. This synchronization could support agency not only at a sensorimotor level, as theorised by Newbold et al. [40] but also at a semantic-normative level, as described by Ley-Flores et al. [34], i.e. through the identities and understandings the user brings to the interaction. However, both Newbold et al. and Ley-Flores et al. characterise agency in terms of immediate control over the sonification – this overlooks the opportunities for action created in the present environment or in the participant's life as a whole; for example, by letting them reflect on experiences in ways they would typically avoid due to gender norms (cf. P9). These wider social normative dynamics are a key aspect of chronic pain [31] and it is promising that music sonification could help to express personal experiences or mediate social interactions. Tomlinson argues that music offers us a unique kind of semantic indeterminacy [63]: while music is a powerful indexical system in directing our experiences, its meaning is open to multiple interpretations. We can experience a piece of music as a direct and honest expression of something in our situation and find that it means something different at other times and with other people [8]. In the present study, FFAME could itself be an interlocutor "collaborating" (P2) in their sensemaking or simply "reassuring" (P7) them of the reality and value of their experience. This strongly aligns with Singh et al.'s [53] finding that participants saw the system as a "companion" in feared and undesirable activity. However, a contrast can be drawn between the "supervisory role" characterised by Singh et al., and the more tentative bidirectional role it could play in the present study. We emphasise that the sonification was not a detached observer: participants adapted their activity because the system "didn't like that" (P14), used it to "sense out my place" (P7), pursued aesthetically pleasing effects, and otherwise incorporated the sonification in their activity. This creative and dynamic perspective challenges the emphasis on objectivity and reproducibility in current definitions of sonification [25]. While we follow current sonification frameworks in recommending that sonification be reliably manipulable through coupling with user movement [24], we propose additional considerations in designing for agency (cf. [23]). Users could appropriate the sonification to their own ends by drawing on its *responsive ambiguity*: FFAME needed to be sensitive enough to (covary with) aspects of the participant's experienced environment but also rich textured enough to ground polysemy [46]. This facilitated participants in creating their own affective scaffolding, producing and exploring valued experiences.

6.3 Limitations and future work

The perspectives of participants and physiotherapists highlight both the potential and the challenges of integrating the FFAME system into everyday life or clinical practice. The system's potential use in graded-activity exposure therapy and its ability to provide a less prescriptive, more exploratory approach to movement align well with current trends in pain rehabilitation [65]. As prior work argues [54], calibration in the use of the system can allow users to take ownership of movements and experiment with their own boundaries, instead of relying on predetermined assessments of movement. In addition, offering a wider range of parameters for sonification and ways of mapping these to movement could increase the affordance offered to users of the system (as one of the participants identified as a need). From a musical perspective, this would increase the articulative possibilities for a user, allowing them to shape the music in a more creative way, for example, changing overall tempo (through time-stretching audio) or overall gain mapped to lean or limb gesture, alongside the existing trunk flexion for filter control. A finer-grained approach allowing a participant to control separate aspects of instrumental balance and articulation might require deconstructing the participant's nominated music into its component instrument tracks that could then be individually manipulated, e.g. manipulation of gain balance for non participant-nominated audio can be seen in previous work on sonifying attention [22]. Separation of commercially-produced audio like this poses technical and possibly legal obstacles to overcome but could be valuable to explore to support users who wish to work with a richer space of body movement expression.

Participants and physiotherapists noted limitations such as the narrowness of the focus on trunk flexion. Future work could explore ways for participants to select the plane of movement or combinations of planes for sonification (e.g. in relation to the activity they are engaging). In [55], participants with chronic pain were appropriating the calibration of the boundary of the movements to be sonified to the specific activity to learn more about their body. Here, the calibration could go beyond this focus on the movement, to also consider the semantics of the music in relation to the pain experience as a factor to leverage in the calibration.

There were diverging perspectives between physiotherapists and participants on whether uses of FFAME would transfer to everyday contexts. Future work should examine the long-term impact of FFAME on chronic pain management by exploring how the system could be utilised in participant homes as they perform real everyday activities or pain self-care practices, as in [53]. A longitudinal study could also explore to what extent our reported findings are subject to a "novelty effect". FFAME may be less vulnerable to such effects than other technologies because of the ability to create new experiences through music choices (study participants had sustained practices of listening to music to manage pain without reporting boredom from them) and because, in contrast to traditional forms of physiotherapy focused on repetition, the goal here is to holistically build movement confidence.

Though this paper builds on prior work [26, 52] to argue that the selection of music can support agency, this was still limited by the study protocol. Participants made song choices prior to experimenting with the system and naïve to the study aims. Many reported they would have chosen a different music track having explored the sonification system. Future work could give participants greater freedom in selecting music from their personal library, as well as allowing them to choose between tonal and music sonification. This could involve changing their selection as part of calibration and experimentation with the system and selecting different tracks for different contexts. This work could more directly explore the role of song familiarity on the effects of the sonification. While prior work has established a connection between music familiarity and its effectiveness for pain management [14, 16], the present study suggests some additional mechanisms to explore here, such as the relationship between familiarity and perceived complexity of the sonification, and the impact of familiarity on agency.

Although the findings are promising, they also reveal challenges and opportunities for future HCI research in this domain. These include developing more adaptive and context-aware systems (such as detection of common household chores, cf. [42]), exploring multimodal feedback mechanisms [2], supporting experiences of embodiment through additional sensors (such as HRV [28]), and designing interfaces that better support the communication of pain and other experiences, as well as long-term engagement.

7 Conclusion

This study demonstrates the potential of music-based sonification as a novel interface for supporting movement and agency in people with chronic musculoskeletal pain. The FFAME framework illustrates how personalization in music sonification can contribute to the design of pain management technologies. The sonification could offer an immersive and multifaceted experience that supports movement or distracts from pain without creating undue pressure.

Instead of positioning the sonification system as a passive source of information for repeated movements, as in previous studies, our findings demonstrate the serendipitous and creative ways in which sonification can become incorporated in activity, forming feelings, expressing experiences, scaffolding activities towards personal ends, and mediating social and material interactions. The complex dynamics between the music and the body created new opportunities for acting and understanding. These dimensions are key to consider when designing for users with chronic pain, where the goal of sonification is not rehabilitation but challenging fear and expanding opportunities for action. This work addresses a gap in HCI in demonstrating the value of familiar music in this context.

As interactive technologies continue to play an increasing role in healthcare, this work contributes to our understanding of how to design systems that are not just functional, but also engaging, empowering, and sensitive to the complex needs of people living with chronic pain. Future HCI research in this area has the potential to significantly impact the quality of life for millions of people worldwide affected by chronic pain conditions.

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References

[1] Nicole Emma Andrews, Jenny Strong, Pamela Joy Meredith, Kellie Gordon, and Karl Singh Bagraith. 2015. "It's very hard to change yourself": an exploration of overactivity in people with chronic pain using interpretative phenomenological analysis. *Pain* 156, 7 (2015), 1215–1231.

[2] Yee Mon Aung. 2016. *Augmented reality system for rehabilitation: new approach based on human interaction and biofeedback.* PhD Thesis. University of Technology Sydney. https://opus.lib.uts.edu.au/handle/10453/43461

[3] Gregory Booth, Ana Howarth, Brendon Stubbs, and Michael Ussher. 2022. The effectiveness of interventions and intervention components for increasing physical activity and reducing sedentary behaviour in people with persistent musculoskeletal pain: a systematic review and meta-analysis. *The Journal of Pain* 23, 6 (2022), 929–957.

[4] Yves Candau, Jules Françoise, Sarah Fdili Alaoui, and Thecla Schiphorst. 2017. Cultivating kinaesthetic awareness through interaction: Perspectives from somatic practices and embodied cognition. In *Proceedings of the 4th International Conference on Movement Computing*. ACM, London United Kingdom, 1–8. doi:10.1145/3077981.3078042

[5] J.P. Caneiro, Peter O'Sullivan, Anne Smith, G. Lorimer Moseley, and Ottmar V. Lipp. 2017. Implicit evaluations and physiological threat responses in people with persistent low back pain and fear of bending. *Scandinavian Journal of Pain* 17, 1 (Oct. 2017), 355–366. doi:10.1016/j.sjpain.2017.09.012

[6] Guillaume Christe, Geert Crombez, Shannon Edd, Emmanuelle Opsommer, Brigitte M Jolles, and Julien Favre. 2021. Relationship between psychological factors and spinal motor behaviour in low back pain: a systematic review and meta-analysis. *Pain* 162, 3 (2021), 672–686.

[7] Sabrina Coninx and Peter Stilwell. 2021. Pain and the field of affordances: an enactive approach to acute and chronic pain. *Synthese* 199, 3 (2021), 7835–7863.

[8] Ian Cross. 2015. Music, Speech and Meaning in interaction. *Music, Analysis, Experience. New Perspectives in Musical Semiotics* (2015), 19–30.

[9] Jérémy Danna and Jean-Luc Velay. 2017. On the Auditory-Proprioception Substitution Hypothesis: Movement Sonification in Two Deafferented Subjects Learning to Write New Characters. *Front Neurosci* 11 (2017), 137. doi:10.3389/fnins.2017.00137

[10] Tia DeNora. 2000. *Music in everyday life.* Cambridge university press. https://books.google.co.uk/books?hl=en&lr=&id=LXOhKHXUQeIC&oi=fnd&pg=PR8&dq=DeNora,+T.+(2000).+Music+in+Everyday+Life.+New+York:+Cambridge+UP&ots=rbxF7FslPT&sig=OKdAY-FH6gqyhO-CUl-9u_F18NA

[11] Ezequiel Di Paolo, Thomas Buhrmann, and Xabier Barandiaran. 2017. *Sensorimotor life: An enactive proposal.* Oxford University Press. 117 pages. https://books.google.co.uk/books?hl=en&lr=&id=F0DVDgAAQBAJ&oi=fnd&pg=PT8&dq=sensorimotor+life&ots=usPpBQTnNC&sig=aoCEp1OykUNlre6PJ4FRbFSVAnk

[12] Gaël Dubus. 2012. Evaluation of four models for the sonification of elite rowing. *J Multimodal User Interfaces* 5, 3-4 (May 2012), 143–156. doi:10.1007/s12193-011-0085-1

[13] Anna Estany and Sergio Martínez. 2014. "Scaffolding" and "affordance" as integrative concepts in the cognitive sciences. *Philosophical Psychology* 27, 1 (Jan. 2014), 98–111. doi:10.1080/09515089.2013.828569

[14] Katherine A Finlay and Krithika Anil. 2016. Passing the time when in pain: Investigating the role of musical valence. *Psychomusicology: Music, Mind, and Brain* 26, 1 (2016), 56.

[15] Katie Fitzpatrick, Hilary Moss, and Dominic Colman Harmon. 2019. The use of music in the chronic pain experience: an investigation into the use of music and music therapy by patients and staff at a hospital outpatient pain clinic. *Music and Medicine* 11, 1 (2019), 6–22. http://mmd.iammonline.com/index.php/musmed/article/view/639

[16] Katie Fitzpatrick, Hilary Moss, and Dominic Colman Harmon. 2019. The use of music in the chronic pain experience: an investigation into the use of music and

music therapy by patients and staff at a hospital outpatient pain clinic. *Music and Medicine* 11, 1 (2019), 6–22.

[17] Thomas Hans Fritz, Samyogita Hardikar, Matthias Demoucron, Margot Niessen, Michiel Demey, Olivier Giot, Yongming Li, John-Dylan Haynes, Arno Villringer, and Marc Leman. 2013. Musical agency reduces perceived exertion during strenuous physical performance. *Proceedings of the National Academy of Sciences* 110, 44 (2013), 17784–17789.

[18] Andrea Gambarotto and Auguste Nahas. 2023. Nature and Agency: Towards a Post-Kantian Naturalism. *Topoi* 42, 3 (July 2023), 767–780. doi:10.1007/s11245-023-09882-w

[19] Robert J. Gatchel. 2004. Comorbidity of Chronic Pain and Mental Health Disorders: The Biopsychosocial Perspective. *American Psychologist* 59, 8 (2004), 795–805. doi:10.1037/0003-066X.59.8.795

[20] Louise J Geneen, R Andrew Moore, Clare Clarke, Denis Martin, Lesley A Colvin, and Blair H Smith. 2017. Physical activity and exercise for chronic pain in adults: an overview of Cochrane Reviews. *Cochrane database of systematic reviews* 4 (2017).

[21] Ann Gold and Ajay Clare. 2013. An exploration of music listening in chronic pain. *Psychology of Music* 41, 5 (Sept. 2013), 545–564. doi:10.1177/0305735612440613

[22] Nicolas E. Gold, Chongyang Wang, Temitayo Olugbade, Nadia Berthouze, and Amanda Williams. 2020. P (l) aying Attention: Multi-Modal, Multi-Temporal Music Control. In *Proceedings-International Conference on New Interfaces for Musical Expression*. NIME. https://discovery.ucl.ac.uk/id/eprint/10096663/7/Gold_etal_NIME2020_Poster.pdf

[23] Visda Goudarzi. 2018. Sonification and HCI. In *New Directions in Third Wave Human-Computer Interaction: Volume 1 - Technologies*, Michael Filimowicz and Veronika Tzankova (Eds.). Springer International Publishing, Cham, 205–222. doi:10.1007/978-3-319-73356-2_12

[24] Joao Guerra, Lee Smith, Domenico Vicinanza, Brendon Stubbs, Nicola Veronese, and G. Williams. 2020. The use of sonification for physiotherapy in human movement tasks: A scoping review. *Science & sports* 35, 3 (2020), 119–129. https://www.sciencedirect.com/science/article/pii/S0765159720300046

[25] Thomas Hermann. 2008. Taxonomy and Definitions for Sonification and Auditory Display. In *Proceedings of the 14th International Conference on Auditory Display* (2008-06-24/2008-06-27). Paris, France. ICAD 2008.

[26] Claire Howlin, Rosemary Walsh, Paul D'Alton, and Brendan Rooney. 2022. How do people with chronic pain choose their music for pain management? Examining the external validity of the cognitive vitality model. *Front Psychol* 13 (2022), 969377. doi:10.3389/fpsyg.2022.969377

[27] Linda M Hunt and Nedal H Arar. 2001. An analytical framework for contrasting patient and provider views of the process of chronic disease management. *Medical anthropology quarterly* 15, 3 (2001), 347–367.

[28] Vilelmini Kalampratsidou and Elizabeth B. Torres. 2020. Sonification of heart rate variability can entrain bodies in motion. In *Proceedings of the 7th International Conference on Movement and Computing*. ACM, Jersey City/Virtual NJ USA, 1–8. doi:10.1145/3401956.3404186

[29] Youngjoo Kang, Louise Trewern, John Jackman, Anushka Irani (nee Soni), and David McCartney. 2024. Chronic pain: supported self-management. *BMJ* 384 (Jan. 2024), e072362. doi:10.1136/bmj-2022-072362

[30] Prithvi Ravi Kantan, Sofia Dahl, Helle Rovsing Møller Jørgensen, Chetali Khadye, and Erika G. Spaich. 2022. Designing Sonified Feedback on Knee Kinematics in Hemiparetic Gait Based on Inertial Sensor Data. In *SoniHED 2022: Conference on the Sonification of Health and Environmental Data*. Zenodo. https://vbn.aau.dk/en/publications/designing-sonified-feedback-on-knee-kinematics-in-hemiparetic-gai

[31] Kai Karos, Amanda C. de C. Williams, Ann Meulders, and Johan WS Vlaeyen. 2018. Pain as a threat to the social self: a motivational account. *Pain* 159, 9 (2018), 1690–1695. https://journals.lww.com/pain/fulltext/2018/09000/Pain_as_a_threat_to_the_social_self__a.6.aspx

[32] Max Kleiman-Weiner and Jonathan Berger. 2006. The Sound of One Arm Swinging: A Model for Multidimensional Auditory Display of Physical Motion. In *Proceedings of the 12th International Conference on Auditory Display* (2006-06-20/2006-06-23). London, UK. ICAD 2006.

[33] Joel Krueger. 2019. Music as affective scaffolding. In *Music and Consciousness II*. Oxford University Press. https://ore.exeter.ac.uk/repository/handle/10871/29897

[34] Judith Ley-Flores, Laia Turmo Vidal, Nadia Berthouze, Aneesha Singh, Frédéric Bevilacqua, and Ana Tajadura-Jiménez. 2021. SoniBand: Understanding the Effects of Metaphorical Movement Sonifications on Body Perception and Physical Activity. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–16. doi:10.1145/3411764.3445558

[35] Mira Meeus, Jo Nijs, Paul Van Wilgen, Suzie Noten, Dorien Goubert, and Ivan Huijnen. 2016. Moving on to movement in patients with chronic joint pain. *Pain: Clinical Updates* 24, 1 (2016), 1–8.

[36] Ann Meulders. 2019. From fear of movement-related pain and avoidance to chronic pain disability: a state-of-the-art review. *Current Opinion in Behavioral Sciences* 26 (April 2019), 130–136. doi:10.1016/j.cobeha.2018.12.007

[37] Érica Brandão de Moraes and Cibele Andrucioli de Mattos Pimenta. 2014. Chronic pain, fear of pain and movement avoidance belief. *Rev. dor* 15 (June 2014), 77–77. doi:10.5935/1806-0013.20140033

[38] Lilly Neubauer, N. Gold, Temitayo Olugbade, A. Williams, and Nadia Berthouze. 2021. Functional musical sonification for chronic pain support. In *Ubiquitous Music 2021*. Ubiquitous Music 2021. https://discovery.ucl.ac.uk/id/eprint/10130642/1/s6.%20camera%20ready%20FINAL.pdf

[39] Joseph W. Newbold, Nadia Bianchi-Berthouze, and Nicolas E. Gold. 2017. Musical Expectancy in Squat Sonification for People Who Struggle with Physical Activity. In *Proceedings of the 23rd International Conference on Auditory Display - ICAD 2017*. The International Community for Auditory Display, University Park Campus, 65–72. doi:10.21785/icad2017.008

[40] Joseph W. Newbold, Nadia Bianchi-Berthouze, Nicolas E. Gold, Ana Tajadura-Jiménez, and Amanda CdC Williams. 2016. Musically Informed Sonification for Chronic Pain Rehabilitation: Facilitating Progress & Avoiding Over-Doing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA, 5698–5703. doi:10.1145/2858036.2858302

[41] Thomas H. Nown, Priti Upadhyay, Andrew Kerr, Ivan Andonovic, Christos Tachtatzis, and Madeleine A. Grealy. 2022. A mapping review of real-time movement sonification systems for movement rehabilitation. *IEEE Reviews in Biomedical Engineering* 16 (2022), 672–686. https://ieeexplore.ieee.org/abstract/document/9813380/

[42] Temitayo Olugbade, Raffaele Andrea Buono, Kyrill Potapov, Alex Bujorianu, Amanda C. de C Williams, Santiago de Ossorno Garcia, Nicolas Gold, Catherine Holloway, and Nadia Bianchi-Berthouze. 2024. The EmoPain@ Home Dataset: Capturing Pain Level and Activity Recognition for People with Chronic Pain in Their Homes. *IEEE Transactions on Affective Computing* (2024). https://ieeexplore.ieee.org/abstract/document/10504978/

[43] Temitayo A Olugbade, Aneesha Singh, Nadia Bianchi-Berthouze, Nicolai Marquardt, Min SH Aung, and Amanda C De C Williams. 2019. How can affect be detected and represented in technological support for physical rehabilitation? *ACM Transactions on Computer-Human Interaction (TOCHI)* 26, 1 (2019), 1–29.

[44] María Ospina and Christa Harstall. 2002. *Prevalence of Chronic Pain: An Overview*. Health Technology Assessment 29. Alberta Heritage Foundation for Medical Research, Edmonton. 103–147 pages.

[45] Teresa Paolucci, Carmine Attanasi, Walter Cecchini, Alessandra Marazzi, Serena V Capobianco, and Valter Santilli. 2018. Chronic low back pain and postural rehabilitation exercise: a literature review. *Journal of pain research* (2018), 95–107.

[46] Kyrill Potapov. 2023. *Understanding and Orchestrating Adolescents' Interpretation of Personal Informatics Data: Social Practices in School and at Home*. Ph. D. Dissertation. University of London, University College London (United Kingdom).

[47] Kyrill Potapov. 2025. Emotions & Vygotsky's materialist semiotics: reply to Oittinen. *Culture and Education* 37, 1 (2025).

[48] Euan Sadler, Charles DA Wolfe, and Christopher McKevitt. 2014. Lay and health care professional understandings of self-management: a systematic review and narrative synthesis. *SAGE open medicine* 2 (2014), 2050312114544493.

[49] Gerd Schmitz, Daniela Kroeger, and Alfred O Effenberg. 2014. A mobile sonification system for stroke rehabilitation. *New York* (2014).

[50] Daniel S. Scholz, Sönke Rohde, Nikou Nikmaram, Hans-Peter Brückner, Michael Großbach, Jens D. Rollnik, and Eckart O. Altenmüller. 2016. Sonification of arm movements in stroke rehabilitation–a novel approach in neurologic music therapy. *Frontiers in neurology* 7 (2016), 106. https://www.frontiersin.org/articles/10.3389/fneur.2016.00106/full

[51] Dylan van der Schyff, Andrea Schiavio, and David J. Elliott. 2022. *Musical Bodies, Musical Minds: Enactive Cognitive Science and the Meaning of Human Musicality*. MIT Press.

[52] Sandra L. Siedliecki and Marion Good. 2006. Effect of music on power, pain, depression and disability. *Journal of Advanced Nursing* 54, 5 (2006), 553–562. doi:10.1111/j.1365-2648.2006.03860.x

[53] Aneesha Singh, Nadia Bianchi-Berthouze, and Amanda CdeC Williams. 2017. Supporting Everyday Function in Chronic Pain Using Wearable Technology. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA, 3903–3915. doi:10.1145/3025453.3025947

[54] Aneesha Singh, Annina Klapper, Jinni Jia, Antonio Fidalgo, Ana Tajadura-Jiménez, Natalie Kanakam, Nadia Bianchi-Berthouze, and Amanda Williams. 2014. Motivating people with chronic pain to do physical activity: opportunities for technology design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Toronto Ontario Canada, 2803–2812. doi:10.1145/2556288.2557268

[55] Aneesha Singh, Stefano Piana, Davide Pollarolo, Gualtiero Volpe, Giovanna Varni, Ana Tajadura-Jiménez, Amanda CdeC Williams, Antonio Camurri, and Nadia Bianchi-Berthouze. 2016. *Go-with-the-Flow* : Tracking, Analysis and Sonification of Movement and Breathing to Build Confidence in Activity Despite Chronic Pain. *Human–Computer Interaction* 31, 3-4 (July 2016), 335–383. doi:10.1080/07370024.2015.1085310

[56] Kathleen A Sluka, Laura Frey-Law, and Marie Hoeger Bement. 2018. Exercise-induced pain and analgesia? Underlying mechanisms and clinical translation. *Pain* 159 (2018), S91–S97.

[57] Danilo Spada and Emmanuel Bigand. 2017. Coupling music and motion: from special education to rehabilitation. In *The Routledge Companion to Embodied Music Interaction*. Routledge, 264. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315621364-29/coupling-music-motion-danilo-spada-emmanuel-bigand

[58] Ólöf Anna Steingrímsdóttir, Tormod Landmark, Gary J. Macfarlane, and Christopher Sivert Nielsen. 2017. Defining chronic pain in epidemiological studies: a systematic review and meta-analysis. *PAIN* 158, 11 (Nov. 2017), 2092. doi:10.1097/j.pain.0000000000001009

[59] Mark D Sullivan. 2023. Caring for patients with chronic illness: is respecting patient autonomy enough or must we promote patient autonomy as well? *Family Practice* (June 2023), cmad066. doi:10.1093/fampra/cmad066

[60] Michael J. L. Sullivan, Beverly Thorn, Jennifer A. Haythornthwaite, Francis Keefe, Michelle Martin, Laurence A. Bradley, and John C. Lefebvre. 2001. Theoretical Perspectives on the Relation Between Catastrophizing and Pain. *The Clinical Journal of Pain* 17, 1 (March 2001), 52. https://journals.lww.com/clinicalpain/fulltext/2001/03000/Bias__Effects_in_Three_Common_Self_Report_Pain.00008.aspx

[61] Ana Tajadura-Jiménez, Helen Cohen, and Nadia Bianchi-Berthouze. 2017. Bodily Sensory Inputs and Anomalous Bodily Experiences in Complex Regional Pain Syndrome: Evaluation of the Potential Effects of Sound Feedback. *Front. Hum. Neurosci.* 11 (July 2017). doi:10.3389/fnhum.2017.00379

[62] Aksel Tjora. 2018. *Qualitative research as stepwise-deductive induction*. Routledge. https://www.taylorfrancis.com/books/mono/10.4324/9780203730072/qualitative-research-stepwise-deductive-induction-aksel-tjora

[63] Gary Tomlinson. 2015. *A million years of music: The emergence of human modernity*. Zone Books. p. 276 pages. https://www.torrossa.com/gs/resourceProxy?an=5559672&publisher=FZO137

[64] Martine M. Veehof, Hester R. Trompetter, Ernst T. Bohlmeijer, and Karlein M.G. Schreurs. 2016. Acceptance- and mindfulness-based interventions for the treatment of chronic pain: a meta-analytic review. *Cognitive Behaviour Therapy* 45, 1 (Jan. 2016), 5–31. doi:10.1080/16506073.2015.1098724

[65] Johan W.S. Vlaeyen and Geert Crombez. 2020. Behavioral Conceptualization and Treatment of Chronic Pain. *Annu. Rev. Clin. Psychol.* 16, 1 (May 2020), 187–212. doi:10.1146/annurev-clinpsy-050718-095744

[66] Katharina Vogt, David Pirrò, Ingo Kobenz, Robert Höldrich, and Gerhard Eckel. 2010. PhysioSonic - Evaluated Movement Sonification as Auditory Feedback in Physiotherapy. In *Auditory Display*, Sølvi Ystad, Mitsuko Aramaki, Richard Kronland-Martinet, and Kristoffer Jensen (Eds.). Springer, Berlin, Heidelberg, 103–120. doi:10.1007/978-3-642-12439-6_6

[67] Lev Semenovich Vygotsky. 2012. The collected works of LS Vygotsky: The History of the Development of Higher Mental Functions. Vol. 4. Springer Science & Business Media, 44–45. https://books.google.co.uk/books?hl=en&lr=&id=XGx3BQAAQBAJ&oi=fnd&pg=PA1&dq=vygotsky+collected+works+history+of+the+development&ots=zod3oWbWDq&sig=0UlgRdtPRtv1OfV-VuadhWnIs8U

[68] Rob Withagen, Duarte Araújo, and Harjo J. de Poel. 2017. Inviting affordances and agency. *New Ideas in Psychology* 45 (2017), 11–18. doi:10.1016/j.newideapsych.2016.12.002

[69] Emily L. Zale and Joseph W. Ditre. 2015. Pain-related fear, disability, and the fear-avoidance model of chronic pain. *Current Opinion in Psychology* 5 (Oct. 2015), 24–30. doi:10.1016/j.copsyc.2015.03.014

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