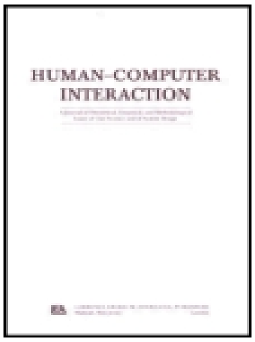

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Go-with-the-Flow: Tracking, Analysis and Sonification of Movement and Breathing to Build Confidence in Activity Despite Chronic Pain

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Chronic (persistent) pain (CP) affects 1 in 10 adults; clinical resources are insufficient, and anxiety about activity restricts lives. Technological aids monitor activity but lack necessary psychological support. This article proposes a new sonification framework, *Go-with-the-Flow*, informed by physiotherapists and people with CP. The framework proposes articulation of user-defined sonified exercise spaces (SESs) tailored to psychological needs and physical capabilities that enhance body and movement awareness to rebuild confidence in physical activity. A smartphone-based wearable device and a Kinect-based device were designed based on the framework to track movement and breathing and sonify them during physical activity. In control studies conducted to evaluate the sonification strategies, people with CP reported increased performance, motivation, awareness of movement, and relaxation with sound feedback. Home studies, a focus group, and a survey of CP patients conducted at the end of a hospital pain management session provided an in-depth understanding of how different aspects of the SESs and their calibration can facilitate self-directed rehabilitation and how the wearable version of the device can facilitate transfer of gains from exercise to feared or demanding activities in real life. We conclude by discussing the implications of our findings on the design of technology for physical rehabilitation.

CONTENTS

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1. INTRODUCTION

Chronic pain (CP) is pain that persists for more than 3 months without a treatable cause (Turk & Rudy, 1987). Whereas acute pain usually resolves with healing, CP can continue indefinitely despite treatment attempts. Studies in Europe estimate that about one in seven adults has CP (Breivik, Collett, Ventafridda, Cohen, & Gallacher, 2006; Donaldson, 2009). An interdisciplinary approach to rehabilitation, primarily involving psychology and physiotherapy, is the treatment of choice (Kerns, Sellinger, & Goodin, 2011). The aim is for the person with CP to achieve a better quality of life despite ongoing pain (rather than contingent on reducing pain) using evidence-based approaches such as cognitive behavior therapy (Smith & Torrance, 2011; Williams, Eccleston, & Morley, 2012). Other than pain, barriers to achieving better quality of life are primarily psychological, in particular, anxiety about activity causing damage and increased pain.

Pain management programs reduce these anxieties and associated distress and improve physical function (Williams et al., 2012), but gains are hard to maintain in the long term (Turk, 2002) without clinical support, which is unaffordable (Donaldson, 2009).

Technology can fill this gap by helping people with CP to maintain and build on treatment gains by providing support and tools for self-management. To be effective, technology has to be designed to address the specific needs, both physical and psychological, of the conditions as identified by all stakeholders (Paraskevopoulos et al. 2014). In CP, fear that increasing physical activity will cause further pain and damage frequently leads to avoidance of demanding activities and movements, and/or to adopting protective behaviors (e.g., moving stiffly, guarding, limping; Aung et al., in press; Sullivan, 2008) which may lead to increased pain and hence to further avoidance. In studies of people with CP and of physiotherapists treating them, Singh et al. (2014) identified strategies used by people who actively manage their CP and by physiotherapists to support and encourage them in increased physical activity. It emerged that physiotherapists encourage people to move more and to engage in feared movements. Rather than focusing on "correcting" movement as it reinforces anxieties about damage, they encourage people to rediscover body capabilities and redirect attention to pleasurable sensations (e.g., breathing) to facilitate physical activity. Transfer from physical activity to everyday functioning is at the core of pain management that includes identifying environmental barriers and ways to address them through better use of physical and psychological resources.

These requirements and strategies differ from those instantiated in technology for physical rehabilitation that are often based on correcting movement by exploiting *shift-of-attention* mechanisms to facilitate endurance during activity, and maximizing performance by constant challenge (Holden, 2005; Lewis & Rosie, 2012). Physical progress is the only measure of efficacy embedded and driving the design and the form of support provided during physical rehabilitation in CP (Jansen-Kosterink et al., 2013; Schönauer, Pintaric, Kaufmann, Jansen-Kosterink, & Vollenbroek-Hutten, 2011). In addition, transfer to everyday functioning, when addressed, is limited to simulated real-life activities (Paraskevopoulos et al., 2014) in games or virtual reality environments. Although this approach appears effective in motivating and increasing physical performance in certain conditions, the simulated environment falls short in modeling the complex real world, especially when psychological factors are a barrier to function. So it is also important to ask how technology can go beyond exercise and act as a bridge to function.

In this article we investigate the use of sound feedback to implement strategies identified in Singh et al. (2014) for chronic pain rehabilitation, and we augment them through sensing technologies. Although sound feedback in physical rehabilitation is not novel, we propose that specifically designed sound feedback can represent relevant information about movement and related physiological processes in a way that is pleasurable, easy to attend to, and devoid of anxiety-related information. The tailoring of the sonification process to the psychological needs of the person rather than only physical needs, first presented in Singh et al. (2014), is extended here in three ways. First, an iterative process with stakeholders (physiotherapists and people with CP) is used to refine and extend the tracking technology by including different types of sensors.

Second, we extend the concept of self-defined sonified exercise space by proposing a framework where sonification elements are designed and combined to address specific needs that emerged from our qualitative studies and provide richer information about movement and other physiological processes. Third, through quantitative and qualitative studies, we elucidate how different elements of the sonified exercise space can facilitate different aspects of self-directed rehabilitation and everyday functioning.

In the next section, we review the literature on CP and its associated problems and discuss available technology to increase physical activity in CP. Next, we review the evidence of how sound feedback and sonification can creatively motivate movement and affect body perception. Building on this literature, we then propose the concept of self-defined sonified exercise spaces and the *Go-with-the-Flow* framework to build them. Two devices are presented that were iteratively built with inputs from physiotherapists and people with CP: a smartphone-based wearable (ubiquitous) and a Kinect-based platform (granular). These two platforms were designed to address different research propositions: wearable technology can facilitate exercise and its transfer to functioning in the real world by providing ubiquitous support; the Kinect-based technology can track full body movement allowing a wider exploration of sonification. We report quantitative and qualitative studies on the role and efficacy of our approach, especially with respect to psychological factors. We conclude by discussing the implications of our findings.

2. BACKGROUND

2.1. Chronic Pain

CP is the result of changes in the central and peripheral nervous system resulting in amplification of pain signals: overactivity in pain pathways at multiple levels from the periphery to the brain, and underactivity in descending pathways that modify pain signals (Tracey & Bushnell, 2009). These changes are intricately linked with distress and with normal and abnormal patterns of physical activity (Gatchel, Peng, Peters, Fuchs, & Turk, 2007). An integrated biopsychosocial framework (Gatchel et al., 2007) attempts to represent the interaction of physical, psychological, and social factors in the pain experience, including the adverse impact on quality of life. These changes apply across persistent pain with or without diagnosable cause, giving rise to the suggestion that CP may be a disease in its own right (Tracey & Bushnell, 2009).

Psychological aspects of pain incorporate cognitive content and process, and emotion (Gatchel et al., 2007). Cognitive content predominantly describes unhelpful beliefs about what pain means, interpreting it as threat and responding by withdrawal, escape, and avoidance. Over time this leads to loss of range and extent of activity, impacting on work, family, and social life. Correction of these beliefs in the context of an accurate understanding of CP underpins engagement in rehabilitation. Cognitive processing can show marked bias, in particular catastrophizing, the overestimation of threat and underestimation of capacity to cope, which also leads to overcautious behavior (Gatchel et al., 2007). Reduced activity causes loss of physical condition, of valued activities, and of social contact, all of which are risks to health and overall well-being. Emotional difficulties associated with pain are mainly anxiety about the meaning and implications of pain, depression related to losses of lifestyle and planned future, and frustration with day-to-day difficulties and the shortcomings of medicine.

A multidisciplinary approach to treatment in pain management programs provides psychological therapy targeting the problems just described, and physical therapy for a steady return toward activity and better physical health without exacerbating pain (Harding & Williams, 1995); the goal is to help people to understand and manage their pain and learn to optimize their quality of life. Although such programmes are effective (Williams et al., 2012) in improving quality of life in people despite pain, maintaining treatment gains in the long term is hard. To self-manage physical activity, people with CP consciously and unconsciously adopt protective behaviors (e.g., guarding, bracing, etc.) to reduce anxiety about movement (Sullivan, 2008; Vlaeyen, De Jong, Geilen, Heuts, & Van Breukelen, 2002). Although this may have short-term benefits, the long-term effects are decreased motor control, dysfunction of the proprioceptive system (Della Volpe et al., 2006), and increased pain (Martel, Thibault, & Sullivan, 2010; Rainville et al., 2004; Vlaeyen et al., 2002). Hence, it is important to regain awareness of these behaviors, especially if they have become automatic, along with increasing physical activity.

2.2. Technology for Physical Activity

Technology for Physical Activity in CP

Research on designing interactive technology for people with CP is limited (Rosser et al., 2011). Most technologies aimed at people with CP provide information on pain and pain reduction through web-based resources and more recently through smartphone apps (Rosser & Eccleston, 2011a, 2011b; e.g. Habit Changer: Pain Reduction on iPhone), or have routines for strengthening and relieving tension, and promoting relaxation, predominantly meditative (e.g. Pocket Therapy). Some apps (e.g., Chronic Pain Tracker; WebMD PainCoach) allow setting and monitoring of goals, mood, pain, and activity levels, as well as provide reminders such as for medication or medical appointments. However, in a review of apps, Rosser and Eccleston (2011a) found limited support of psychological and behavioral issues and no applications of advanced tracking technology for run-time psychological support during physical activity.

Recent work has addressed some of these shortcomings using low-cost full-body game technology with motion tracking capabilities to facilitate physical activity in CP (Jansen-Kosterink et al., 2013; Schönauer et al., 2011). The model used by these technologies is imported from technology for physical rehabilitation of other conditions (e.g., stroke), and uses sensing technology to introduce fun and provide rewards to reduce attention to pain. However, these technologies are not designed to address the psychological factors just described (Legrain et al., 2009). Whereas protective behavior in CP may resemble compensatory movements in other conditions (e.g., stroke), they are attributable to anxiety about movement not to motor impairment. People with CP have experience of setbacks when activity has exacerbated their pain, so they cannot be certain of what is “safe” (Harding & Williams, 1995). Simply correcting movement without addressing the psychological factors can result in increased anxiety, which is countertherapeutic. In CP rehabilitation, activity is built by setting baselines that are manageable even on "bad pain" days with small increments as physical fitness increases, without increasing average pain. Unfortunately, current physical rehabilitation technology, such as the serious game by Schönauer et al. (2011), does not allow for slow progress common in people with CP, or setbacks, increased anxiety, or low mood, all of which risk discouragement and abandonment of rehabilitation (Harding & Williams, 1995). Although these psychological factors are considered in technology for meditation, little attention has been paid to physical activity. For example, Gromala, Tong, Choo, Karamnejad, and Shaw (2015) investigated biofeedback in CP using virtual reality and stereoscopic sound, but their main aim was learning mindfulness skills and the physical activity was limited to walking. A few other interventions (Cepeda, Carr, & Lau, 2006) that use fun and pleasant experiences have been tried for CP, but effects are weak on average. There is potential for pleasant exercise experience for people with pain (Legrain et al., 2009), but better understanding of engagement and maintenance is needed.

Through observation studies, focus groups, and interviews with people with CP and with physiotherapists, Singh et al. (2014) identified requirements and strategies to facilitate physical activity despite pain:

- *Increasing awareness of body movement without increasing anxiety* to increase people's confidence in everyday activity.
- *Increasing exposure to pleasurable experience of activity and pleasant* body sensations e.g., increased focus on quality of breathing, rather than performance.
- *Limiting exposure to negative experiences* by recognizing normal responses and limits as unthreatening to support work towards rehabilitation goals.
- *Taking control in self-management* by learning skills from physiotherapists who used graded support during exercise sessions and by encouraging reflection to increase autonomy and a sense of control.

Following these findings, they also explored the use of self-defined sonified exercise spaces to implement and empower the identified strategies; their pilot study showed positive results where people with CP reported an increased focus on movement rather than on pain. They reported that sound enhanced the perception of being active and increased awareness of the performed movement. In this article, we extend this work through the involvement of stakeholders and propose a sonification framework for creating sonified exercise spaces to support physical and psychological needs in people with CP. Before presenting our framework, we briefly review the literature on the use of sound and sonification to facilitate body awareness, motor learning and positive experience.

Sonification for Representing, Understanding, and Motivating Body Movement

Neuroscience research has shown that our brains use all available sensory feedback, including sound, to keep track of the changing structure and position of the body in space (Botvinick & Cohen, 1998; De Vignemont, Ehrsson, & Haggard, 2005) and to adjust actions (Wolpert & Ghahramani, 2000). For instance, the sound of tapping with an object on one's hand provides information about hand position, arm length (Tajadura-Jiménez et al., 2012), and force applied (Tajadura-Jiménez, Furfaro, Bianchi-Berthouze, & Bevilacqua, in press), or the timing of steps when walking (Menzer et al., 2010). Using this information, the individual can adjust movements. This relation between sound and movement is supported by tight links between auditory and motor areas of the brain. For instance, listening to rhythms activates motor and premotor cortical areas (Bengtsson et al., 2009; Peretz & Zatorre, 2005), hence the use of rhythmic acoustic feedback to entrain movement (Kenyon & Thaut, 2005). In addition, natural (e.g., Bradley & Lang, 1999) or artificial sounds such as tones and music have been shown to trigger emotional responses in listeners. Studies on the human brain have shown unlearned preference for certain types of sound, such as harmonic and periodic sounds (Lenti Boero & Bottoni, 2008), of which music is a particular case (Juslin & Västfjäll, 2008; for overview, see Juslin & Sloboda, 2001). This growing body of work supports the use of sonification of movement and related processes as a powerful way to increase positive body awareness in CP and facilitate engagement with movement.

Indeed, sonification of body movement, as a means to inform, has been shown to improve motor control and possibly motor learning (Effenberg, 2005; Effenberg, Fehse, & Weber, 2011; Effenberg, Weber, Mattes, Fehse, & Mechling, 2007) in sports training studies (golf swing: Kleiman-Weiner & Berger, 2006; interactions within a sports team: Höner, Hermann, & Grunow, 2004; rowing: Dubus, 2012; Schaffert, Mattes, & Effenberg, 2010; aerobics for visually impaired people: Hermann & Zehe, 2011; skier's center of gravity: Hasegawa, Ishijima, Kato, Mitake, & Sato, 2012). Sonification is not new in physical rehabilitation either. It has been shown that sequences of tonal beeps can facilitate robotic-assisted movement training after stroke or spinal cord injury (Rosati, Rodà, Avanzini, & Masiero, 2013; Wellner, Schaufelberger, & Riener, 2007). Sonification of electromyographic data during rehabilitation can guide the person toward a target movement (Pauletto & Hunt, 2006); PhysioSonic (Vogt, Pirrò, Kobenz, Holdrich, & Eckel, 2009) transforms 3D movement analysis of shoulder joint kinematics into audio feedback to correct posture or coordinate a therapeutic exercise. This type of sonification can help coordination in patients with poor proprioception (Chez, Rikakis, Dubois, & Cook, 2000; Matsubara, Kadone, Iguchi, Terasawa, & Suzuki, 2013), a relevant problem for some people with CP (Lee, Cholewicki, Reeves, Zazulak, & Mysliwiec, 2010). However, it is important to understand how to design such sonification in order to provide effective support in CP physical rehabilitation that would go beyond physical performance to address psychological barriers and needs.

Sonification has been investigated as a scientific method to facilitate understanding of complex information. The most recent and complete definition of sonification is "data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method" (Hermann, 2008). Dubus and Bresin (2013) provided a recent survey on sonification, and general design guidelines, across different research fields. Interactive sonification—"the use of sound within a tightly closed human-computer interface where the auditory signal provides information about data under analysis, or about the interaction itself, which is useful for refining the activity" (Hermann & Hunt, 2005, p. 20)—offers real-time interaction between an individual and an auditory display.

In sports and physical rehabilitation contexts, variables describing the movement are mapped into sounds to enhance the perception of the quality of the movement or its deviation from a particular model. Metaphors are used to facilitate the mapping between movement qualities and sound. Music, however, is not generally used unless for aesthetic or relaxation purposes (Gromala et al., 2015; Nazemi, Mobini, Kinnear, & Gromala, 2013; Vidyarthi & Riecke, 2013). In fact, according to Hermann's definition of sonification, using music material may not fully comply with the requirements that sonification should be systematic, objective, and reproducible. However, Varni and colleagues (2011) showed that the mapping of data on high-level properties of music such as tempo, articulation, timbre, and so on, can be used for sonification provided that its goal is not purely aesthetic but rather consists of improving the understanding or the communication of information about the original data domain, referred to as active music listening.

Whereas sonification consists of a systematic mapping of data streams onto specific sound features, active music listening provides users with ways of intervening on the music content they are listening to in order to change and mold it according to their wishes, intentions, or aesthetic preferences. In early work on active music listening, Camurri (1995) and Goto (2007) proposed a content-centric system for intervening on prerecorded music with signal processing techniques to select sections, skip, and navigate parts of the recording. More recently, Volpe and Camurri (2011) and Varni et al. (2011) developed active music listening applications controlled by full-body movement and expressive gesture; they showed that alteration of music through body movements resulted in convergence of peoples' movements, thus showing an effect in driving movement behavior.

Building on this body of work, in the next sections we present our sonification framework to facilitate physical rehabilitation in CP and overcome the psychological barriers that people face. Two main studies were carried out. The first is an iterative design study to design the sonification framework and the body-sensing devices to explore it. The second study makes use of instantiations of the sonification framework to evaluate its effectiveness and better understand how people with CP may appropriate it. All studies have National Health Service and University College London ethics approval and were conducted in accordance with ethics guidelines.

3. DESIGN STUDY: SONIFICATION FRAMEWORK AND SENSING DEVICES

The aim of this design study was to create the *Go-With-the-Flow* sonification framework for defining Sonified Exercise Spaces (SESs), within which people feel confident in moving and can gradually build their psychological and physical capabilities. The framework evolved through iterative revisions that were instantiated into prototypes (body tracking and sonifying devices) for discussing and exploring concepts with physiotherapists and people with CP. We aimed to address four research questions in this study:

1. Can sound be used to support physical activity in people with chronic pain?
2. Can sound be used to facilitate learning of self-management skills?
3. What pain management principles must be encapsulated in the auditory feedback to make it effective for use in physical activity sessions?
4. How should the principles be translated into sonification elements?

Four iterative focus group sessions were run to elicit views of pain management from specialist physiotherapists and people with CP. During each iteration, a new version of the body tracking and sonifying device was presented to provide examples of SESs that reflected the revised framework. Three physiotherapists from the University College London Hospitals trained in cognitive behavioral therapy, each with more than 6-years of experience in pain management participated in the focus groups. The final iteration was conducted during a pain management session at the hospital with two people with CP using the device.

For brevity, we first present the framework that emerged at the end of this iterative design study. Then we report the findings from the iterative focus group studies. Last, we describe the final design of the devices, informed by the focus groups.

3.1. *Go-With-the-Flow* Framework

The *Go-with-the-Flow* framework consists of three parts: (a) SES design principles derived from strategies that physiotherapists and people with CP use to facilitate physical activity, (b) sonification paradigms and elements that implement the principles and are combined to create SESs, and (c) sonification alteration methods to increase awareness of use of avoidance or protective strategies. These three parts are described in Figure 1. The framework evolved through exploration with physiotherapists and was based on previous literature on sound discussed in Section 2. Figure 2 shows a wearable sensing and sonifying prototype and two examples of SESs built with this framework.

3.2. Iterative Evaluation With Physiotherapists and People with CP

The sonification framework was implemented through sensing devices that tracked and sonified body movement and breathing patterns of a person in real time; one of the devices was wearable and the second was Kinect-based. The framework and the devices were iteratively tested and refined through four focus groups. The focus groups were audio- and video-recorded, and transcribed data were analysed using thematic analysis (Braun & Clarke, 2006). Emergent themes are described next. The final version of the devices is presented in Section 3.3.

FIGURE 1. The three parts of the *Go-with-the-Flow* framework.

BOX 1

Go-with-the-Flow Framework – Part 1

SES DESIGN PRINCIPLES

Principle 1: Provide an enhanced perception of moving through sonification that provides an enhanced and pleasurable perception of movement, particularly when i) movements are restricted and perceived as not worth attempting; or ii) anxiety is high and attention is on pain.

Principle 2: Provide a sense of progress through movement to increase self-efficacy. Different sonification assigned to different phases of an exercise can address varied barriers and needs.

Principle 3: Facilitate *going-with-the-flow* by reducing the need for continuous monitoring (to free cognitive resources); the sonification should represent the body in space (e.g. by targets reached).

Principle 4: Provide sense of achievement and reward through the use of specific sonification to mark target attainment. We refer to these specific targets as anchor points.

Principle 5: Increase awareness of avoidance through alteration of sonification, in a way easy to understand and which encourages movement exploration. To avoid increasing anxiety or beliefs about threat, the signal should not be perceived as indicating wrong movement or danger

Principle 6: Encourage preparatory movements (e.g., bending forward before standing up in a sit-to-stand movement) by using different sonifications from those used for the exercise which have been avoided (due to fear of increased pain or automaticity) but in fact facilitate normal movement.

Principle 7: Develop self-management skills by tailoring sonification to the appropriate level of pacing for the person's physical and psychological capabilities and current pain level can help to: 1) discover physical capabilities and psychological needs; 2) learn to tailor activity to physical and psychological resources; 3) perceive progress and gradually build capabilities.

Principle 8: Underdoing vs. overdoing: SES boundaries should be designed to encourage movement but not overactivity with a risk of setbacks.

BOX 2

Go-with-the-Flow Framework – Part 2

SES SONIFICATION PARADIGMS AND ELEMENTS

Simple tone: This is the simplest sound content that can be played at different pitches. The use of simple tones enhances the perception of each unit of movement (Principle 1).

Sonic phrase paradigm: A set of correlated sonic events characterised by variations (discrete or continuous) of one or more sonic features can be used to provide a sense of progress (Principle 2). For example, discrete pitch in a tone scale; or timbre (e.g., from dark to bright) in a rich spectral sound.

Combination of phrases: Different phrases can be used to sonify different parts of a movement to further enhance progress through it (Principle 2). For example, an ascending scale of tones can be used as a metaphor to highlight a sense of progressing towards a desired achievement, whereas a descending scale can be used to provide a sense of progressing towards the ending of a difficult movement.

A**nchor points and SES boundaries:** Endings of phrases, changing between consecutive phrases, or other clearly identifiable sounds can be used to mark milestones and targets to enhance achievements (Principle 3), facilitate awareness of body position (Principle 4) and signal boundaries of SESs to reduce hypervigilance (Principle 4). Movement beyond the boundaries of the SES may be sonified to encourage building capabilities (Principle 8).

Naturalistic sound: a sound simulating or evoking everyday life sound objects or sounds of living beings, usually characterised by continuously varying time-frequency model over time: from simple white noise (wind-like sound) to complex sounds resulting from a set of equations and algorithms simulating a physical source of sound (Rocchesso, Bresin & Fernstrom, 2003). Naturalistic sounds can be more relaxing and preferable in longer sessions (Principle 1), since they cause less fatigue in the auditory system due to the continuously varying time-frequency features. The use of single naturalistic sound can be used to enhance the perception of each unit of movement (Principle 1).

FIGURE 1. (Continued).

Soundscape paradigm: a (possibly non-linear) structured composition of naturalistic sounds, inspired by electroacoustic music (e.g., Berry Truax) and sound synthesis techniques (e.g., granular synthesis). A soundscape can provide a sense of progress through a movement, (e.g., feeling of approaching a sound source (Principle 2)), facilitate *going-with-the-flow* by inducing relaxation (Principle 3), and provide a sense of achievement (e.g., feeling of arriving at a sound source (Principle 4)).

Active listening paradigm: an extension of interactive sonification based on the real-time interactive manipulation and moulding of (possibly personalised) pre-recorded music content. Interactive manipulation includes interventions on the orchestration, e.g., the continuous control of the single voices and instruments forming a music piece, and the control and manipulation of timbral and rhythmic features. The manipulation of a known music piece may link to personal experience in the subject, and may thus contribute to stronger participation and engagement in sonification (Principles 1 and 4). Thus through the movement, the person engages in simulating creative mixing of the available music tracks. The selected music pieces should range across musical preferences but be sufficiently rich to enable isolation and dynamic mixing of a sufficient number of different instrumental sections.

Self-Calibration: the definition of the SES (selection, combination and tuning of sonification elements) should be carried out by the person through exploration to facilitate understanding of one’s physical and psychological capabilities and progress (Principle 7). The calibration should be re-adjusted as needed including setbacks and bad days (Principle 8).

BOX 3	*Go-with-the-Flow* Framework – Part 3
	SES SONIFICATION ALTERATIONS

Alterations of the sonification should encourage exploration of movement capabilities rather than provide a sense of danger or “wrong” (vs correct) movement. The alterations investigated are:

Use of lateral protective movements: altering the sound in a way that highlights the body part where the movement is avoided. For example, if a person avoids using one part of the body during a symmetric movement, sound is played only on the opposide side (e.g., the ear corresponding to the part of the body that is used). This should induce exploration of the avoided body part to recover lost sound.

Use of protective movements (either backward or forward) to avoid shift of centre of body mass: shifting the tone scale to a lower or a higher octave (without distortion). For example, during a forward reach exercise, the pelvis may be pushed backward while moving the trunk forward to keep the centre of body mass aligned with the feet.

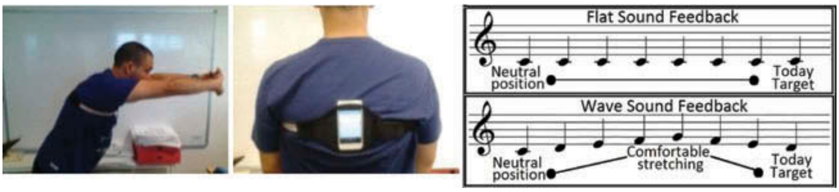
Avoidance of preparatory movements: The sonification associated with the preparatory movement is not played or not fully played, and the subsequent sonification of the exercise itself is distorted. This alteration aims to convey the feeling of not have gained sufficient energy to complete the movement.

Fast pacing to avoid engaging with the movement: The volume of the sound is decreased when the movement is performed too fast to increase awareness of pace and encourage slowing down. A decrease rather than an increase in volume was proposed as an increase in volume could either reinforce arousal and reward speed or lead to increased anxiety as it may signify alarm.

Shallow breathing: breathing sounds are produced over the movement sonification to invite breathing.

***Note.* SES = sonified exercise spaces.**

FIGURE 2. (Middle) Device attached to person's back for sonifying trunk movement during the forward reach exercise (Left). (Right) Examples of SESs for a forward reach exercise: The Flat sound is a repetition of the same tone played between the starting standing position and the maximum stretching position. The Wave sound is a combination of two tone scales (phrases), an ascending one ending at the easier stretching target and a descending one to the final more challenging target. The reaching of the easier target is marked by the highest tone (Singh et al., 2014).



Engagement, Awareness, and Reward

Physiotherapists found the use of sonification feedback motivating and informative. They particularly commended the possibility of calibrating the sonified exercise space to each individual. They thought people with CP would find the feedback engaging and anticipated its use not only to facilitate practicing movements but also to encourage movement exploration, which is an important aspect both in the initial phases of the pain management journey and later in adapting to daily needs (Singh et al., 2014). Initially when building physical and psychological capabilities, people need to explore what their body can do without overdoing; on bad days and during setbacks, people need to adjust their targets to avoid pain exacerbation. Physiotherapists also felt that the device would be particularly rewarding for very restricted movements, which are often demotivating as people do not value performing them and may even be unaware of doing them. Thus, tailoring the exercise space to the person's capabilities using the device could enable tailoring rewards to ability, rewarding even small movements to enhancing awareness of and motivation in performing them. Physiotherapists thought that discrete steps in sound could provide a sense of progress that could be lost in continuous sound especially when movements are constrained, for example, a very limited bending of the trunk. When discussing boundaries of SESs, they were critical of what they perceived as the technology signaling a "safe" zone for exercise, as that implied an "unsafe" zone beyond, reinforcing an unhelpful model of pain as warning of damage. Instead, they emphasized that small increments and regular physical activity would build confidence in movement. They also expressed concern that focus on a target could distract from quality of movement and encourage strain or lead to disappointment about underperformance when the target was not met. Physiotherapists also wanted the sonification to continue after the maximum target, as they felt stopping the sonification at this point was like "punishing people for trying harder."

What to Track Beyond Movement

From the first iteration, physiotherapists suggested that the device could target other pleasurable sensations for body awareness such as breathing. Because breathing rate rises with anxiety, and patients often hold their breath if they are anxious or overly focused on a movement, physiotherapists suggested calibrating the breathing depending on (a) apical versus abdominal breathing and (b) the number of breaths per minute in a relaxed state, using superimposed breathing sounds as a prompt to breathe calmly. Physiotherapists commented also on the functionality to increase awareness about protective movement by altering the sonification. For example, when the person leaned more to the left, the sound was louder in the left ear. Physiotherapists liked this feature, as it informed without being corrective or prescriptive and emphasized that this alteration should not be designed in such a way that it was perceived as an indicator of "wrong movement." On the possibility of providing muscle activity feedback, physiotherapists were concerned that this could generate anxiety about doing movements "wrong" or in a "damaging" way; this would be contrary to their message of "moving little and often" to build activity rather than moving "correctly."

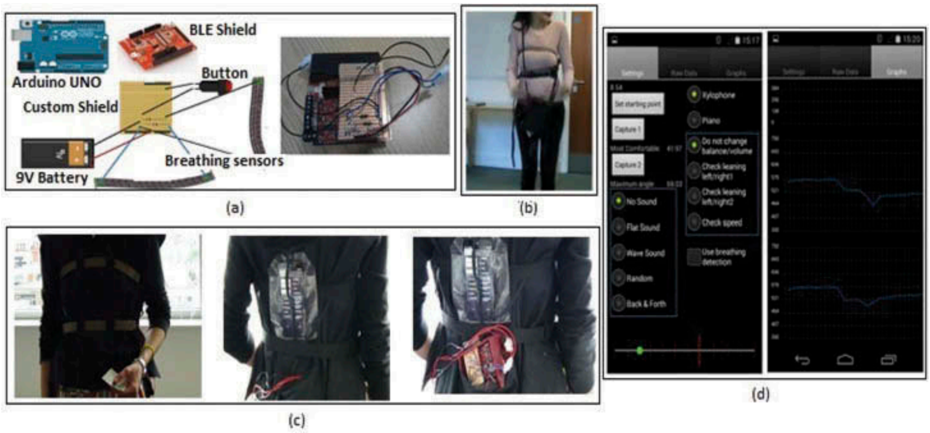
Going From Physiotherapist-Driven to Patient-Driven Activity

The use of the device to teach self-management skills was also discussed. Physiotherapists thought that their patients would "love exploring their movement with the sound," especially those with limited movement. Thus, the device could function as a bridge between clinic and home during the pain management programmes run by hospitals (about 6 weeks long). When anxiety about a particular movement was high, physiotherapists typically set a modest baseline, which could be set using the device, and the sound feedback used to reward people for movement and provide reassurance, thus enabling people to explore and practice movements at home. Finally, physiotherapists felt that they could use the device together with patients to explore other body cues that could be used to tailor daily exercise. Physiotherapists often suggest cues to be used for facilitating movement. For example, it may be useful to bend forward or look down while doing certain activities to make it easier (not "safer" or "correct"), and sound feedback could be used to trigger such preparatory movements. They suggested that the device could reinforce doing the movement as the goal and not just reaching a certain target.

3.3. Devices Design

Two versions of the *Go-with-the-Flow* device were developed to explore both the advantages of mobile wearable tracking devices and of full-body tracking systems. The wearable device (Figure 2 [Left and Middle]: initial prototype; Figure 3: final prototype) used a smartphone for tracking a part of the body while investigating different sonification options for transfer from exercise (e.g., forward reach) to everyday functioning (e.g., forward reach to get something from a shelf). The second system used the Microsoft Kinect to track the full body and was developed to explore more complex sonification paradigms. A brief description of the devices and calibration process is provided next. Details on how each device tracks movement, breathing and avoidance/protective strategies are provided in Appendix A.

FIGURE 3. Final design of the wearable device: (a) Architecture of the breathing module built using Arduino UNO. (b) Breathing sensors. (c) Front and back views of the tabard with integrated breathing sensors, button held in the person's hand for calibration, the smartphone in its pocket on the back of the trunk and the breathing sensing module shown outside its corresponding pocket. (d) Smartphone interface for selecting sonified exercise spaces and visualization of the tracked signals.



Wearable Device

The wearable device (Figure 3) is comprised of an Android Google Nexus 5 smartphone and two respiration sensors. The smartphone sensors are used to detect the amount of bending of a particular part of the body where the smartphone is worn (e.g., of the trunk). Two respiration sensors (Mancini et al., 2014), one to measure diaphragmatic (abdominal) breathing and the second for apical breathing (Figure 3a–b) were designed to measure lung volume, and hence respiration, through the proxy of thoracic and/or abdominal circumference. Each respiration sensor consists of a band with a stretchy section made of conductive material, expansions and contractions of which cause a change in voltage that is detected by the Arduino-based breathing sensing device. A tabard, of adjustable girth and to be worn over existing clothes, was designed with a transparent back pocket for the smartphone and Velcro loops on the front to keep the breathing sensors in place (Figure 3-c). The breathing device was placed in a laser-cut acrylic case that was put in the back pocket of the tabard (Figure 3-c). A smartphone was used to track, sonify, and store information about movement of the body part where the smartphone was worn. A simple visual interface was designed with a choice of sonification options (Figure 3d) to allow selection of the sonification to be investigated within each experiment and to monitor the data collection. Because the smartphone could be worn on any body part (e.g., on the trunk; see Figure 3c), a button connected via a wire to the Arduino module was added to facilitate the calibration process.

Kinect-Based System

To test whether more complex and information-rich sonification was more motivating, we also developed a system using a Kinect Windows 2 input sensor and designed using the EyesWeb XMI software platform (eyesweb.infomus.org). A graphical user interface (GUI) developed to enable the user to control the system in real time also allowed selection of the exercise and SES. Applications (patches) were developed using EyesWeb to track exercise progress and generate sonifications based on the conditions selected in the GUI and the progress of the exercise. Speakers were placed in the room to produce the sound feedback.

Calibration Process

Given the high variability between physical and psychological capabilities in people with CP, it is important to calibrate the device accurately for sonification. In a forward reach exercise, for example, trunk bending may vary between a few degrees to almost 90° (Singh et al., 2014). The calibration of the sonification (SESs) was performed through self-exploration of the movement followed by setting three anchor points associated with particular body positions. In case of the Kinect, the person would stand in front of the device and signal verbally when he or she had reached the desired body position (e.g., maximum stretch), and the researcher would set the particular anchor point through the GUI and confirm to the user. In case of the wearable device, participants would press the calibration button they were holding, and the smartphone (worn on the trunk) would capture the orientation of the smartphone device (associated with the degree of trunk bending) as the specific anchor point and confirm the calibration through voice feedback. Anchor points are associated with specific sounds, and the space between them is equally divided into intervals that serve as intermediate milestones to drive the sonification. The number of intervals depends on the sonification used, as described in the next section.

In the next sections, we report on three studies to evaluate the *Go-with-the-Flow* framework with people with CP. Section 4 describes the evaluation of the framework in a controlled situation. Section 5 reports the results from a focus group following the control study, home studies, and a survey conducted with people with CP at the hospital at the end of their usual pain management session. Finally we discuss the implications of the results and suggest further refinements of the framework.

4. *GO-WITH-THE-FLOW* FRAMEWORK EVALUATION STUDY

Various studies were carried out to evaluate the effectiveness of the *Go-with-the-Flow* framework in supporting psychological aspects of physical rehabilitation. A set of SESs was created by using the framework (Figure 3-c) of Section 3 and implemented in the two sensing and sonifying platforms just described. We hypothesized the following:

1. The use of sonification (vs. silence) is more motivating, increasing self-efficacy and body awareness during anxiety-inducing exercises. The richer the information the SES provides about a person's movement, the more effective it is in increasing self-efficacy, awareness, and motivation in doing the movement.
2. Simple tone-based sonification paradigms enhance self-efficacy and sense of control given their simple mapping between movement and SES. In contrast, naturalistic soundscape paradigms induce relaxation and promote exploration of movement; active music listening increases motivation given the more complex sonification and creative process involved.
3. SESs calibrated to perform functional movements can facilitate transfer of physical capabilities from exercise to everyday life activity.
4. Sonification alteration techniques enhance awareness of use of avoidance strategies and induce exploration without increasing anxiety.

4.1. Methodology

Implemented SESs

Using the *Go-with-the-Flow* framework and the aforementioned devices, a set of SESs were designed to run user studies to investigate the validity of the framework and suggest further refinement. The sonic material used to implement the SESs consisted of prerecorded sampled sounds with instrumental or naturalistic content, music tracks, and breathing sounds as described in **Figure 4**.

The first set of SESs was based on a *forward reach stretch* exercise commonly used in physical rehabilitation of chronic low back pain (CLBP). The forward reach stretch has two phases: reaching forward and returning to a neutral standing position. This exercise induces anxiety due to the stretching movement and the forward shift of the body's center of mass creating a less stable position. This set of SESs was implemented on both wearable and Kinect-based devices. Next, a set of SESs was implemented on the Kinect for the *sit-to-stand* movement to explore generalization of the framework across exercises and investigate sonification to facilitate preparatory movements. Sit-to-stand is complex, with two main phases including a preparatory one where the trunk is bent forward to provide momentum to stand up. Stiffness and anxiety are associated with avoiding the preparatory forward bending leading to increased difficulty, instability, and possibly increased pain on standing. Details on how the device tracks movements and implements the avoidance strategies are provided in Appendix A.

For these two exercises, three anchor points, hereafter referred to as S, M, and C, were designed to define boundaries and milestones within the SESs. *S* corresponds to the body position before starting the exercise. This is important, as people with CLBP may have an asymmetric standing position due to pain. *M* indicates the maximum

FIGURE 4. **Description of the Implemented Sonified Exercise Spaces (SESs) for the Forward Reach Exercise.**

SESs for Forward Reach and for Sit-to-Stand (Phase 1)					
Sound Name	Sonification of Trunk Bending	Anchor S: Standing Position	Anchor C: Point of Comfortable Stretch	Anchor M: Today's Maximum Stretch	SES Boundaries
Flat (Figure 1 top)	11 repetitions of the same tone from a piano instrument. These were spaced equidistant from each other between S and M.	Sound starts as soon as bending forward starts	None	Sonification stops	Kinect: The sonification occurs only between S-M Wearable: The sonification continues on the lowest tone after M
Wave (Figure 1 bottom)	Formed by 2 major scales separated by the anchor point C: 7 equidistant ascending tones before C and 4 equidistant descending tones after C. The piano instrument was selected		Highest tone	Lowest tone of the descending scale Note: In phase 2 of sit-to-stand a tone from the clarinet was played	The sonification is played in reverse as the person moves backwards
Water	Continuous sound of moving water with a sound of a splash suggesting the body enters the water		Splash	None	The sound is continuously played until the person returns to S
Windchimes	Continuous sound of windchimes		None	None	

FIGURE 4. (Continued).

SESs for Forward Reach and for Sit-to-Stand (Phase 1)					
Sound Name	Sonification of Trunk Bending	Anchor S: Standing Position	Anchor C: Point of Comfortable Stretch	Anchor M: Today's Maximum Stretch	SES Boundaries
A walk in the forest	Soundscape: stepping on leaves, birdsong, a river, sheep bleating, nightingale. The list of sounds is played sequentially in the order above as the amount of stretching increases.		River sound	Nightingale	Beyond M, sound played at M continues. The sonification is played in reverse as the person moves backwards
A song	Active Music Listening: interactive orchestration of the song ("*I'll Be There for You*"). Instrument tracks (shakers, percussion, lead vocal, piano, string) are incrementally added as the amount of stretching increases		Lead vocal track	All instrument tracks together	Note: In phase 2 of sit-to-stand the sound at M is continuously played.

Note. These SESs were also used to sonify the bending forward (till C) of the sit-to-stand first phase. The description of how movement was tracked is provided in Appendix A.

amount of movement to be performed that day (today's target), and *C* is an intermediate body position between S and M. The anchor points mark specific boundaries within the SES so that people could easily understand the position of their body within the space; anchor points could also be used to signal the reaching of defined milestones to provide a sense of achievement and were calibrated before starting the exercise as described in Section 3.

The set of SESs created for the forward reach stretch are described in **Figure 4**. The C anchor point for the forward reach corresponds to a comfortable amount of stretch (not inducing anxiety). For the sit-to-stand exercise, sonification had two parts: (a) sonification of the preparatory movement (bend forward) using the SESs defined for the forward reach (**Figure 4**), and (b) sonification of the standing-up movement on the vertical axis triggering different effects depending on the sound choice (see **Figure 4**: Anchor M and SES boundaries), ending when the person was fully standing. In terms of anchor points, the C position in sit-to-stand corresponded with a comfortable trunk bending position for the person before standing up. No maximum bend position was set. Even though, in an ideal case, the shoulder should be aligned over the ankles to provide sufficient momentum to stand up, not all people with CP can reach such a bend position due to anxiety or body size. Hence, people were asked to bend to a comfortable extent to facilitate the shift of weight forward for standing up. The M position of the sit-to-stand corresponds to the standing posture at the end of the sit-to-stand movement.

Participants and Setting

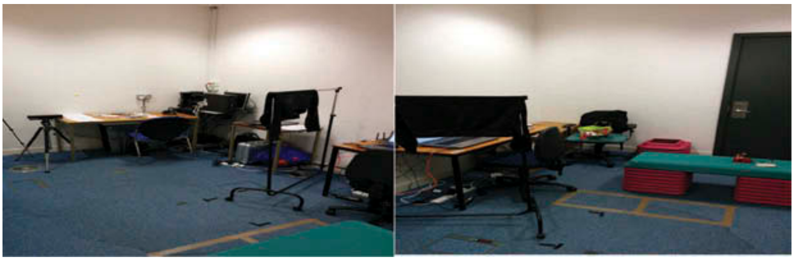
Fifteen people (36–68 years; 10 female, 5 male) with CLBP for 6 to 40 years were recruited from the National Health Service and using social media and the Emo&Pain project website (http://www.emo-pain.ac.uk). Participants completed questionnaires about medical information, physical activity, and pain catastrophizing and rated their pain level at the time on a scale of 0 (*no pain*) to 10 (*worst pain*), and comfort level in stretching exercises.

The study was conducted in a lab setting. An adjustable bench was used for variable seating height when doing the sit-to-stand exercises. The Kinect sensor was placed facing the seat (Figure 5), and a single video camera was placed next to it to record experiments for later analysis and discussion. The Kinect sensor was 1 m from the floor and between 2 and 2.5 m from the participant as recommended in the device specification. Participants wore the wearable device (tabard and breathing sensors; see Figure 3) throughout the study. Participants stood in front of the seat facing the Kinect to exercise. All behavioral data from the motion sensors and from breathing sensors were captured and stored.

Procedure

After a familiarization session with the devices and the sonifications listed in **Figure 4**, the study was conducted in four consecutive parts:

FIGURE 5. Layout of room for evaluation study for both devices.



- **Part 1: Effect of sonification paradigms.** The Kinect device was used to investigate the effect of three different sonification paradigms (wave sound, soundscapes, and active listening) on forward reach and sit-to-stand exercises.
- **Part 2a-b: Effect of information.** The wearable device was used to investigate how the different amount of movement information provided by the sonification (i.e., shape and anchor points) facilitated the forward reach exercise. The four sound conditions (no sound, flat sound, wave sound, water sound) were repeated without (Part 2a) and with (Part 2b) breathing sounds.
- **Part 3: Effect of information on skills transferring**. The wearable device was used to understand how sonification could facilitate the transfer of skills from exercise to a functional activity. Participants were asked to reach forward to get something from a shelf at a challenging height (with a target: the shelf) or to simulate taking something from the same height (without a target in front). M was recalibrated according to the stretch needed to reach the shelf. The four sound conditions (no sound, flat sound, wave sound, water sound) without breathing sounds were explored.
- **Part 4: Effect of sonification alterations on movement avoidance**. This was run as a qualitative study. At the end of Parts 1–3, the sonification alteration option was activated on each of the devices, and participants were invited to explore the various techniques implemented (Box 3) and comment on their usefulness in increasing awareness of avoidance strategies.

For each part of the study, participants calibrated the anchor points (S, C, M) for each device (Kinect or smartphone) according to their physical and psychological capabilities. For the sit-to-stand, the height of the bench allowed an approximate 90° angle at the knee, with feet just behind knees, to encourage the preparatory bend forward position preceding standing. In each study, the presentations of the sound conditions were randomized.

During the familiarization session, participants explored their movement with each sound condition, giving researchers a commentary on their movement and any pain or anxiety ratings. This enabled participants to become familiar with the devices and exercises and researchers to informally sample effects. In each part of the study, immediately after each sound condition, participants were asked to rate their pain on a scale from 0 (*no pain*) to 10 (*worst pain*), and their perceived bend angle on a 5-point scale (five bins centered at 15°, 30°, 45°, 60°, 75°). Such a fine-grained scale was selected as we expected small variation effects due to anxiety. After completing the four parts of the study, participants indicated their preferred sounds and how each sound affected their awareness of movement, motivation, performance (measure of confidence), and relaxation on a scale of 0 (*worst*) to 6 (*best*). It should be said that the ratings related to motivation indicated how the person felt during the execution of the exercise (desire to perform the movement). Long-term studies will be needed to assess the long-term motivational effects of the sonification conditions. **Figure 6** summarizes the four parts of the study with descriptions of the corresponding independent and dependent variables.

Each participant took between 60 and 90 min to complete the full study over 2 weeks of data collection. The analysis of the participants' movement is discussed in the next section. The participants' comments were used to inform the design of the focus group (Section 5) and are reported with those findings.

4.2. Results

In this section, we report the statistical comparison of sonification effects during physical activity using questionnaires and behavioral data from the movement sensors. The independent variables (**Figure 6**) were the sound conditions: three in Part 1 with the Kinect device; four sound conditions in Part 2 using the wearable device; four sound conditions with the addition of breathing feedback in Part 3. For each measure, nonparametric Friedman's tests between the sound conditions and planned pairwise comparisons using Wilcoxon were performed for the non-normal data, whereas parametric analysis of variance with sound conditions as within-subject factor and planned pairwise *t* tests comparisons were performed for the normal data (normality was checked with Shapiro-Wilks tests). Notably, sound feedback did not show a significant effect in pain reports across conditions in either device (Friedman's analysis of variance, all ps $> .1$). Detailed statistics are reported in Appendix B.

Parts 1–2a. Effect of Different Sonifications on Perceived and Actual Performance

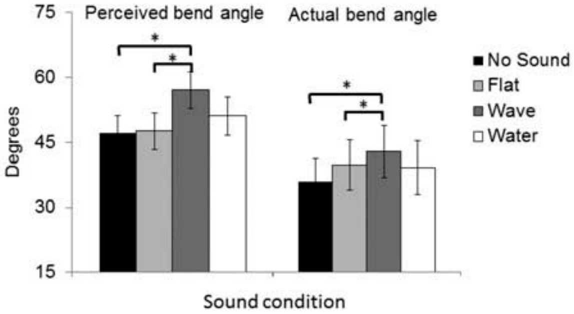
First, we evaluated the effect of the sound feedback conditions for perceived and actual performance (bend angle) in both Part 1 and Part 2a. Whereas no effect of complexity of sonification paradigms (Part 1) on performance was found, an effect was found for the amount of movement information provided by the sonification (Part 2a). The wearable device (Part 2a) provided different levels of information (anchor points and sonic phrase shape) in the sound. The mean values for perceived bend angle, as reported by participants, and for the actual bend angle, as recorded by the sensing device (where 0° corresponds to the vertical position of participants and 90° corresponds to their back being bent forward until reaching a horizontal position), are displayed in Figure 7. Results revealed a significant effect of the sound feedback

FIGURE 6. Description of Independent and Dependent Variables for each Part of the Study.

Experiment	Device	Exercise	Independent variables	Dependent Variables
Familiarization	Both devices	Both exercises	n.a. (all sounds)	n.a (Think Aloud)
Part 1: Effect of sonification paradigms	Kinect-based device	Both exercises	3 SESs: wave sound, naturalistic soundscapes, active listening	—Actual amount of movement measured by the device —Perceived amount of movement —Awareness of movement —Motivation in moving —Confidence in moving —Relaxation
Part 2: effect of sonification information: (2.a) without breathing; (2.b) with breathing	Wearable device	Forward reach	4 SES: no sound, flat sound, wave sound, water sound	
Part 3: Effect of sonification in transferring skills	Wearable device (without breathing)	Forward reach with and without target	4 SES: no sound, flat sound, wave sound, water sound	
Part 4: Efficacy of sonification alterations on awareness of avoidance strategies and movement exploration	Both devices with alteration option on		n.a.: explorative study all alteration techniques presented in Box 3 of Figure 1	n.a: explorative study (Think Aloud)

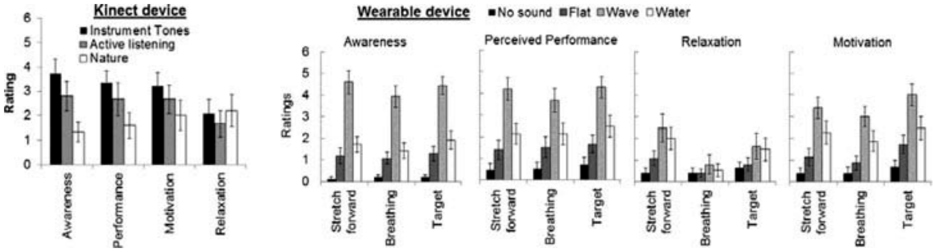
Note. Within each part the sound conditions were randomized. SES = sonified exercise space.

FIGURE 7. Mean (± SE) perceived and actual bend angle for all four sound conditions in the study with the wearable device.



***Note.* The perceived angles were obtained by translating the 1 to 5 ratings to the respective range of angles centred at 15°, 30°, 45°, 60°, 75°. *Significant differences, $p < .05$.**

FIGURE 8. Mean (± SE) ratings (0 = *worst* to 6 = *best*) on awareness, performance, motivation, and relaxation for all four sound conditions in the study with the Kinect (left) and the wearable device (right).



***Note.* For sake of conciseness, the significant differences are reported in the text and in Figures B.2–B.5 in Appendix B.**

condition in both the perceived and the actual performance: Participants felt they were stretching more with the more informative wave sound than with the flat sound or no sound conditions; similar results were found for the actual amount of bend.

Next, we examined participants' reports of how they felt each sound condition influenced their performance, awareness of movement, motivation, and relaxation. Participants' mean ratings, on 0-to-6 scales, are displayed in Figure 8.

Part 1. Effect of Sonification Paradigms on Exercising (Figure B.2 in Appendix B)

Significant differences were found between the different sonification techniques used in the Kinect device (Figure 8, left). Participants reported changes in awareness of their movement according to sound condition, with less awareness of movement in the soundscape (walk in the forest) condition compared with wave sound (tone phrases) and active music listening. In addition, the results suggested that perceived performance was better with the wave sound than in soundscape, although the overall effect of sound on perceived performance did not reach significance ($p = .097$).

Part 2a. Effect of Information (Anchor Points) on Exercising (Figure B.3 in Appendix B)

In the study with the wearable device when participants stretched forward without a target and without respiration feedback, they reported significant differences in all measures. As shown in Figure 8 (right), most participants found sound significantly more useful on all the rating scales than no sound. Results also suggest that more informative sounds are more effective, hence significantly higher ratings with the wave sound (with 3 anchor points and ascending and descending scales) for awareness and performance. For relaxation and motivation, wave and water sounds were significantly better than flat sound but not significantly different from each other.

Part 2.B Breathing Reminders Are Liked but Confusing

When an additional sound to remind people to breathe was added, a minority of participants (six of 15) said it made them more aware of their movement and could help performance, but most found it neither relaxing (14 of 15 participants) nor motivating (13 of 15 participants; see Figure 8, right). Participants commented that although a reminder for breathing was helpful, the two sounds (for movement and breathing) were confusing, and the breathing sound was disliked. No significant difference was found between no sound and having only respiration sound for any of the ratings (all ps $> .5$).

Part 3. Sonification to Facilitate Transfer From Exercise to Function (Figures B.4-B.5 in Appendix B)

We compared the effect of sonification when performing the functional activity of taking an object from a shelf at a challenging height and when simulating the same activity (i.e., without the shelf as a target). Awareness of movement, perceived performance, relaxation, and motivation mean ratings were compared in two-tailed Wilcoxon paired comparisons ($\alpha = 0.05$). The results are shown in Figure 8 (right). Participants reported that they felt more motivated and thought they performed better (12 of 15 participants), and were more aware of their movement (13 of 15 participants) with the shelf present. In the "no sound" conditions, there was no difference in ratings of performance, confidence, or motivation with or without a target (all ps $> .1$). However, with the wave sound, participants felt they performed significantly better with a target compared to without the target ($p < .05$), even if they were less aware of their movement. There were no effects for the other sounds. Motivation was rated significantly better for all sound conditions with a target, but having a target did not significantly affect relaxation ratings for any of the sounds. When comparing the effect of different sonifications on the execution of the movement with target, participants reported a significant increase in awareness, better performance, and greater motivation with more informative sounds. These two results together suggest that both the type of sonification and the type of activity (target-oriented vs. not target-oriented) have an impact on measures.

In Section 5, we report a follow-up focus group, a home study, and a systematic analysis of people's comments from Section 4, to get a better understanding of how the sonification space and strategies proposed address the needs of self-directed rehabilitation and function, and how they could be extended to be more effective. In addition, to confirm the results from Section 4, we include the results from a survey conducted at a weekly drop-in group run by physiotherapists at the pain management centre for people with CP.

5. FACTORS IN DESIGNING SESs FOR EXERCISE AND EVERYDAY FUNCTIONING

Two qualitative studies (a focus group and home interviews) and a survey were run to understand how a device such as *Go-with-the-Flow* (both versions) could be used for exercise sessions and functional activity in everyday life. The study addressed four research questions:

1. Can people design exercise spaces using sound? Can anchor points or other sound-based information increase self-efficacy?
2. To what extent is sound sufficient as a modality to represent information about physical activity?
3. Can sound be used for setting targets for activity and identifying similarities between exercise demands?
4. Can sound be designed to facilitate transfer from exercise to functional activity?

5.1. Methodology

Focus Group

The structure of the focus group was based on findings from discussions with participants during the study reported in Section 4. Five people (four female and one male) from 44 to 58 years of age, with CP for the past 7 to 39 years, participated in the 2-hr focus group. Participants had already participated in the study reported in the previous section and were familiar with the sound conditions. A prefocus group activity was set 1 week before the study, where participants were asked to reflect on and e-mail the researchers about whether the sounds used in the previous study could support them in household or everyday functional activities and exercises about which they were anxious. They were also asked to think about sounds that they find motivating or relaxing while doing activity.

The focus group included a discussion and trials of the sonification options by participants to facilitate discussion. The Kinect was set up at one end of the room for people to try. Sound cards were provided with the sonification options from the study, such as nature sounds, songs, tones, and instrument sounds, to facilitate exploration and discussion. A keyboard was available for the tone scales from various instruments. Further, sound cards were created for sounds mentioned by participants during the evaluation study, such as white noise. We also provided smartphones with the *Go-with-the-Flow* app for people to explore during different stretching exercises. The focus group discussion was recorded with two video cameras at opposite ends of the room and two audio recorders.

Home Study

The home study was run just before the study described in Section 4. Five people with CP (five female participants, 26–58 years of age) participated. Participants were asked to wear the device to explore stretches and everyday tasks around the home, reflecting on how the device could be useful in this context. In a further diary study, three of the participants sent daily reflections via text messages on situations they encountered during the day and how the device could be useful. Two participants dropped out of the diary study.

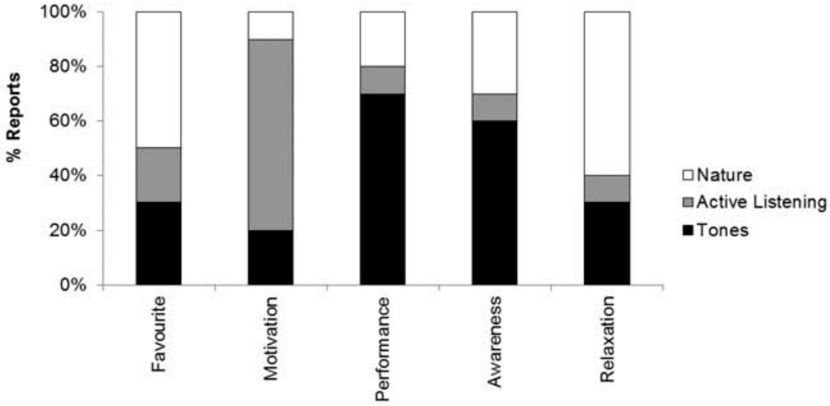
Survey at a Drop-In Session at the Pain Management Center

To further understand how useful the different sonification strategies were to people with CP, we collected data at a weekly drop-in group run by physiotherapists at the pain management center of the National Hospital for Neurology and Neurosurgery for people of different abilities to attend for stretching and exercises. The Kinect and wearable devices were set up in a corner of the room before the pain management class, and interested people were given a demonstration of the movements and corresponding sonification options and encouraged to try both devices and to answer questions. This study was not audio- or video-recorded and ran for 30 min on 2 days. Ten people participated (six female) from 32 to 68 years of age, with CP for 4 to 61 years. They were asked to evaluate all the sonifications, organized in three separate classes: nature sounds (all nature sounds from the Kinect and the smartphone device), tones-based sounds (flat and wave), and active listening sonification.

5.2. Findings

The survey findings (see Figure 9) confirmed the results from the control study: All participants reported that the sounds were useful; sonification was described as encouraging (five people), fun (five people), relaxing (five people), informative (five people), and distracting from pain (one person). Nature sounds (from the Kinect or wearable devices, counted as one for the same person) were most popular, followed by the tones-based sounds (flat and wave) and by the active listening sonification. Nature sounds were also the more relaxing, followed by the tones-based and the active listening sounds. The active listening sound was considered most motivating, followed by

FIGURE 9. Distribution of results for all the sounds.



Note. **Nature-bin refers to both Kinect nature sound and water sound from the Smartphone device. Tones-bin refers to both Smartphone and Kinect tone sound. The flat sound was never selected.**

the wave tones. However, the tones-based sounds were reported to be most helpful for performance and awareness of movement.

The qualitative studies helped to further understand these results and shed more light on the value of the sonification framework. Transcripts and observations from the focus group, interviews, home study, and exploratory sessions described in Section 4 were analyzed together using thematic analysis (Braun & Clarke, 2006). The six main themes that emerged are discussed using the following notation: FG# denotes focus group participants, HCP# denotes participants from the home study, and ES# denotes participants from the evaluation study in Section 4.

Enhancing Awareness Through Sound Feedback

Most people liked sounds that focused attention on their movement, allowing them to understand and adapt or change the movement accordingly. For example, the wave sound was most popular because most participants felt that it accurately described the forward reach movement and they could see the relation between the change in sound and the movement they were doing. FG3 said, “That piano is fine on the way down as well, because I can tell when I’m getting to the comfortable point and I can tell when I’ve got to the extreme point because it stops and I like that.” Participants indicated that it would be useful to have a distinctive sound signal to indicate reaching the target or returning to the start position (e.g., *higher volume* [FG2] or *the clash of cymbals* [FG3]).

Although participants liked the nature sounds, they found them distracting and could not always understand or directly relate their movement to the information being conveyed by different sounds. More complex sounds such as the naturalistic soundscape made some people more anxious about stretching. FG1 said,

> Sounds must not be disruptive and take away from what we're doing, which is the stretch. And if they are disruptive then it doesn't allow us to concentrate on the stretch and there's a danger that we're going to stretch too far—we're going to hurt ourselves.

One of the problems with the complex sounds was that it was difficult to understand where one sound ended and the next started. The speed of performing the movement was a factor: If the movement was executed rapidly, separate sounds were merged or skipped.

Participants also felt that the sound should reflect the type of activity. FG2 said, "So if you're going to do cardiovascular exercise, you don't want gentle music. You want something quite brisk." One suggestion shared by most of the focus group was using sounds that were both relaxing and informative and reflected the "body's rhythm such as beats that are not very loud and set to the pace of the heartbeat" (FG5). FG2 said, "In the same way that the brain and the music won't have a very fast rhythm, you won't have a very intrusive rhythm, track or some techno or something like that." Some participants commented that having a voice telling them to stretch, or reminding them to breathe, could be very reassuring and encouraging. FG4 said, "Some kind voice that's telling you to stretch, because it's something that connects with another human being."

Information About Movement Restriction and Avoidance Strategies

Participants knew that at times, and especially when tired, they used protective or avoidance behaviors such as guarding and restricted movement patterns, posture change (e.g., slouching or leaning to one side); sometimes they were made aware of this by catching their reflection in the mirror or being told by someone else. They liked the idea that they could use the *Go-with-the-Flow* device to get information about these behaviors alongside information about breathing, asymmetric movement, and pace of stretch.

Although protective behaviors are intended to minimize pain, they often exacerbate it in the medium to long term. FG5 mentioned,

> I don't always realize that's [using protective behavior] happening enough and it takes somebody to point it out to me, but if I had some feedback to say I'm leaning forward or I'm leaning to the side or I'm starting to limp, that [awareness] might kick in a little bit sooner.

The *Go-with-the-Flow* app can provide cues about different movement patterns but does not correct; participants felt that it could help them to make a choice to stretch or take a break or simply adjust their movement. FG5 explained,

> Posture for me is something that feels like a weight on my back and it just feels as though I'm carrying this rucksack that I can't take off. I end up, without realising,

> becoming very hunched, and then I end up hobbling around the kitchen and that's when my husband will tell me, "Just go and have a sit down."

Whereas our design provided alterations on the basic sounds, from those that were still aesthetically pleasing to slight distortion, some participants suggested more aversive sound feedback (ES7) could emphasize undesired protective movement or movement restriction. Others suggested that to facilitate conscious avoidance of protective behavior, white noise rather than a more complex sound would help them to focus on the quality of movement by blocking out distractions.

Facilitating Control and Increasing Confidence

Defining and Calibrating a Movement Space

People liked the ability to define their movement space using the three anchor points of starting position, comfortable position, and today's target position. In addition, they felt that they might not always need the maximum point for a target, especially if they were having a bad pain day when they would only try to get to the comfortable point. Participants felt the device could provide additional helpful information for self-directing activity. For example, FG2 mentioned "an element of timing so I was stretching far enough and holding it for long enough."

Having a Rich but Clear Information Soundscape

Although the information conveyed by sound was useful, participants felt that it was important to ensure that the purpose of each dimension of sound was clear. FG5 said, "On the trial that I did, you had music becoming loud and soft as I moved fast, that was useful." FG2 added "one advantage of [sound] is you've got three dimensions: you've got frequency, amplitude and time . . . and distortion—that's a lot of information that can be used." Some sounds also encouraged people to try new movements, not suggested by the researchers. For example, when using the water sound, some people started spontaneously making swimming movements. Hence, the design of the sound could go beyond just pleasurable stimuli and clear information, to designing sound that relates to and may prompt particular movements.

Trusting the Body (Overcoming Caution)

Sound feedback allowed participants to appreciate their range of movement, to build confidence, and to set benchmarks, so that they knew that if they were able to do a certain amount of movement on an average pain day, they could try at least to get to that comfortable point on a day with more pain. FG3 said,

> At the moment I wouldn't go beyond what I think is my comfort point because I'm worried about making it worse. If I know I haven't reached it because the thing hasn't told me I've reached it, I might try and push through to that comfortable

> point. . . . Having got there, I won't go any further, but I think it would encourage me to trust my body to the point I could get to yesterday at the very least.

Setting the comfortable point was also considered reassuring, and most people felt it could help them to overcome the fear of moving and build confidence in movement. For example, FG2 said,

> My proprioception is poor with my back because of fear. And even though the fear is very real, it's not even a conscious fear; it's something that's definitely ever-present. And something like this would tell me, tell my intellect to overcome my fear, because you've got this far, you can go again.

Monitoring the Body, Pain Triggers, and Progress

Participants felt that a *Go-with-the-Flow* device could be useful for tracking stretches over a longer period to track improvement or continued maintenance of stretching ability. FG1 said, "If I could look at it for a whole month and realize 'I've got through a whole month, I've reached my maximum point.'" FG2 added,

> For some people it's just about maintaining something, but for other people it's if you have a degenerative disease, you can see the progression of degenerative disease by loss of ability, so if you can see some element of, "I'm still maintaining the posture where it should be for fifteen years," that is a good thing.

All the participants agreed that viewing progress was motivating. "I've had a couple of low days but generally my comfort point has stayed the same or got slightly further, I think that would be very motivating to see that" (FG5).

For many participants it was important that the device should monitor their movement, breathing, and muscle activity over a period and track flare-up triggers; this would enable the device to help them set limits and pace their activity better. FG3 explained,

> Something like this would be quite useful if it was monitoring that if I'm leaning to one side and it pings at me, I'll know that really today I should use the escalator, it's telling me that I'm already off-centre. . . . It would help me to make a choice, a decision about, "Do I stop now, cause I can now, and do some stretching, right now, using this to help me pull this muscle back out again?" Further the device could be useful to plan for anticipated stressful events.

ES1 said, "I know that we're going on holiday. We've got ten hours on an airplane: I need to make sure I don't overdo it."

Facilitating Transfer and Facilitating Functioning

The *Go-with-the-flow* device, particularly the wearable device, was considered a useful aid to facilitate transfer of skills from physiotherapists and a tool to help maintain activity levels. Focus group participants felt that the device could be very useful to practice after they had worked with a physiotherapist/instructor on calibrating their stretch current capability and set targets. FG2 suggested, "Particularly [useful] if I can work with my physio and my Pilates coach, we can work together to calibrate something like this." Further, a participant of the home study visualized using the device to practice functional tasks "while bending and loading the washing machine, I could use this to (calibrate) how much to bend and practice it with my stretches" (HCP2).

The focus group study also highlighted that it was important for people with CP to interweave activity and exercise or stretching to maximize time for routine chores, to use their time better, or even to avoid increased pain because they felt stiff after doing one thing for a prolonged time. Most participants felt that the device could make them aware of any awkward movements or use of protective behavior while doing functional activity, thus helping to address unhelpful automatic behaviors that had developed over a period. The mobility of the smartphone device was considered advantageous by all participants, as it meant that the device could be used in many naturalistic situations. For example HCP3 said, "I would love to use some gentle music, something to motivate me, take my mind off the pain and grogginess and help me get started. Possibly music to go with stretches I can do in bed."

Most participants described their tendency to be either too active or too inactive, a typical cycle seen in CP where overdoing activity can be followed by rest days to recover. HCP1's diary entry read, "Sound could help me in pacing. If I've been inactive [it could] give me a reminder that I need to move more. Conversely [. . .] remind me to rest. This may help me to maintain activity rather than crashing and burning." Others preferred a tougher approach, "If [a person is] inactive for very long, the app can start buzzing and the person needs to move (even slightly) to get away from the sound."

Type and Location of Feedback and Context of Use

Most participants preferred the sounds coming from the smartphone rather than the speakers in the Kinect scenario, as they felt that the smartphone provided more precise information, in particular the wave sound: They felt "more connected" (FG4) and "the pleasurable sound came from a painful part of the body" (ES1). However, some sounds such as the nature sounds were considered to work better as ambient sounds from speakers. Further, the breathing sounds coming from the smartphone placed on the back of the person was anxiety provoking for some people because they felt it resembled someone breathing heavily just behind them, a threatening cue. This indicated that for some sounds, the location of origin is very important.

Some participants found that the pleasurable sounds distracted them from pain. Certain sounds, such as water, were perceived as relaxing, and people felt that they could use them to stretch on stressful days. Some participants were keen to wear the device as they performed activities in their daily lives. They visualized the device as a phone on their back or a vest with sensors and sound feedback. However, they felt that haptic feedback would work better than sound feedback when they were in public places: "One of the things that would put me off using this in everyday life would be walking down the street having a voice in my back going bing bing bing bing"(FG1).

6. DISCUSSION AND CONCLUSIONS

In this article we proposed the *Go-with-the-Flow* sonification framework for defining SESs for physical rehabilitation in CP. The use of sonification is not novel in physical rehabilitation and motor learning (Hermann & Zehe, 2011; Kleiman-Weiner & Berger, 2006; Schaffert, Mattes, & Effenberg, 2010), but our approach differs as it is tailored for psychological capabilities, that is, what the person feels she or he can perform. Rather than aiming for rapid increase in physical performance (Vogt et al., 2009), our SESs are designed to build confidence in movement and to reduce anxiety. Through tailored sonification using anchor points, the SESs provide information about movement to increase awareness of physical capability, normalize body cues, highlight use of protective behavior, increase motivation, and facilitate transfer of skills to everyday activities that are feared or perceived as demanding by people with CP.

We conducted studies to design and validate the framework with people with CP and physiotherapists through the use of two iteratively built devices: a smartphone-based wearable device and a Kinect home-based system. The evaluation was done using control studies and qualitative studies in the lab, at home, and at the hospital. The results of the control study reveal that people found that sound feedback for all sonification conditions was always preferable to no sound feedback on all rating scales (awareness, performance, motivation, and relaxation). More informative SESs scored significantly higher on all the scales except relaxation. Also, people showed a preference for less complex but more informative sonifications. Sonification alterations were well received by both people with CP and physiotherapists for their potential in improving efficacy of physical activity sessions. In addition, the wearable device demonstrated the possibility of skills transfer from exercise to functional movements through calibration of the device to everyday activities. Qualitative studies confirmed these findings and further highlighted how the device could be calibrated and where and how it could be best used by people with CP.

In the remainder of this section, we present four main points that emerged from this work and discuss implications of the sonification framework and findings from evaluation studies on the design of technology for physical rehabilitation in CP. We use (Pr#) to refer to the principles in Figure 1.

6.1. Informative Personalized SESs Increase Self-Efficacy

Specific sounds are commonly used for signaling goal achievement or providing feedback on the quality of movement (e.g., Wallis et al., 2007). However, we used *anchor* *points* (Pr4) within SESs to tailor the sonification strategy to the psychological needs of the person. Of the three anchor points, we found C (the comfortable anchor point) was the most critical in facilitating exercise in CP. In contrast to other rehabilitation studies, recalibrating C to the physical and psychological needs of the day rather than according to a schedule of continuous progress (Lewis & Rosie, 2012) was an important aspect of self-management (Pr7) to avoid strain in CP. Both people with CP and physiotherapists agreed that M (i.e., maximum stretch) was not always needed and that encouraging a minimum amount of movement was more important. Reaching C (i.e., comfortable point) provided a sense of achievement both on bad pain days and good days (especially if the mood was low; Singh et al., 2014) by marking what the person "needs to do" and motivating them to go a little further, "any extra is a plus." Hence, C rather than M may be seen as the goal that facilitates not only maintenance but also steady incremental building over time of physical and psychological capacity.

As expected, our results showed that the combination of C and M ("today's target") could facilitate maintenance of gains on good days. In the *wave* sound condition, people reported that the achievement of reaching C was a motivation to continue to the final target. However, simply marking the attainment of a *final target or goal* was not in itself effective, even with sounds played at incremental steps (flat sound condition). Even though some participants still pushed themselves to reach the target, endurance without awareness risks strain, in turn producing setbacks and generating protective behavior. Even when relaxing naturalistic sounds (Vogt et al., 2009) are used, simple feedback of progression toward a challenging target may not be sufficient to reduce anxiety (e.g., nature sounds in the Kinect device, and the active listening condition, where meaning was unclear).

6.2. Sonifying Preparatory and Protective Movements for More Effective Movement

The use of sonification to discourage compensatory movements is not novel; many rehabilitation systems have used sound and sound alterations to signal compensatory movements, such as in stroke rehabilitation (Roby-Brami et al., 2014; Rosati et al., 2013) or balance in elderly people (Paraskevopoulos et al., 2014). However, protective movements and avoidance of facilitating movement in CP are usually attributable (until completely habitual) to anxiety about increased pain or injury, so sonification needs to be tailored to these psychological concerns. Hence, increasing awareness (Pr5) and allowing exploration of helpful preparatory movements (Pr6) may be more effective than simply correcting movements, especially because most people with CP (in this study and in Singh et al., 2014) wanted to be made aware of their protective behaviors but they wanted to be in control of their response to the information (e.g., do some counter-stretches, or rest). Hence, it is important to design sonification options in ways that reinforce a sense of control and encourage self-management (Pr7).

We also explored breathing as part of relaxation and to address anxiety during physical activity: using breathing sensors for signaling shallow or mainly thoracic breathing (rather than diaphragmatic) or holding breath, which can potentially affect ease of movement due to anxiety (Perri & Halford, 2004). Breathing well may also make certain movements easier. We used sound feedback to remind people to breathe deeply, but although this increased awareness of breathing, its design was not effective, because the prerecorded breathing sounds were not perceived as self but as another person (too close behind), and distracted from sonified movement probably through auditory overload (Lavie, 2005). The fact that the breathing sound was not accurately synchronized with their own breathing was possibly an important contributing factor. Our experience with breathing demonstrated that the position of feedback may also be an important design consideration: Sounds from behind the listener are more arousing and elicit larger physiological changes than sources in front (Tajadura-Jiménez, Larsson, Väljamäe, Västfjäll, and Kleiner, 2010). One possibility is to integrate breathing rhythms in the movement sonification, starting at the user's rhythm and then slowing and deepening (Liu, Huang, & Wang, 2011). People also suggested using different feedback modalities such as a person's voice that reminded people to breathe during movement or counting to slow breathing (as the physiotherapist does).

6.3. Different Sonification Strategies for Different Phases of Rehabilitation

In Singh et al. (2014), physical rehabilitation is described as a journey with different phases (exploring, building, and maintaining). Our studies show that different sonification strategies could facilitate different needs in these separate phases. For example, simple sonifications, such as the *wave* condition for the forward reach in the mobile device, were more effective in enhancing awareness and performance than complex sounds. Such simple sonifications are examples of direct mapping (Hunt & Wanderley, 2002) of sonic parameters (e.g., pitch) on to movement parameters (e.g., stretch extent). Direct mapping is usually easier to understand, but examples of more complex but still effective mappings (usually designed for music professionals) are found in the literature (e.g., Hunt, Wanderley, & Kirk, 2000). In our studies, complex sonifications appeared to be demanding as a source of information on the execution of an exercise but to have interesting benefits in other aspects of physical rehabilitation, such as relaxation, or practicing movements where people had developed confidence (maintenance phase).

Participant feedback indicated that music or sound that is not perceived as directly related to the performed movement should be avoided (e.g., a sudden single singing bird). The sonic material should not contain any explicit sonic event (e.g., a thump, a thunder, a tap), except where its relation to the user's movement or respiration is obvious (e.g., the water splash indicating that a comfortable point was reached). Sonic materials from sound synthesis techniques such as physical modeling (e.g., Rabenstein & Trautmann, 2001) can ensure that parameters are assigned clear physical meaning: For example, the thickness, length, or tension of a membrane or a string, or the number and amount of vibration of molecules of water in a waterfall. Thus, a fine-grained, ecological modulation of the naturalistic sonic material is obtained, and it may be better suited to the task of reflecting a person's body movement. Moreover, the nature soundscape might "set the scene" before exercise, reducing tension and increasing flow (Gromala et al., 2015). In related work (Timmers, Marolt, Camurri, & Volpe, 2006), to reduce the emotional impact of a piece of music on an audience, a successful strategy was for the pianist to play immediately after arrival, with his ears still saturated by traffic noise. Vidyarthi and Riecke (2013) used breathing sounds to prepare for mindfulness meditation. Similarly, a relaxing, interactive soundscape related to the person's respiration and movement might help him or her to warm up for exercise. Further, in the framework of physical modeling, the application of advanced methods of sonification such as "model-based sonification" (Hermann, 2011) would be worth investigating. Whereas physical modeling techniques for sound synthesis already have proven effectiveness in music performance (e.g., Castagné & Cadoz, 2005), they have only recently been used for sport and rehabilitation (e.g., Roby-Brami et al., 2014; Turchet, Pugliese, & Takala, 2013).

6.4. Body Awareness, Self-Calibration and Wearable Device Can Facilitate Transfer of Skills From Exercise to Function

An important aspect of physical rehabilitation, though often overlooked in technology design (Bruckner, Theimer, & Blume, 2014; Schmitz, Kroeger, & Effenberg, 2014), is transfer of gains from exercise to real-life function. In Singh et al. (2014), people with CP reported that they lost their motivation for physical exercise when they could not see any improvement in their daily functioning or progress toward valued goals. The work reported in this article could help bridge the gap between guidance and feedback from a live physiotherapist, available only to a small minority of people and time-limited, and help with maintaining and building on treatment gains at home and in the person's own environment. Three elements emerged as critical for transfer to function: (a) body awareness, (b) self-directed calibration, and (c) device mobility.

Although the field of technology for physical rehabilitation is moving toward user-controlled methods, the physiotherapist is still at the center. For example, Lewis and Rosie (2012) suggested that the physiotherapist's assistance is important during the initial period of technology use to ensure understanding and appropriate setting of parameters; our findings echo this conclusion. In addition, our study suggested a more critical role for the physiotherapist (e.g., supporting patients' acquisition of self-calibration skills as a part of their awareness of body movement, rather than performing the calibration for them). Our study indicated that physiotherapists can help patients to reflect on their body representations through sound, and to direct their attention to cues that can help in self-directed activity. By using sonification to enhance body awareness (including protective behavior), the device could be used by the person with CP to become aware of his/her own body capabilities and limits (e.g., "at which point of a stretching do I start to use protective behavior"), and to test calibration settings. At the same time, our results showed that external representation by sound can enhance patients' understanding of their own movements and breathing patterns (if embodied), and help with providing personalized explanations and advice, facilitating pacing and goal-setting. The supervisory support by the device could be further enhanced by using functionalities to automatically detect increased pain or more subtle cues of fear of pain from body cues (Aung et al., in press; Olugbade, Aung, Marquardt, De C. Williams, & Bianchi-Berthouze, 2014, 2015) and from facial expressions (Hammal & Cohn, 2012; Kaltwang, Rudovic, & Pantic, 2012; Meng & Bianchi-Berthouze, 2014; Romera-Paredes et al., 2013) and suggest or guide recalibration. Indeed, in a recent follow-up study we carried out on sensing wearable devices, people with CP confirmed the role of technology as a support to learning supervision skills and even to share such the supervisory role in real-life situation where the task at hand requires much attention (Felipe, Singh, Bradley, Williams, & Bianchi-Berthouze, 2015).

The flexibility, mobility, and adaptability of the wearable device make it suitable for use across a range of everyday activities, shown here to be relevant to people with CP. In home studies, in particular, people saw the opportunity to calibrate the device to real targets and then train toward those targets using the sound cues. In the evaluation study (Section 4), participants found using the target more motivating but in certain cases anxiety inducing. The use of a target-calibrated device to practice the movement could facilitate the transition between exercise practice and targeted activity (functional goal).

In conclusion, our studies show that a self-defined sonified space calibrated to the psychological needs of the person helps to increase awareness, motivation, performance, and relaxation in physical activity and can be used by patients to gain confidence in activity and to transfer gains to their everyday lives. People with CP can adapt sonification strategies to their goals and set the device parameters according to their pain level, making it useful even on bad pain days. In addition, although we studied people with CP, this approach could be useful in other chronic problems where progress in physical rehabilitation and self-management are undermined by anxiety about physical vulnerability, which delays return to a more satisfying lifestyle.

NOTES

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APPENDIX A. MOVEMENT DETECTION IN WEARABLE AND KINECT-BASED DEVICES

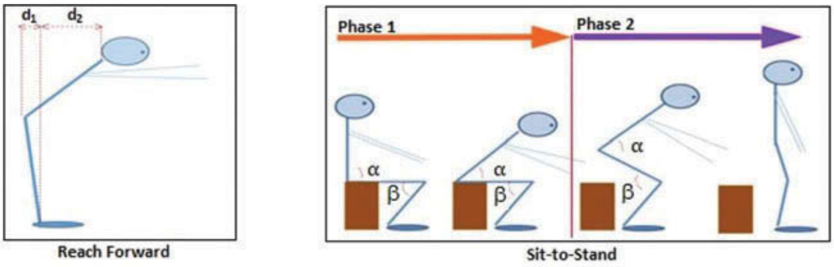
A1. Detection of movement in the Wearable device

The detection of movement is based on the orientation of the smartphone as the person moves and anchor points are calibrated by the smartphone's orientation against the spine position during the calibration process. Only alteration based on asymmetric movements and speed of movement are implemented in the wearable smartphone device. The sound is played only in one ear when the orientation of the device is detected in the sideways direction. The sound can play in the same ear as the movement or the opposite ear. For the speed of movement, volume is reduced when the speed of the movement is very quick, to encourage a slower stretch. Shallow breathing is detected when the ratio between thoracic breathing and abdominal breathing is below a set threshold. These thresholds were set experimentally.

A2. Detection of movement in the Kinect-based device

This is performed by two EyesWeb XMI applications (patches), the *tracker patch* and the *exercise patch*. The former captures and pre-processes Kinect data. The latter computes the progress of the exercise. Given the motion capture data sent by the tracker patch, the progress of the exercise is calculated according to the anchor points set by the user during the calibration process. This patch can control all the

FIGURE A1. (Left) To detect forward reach movement and related guarding strategies, the system monitors the distances between shoulders, hips, and feet. (Right) The progress of the sit-to-stand movement is detected by monitoring the angles between trunk, thigh, and crus.



sonifications for the two exercises and the user can tune various parameters through a GUI (exercise type, panning sensitivity, anchor points, etc.).

Forward reach tracking and sonification: To detect forward reach movement, the system monitors movement of shoulders, hips, and feet. Figure A1 (left) shows how the amount of forward reach movement is computed by the difference between the depth of the centre of the feet and the depth of the centre of the shoulders (d1), d1 is then linearly mapped onto sound to provide awareness of the forward reach progression. The system also monitors the distance between hips and feet (d2) and uses it as a guarding cue: if the hips move backward in such a way that d1 grows bigger than a threshold tg, the system detects an avoidance strategy and alters the sonification. The threshold of backward leaning is defined as $tg = nr * d2$, where nr is a tuneable scale factor ($\text{range} = 0.05 \div 0.7$, default 0.1). A certain amount of backward leaning, proportional to the forward leaning of the shoulders, is normal so the threshold for guarding detection is proportional to the amount of forward stretching. The threshold is parameterized and tuneable in order to adapt the feedback to the user's needs. As in the smartphone app, asymmetric movements are fed back by asymmetrical sound. Other alteration strategies were implemented. For example, change to a lower tone scale if the body's centre of mass was shifted backward, or decreased volume for the other two sonification strategies.

Sit-to-stand tracking and sonification: The sit-to-stand exercise is characterized by two main parts. In the first part, the user, who is sitting, bends forward (facilitating movement); the second main phase begins when the user lifts her/his pelvis from the seat and stands up. Figure A1 (right) shows how these two main phases are detected. The angles between the trunk and the thigh (α) and between the thigh and the crus (β) are computed from the coordinates of the centre of the shoulders, hips, knees, and feet. During phase 1, sonification is controlled by angle α: The progress of the phase is inversely proportional to that angle. The increasing of β in conjunction with an increase of hip height triggers the activation of the second phase. In the second phase, both α and β are related to the phase progress: when they are both close to 180° the sit-to-stand movement is complete. Avoidance behavior is detected if the second phase is triggered while the bending is relatively small (i.e., α is too big). If this condition applies, the sonification during the second phase is altered (e.g., the sound is filtered). As for the asymmetric stretch movement, this is matched by asymmetric audio signal.

Computation of protective/avoidance behavior: Various sonification alterations were used. In the case of asymmetric posturing during the two symmetric exercises, the sound was played only to the ear on the side of the body engaged in the movement. In case of strategies involving either a lack of movement forward or the appearance of a protective movement backward, there were two different effects depending on the sound condition. With the tone-phrases, it appears as a change of octave, instead for the active music listening and naturalistic sounds, it becomes a pitch shifter filter. For the detection of the guarding condition different strategies were applied:

Forward reach: two centres of mass are computed using the 3D body points detected by the Kinect 2 device. The first represents the position of the lower body computed on the basis of the ankle and feet positions. The second represents the position of the hips area composed of spine base and left and right hips. The difference on the depth axis between these two centers of mass is used to compute the amount of guarding behavior.

Sit-to-Stand: two centres of mass are computed. The first represents the upper body position, that is, the center of the area defined by the spine shoulder, left and right shoulders. The second is the position of the hips area of the body, described above. During the preparatory phase of sit-to-stand, the difference on the depth axis between these two centres of mass is used to quantify the amount of guarding behavior.

APPENDIX B. ADDITIONAL DETAILS OF STATISTICAL COMPARISONS OF SONIFICATION EFFECTS

FIGURE B1. Results from Statistical Comparisons between the Sound Conditions (Different Amounts of Information) on Perceived and Actual Bend Angle During Forward Reach Exercising Using the Wearable Device. Bonferroni Correction was Applied to Multiple Comparisons ($p = .008$ Corresponding to a Significance Level of $\alpha = 0.05$).

Effect of Information on Performances (Wearable Device)

Measure	Friedman Tests/ANOVA	Wave vs. No Sound	Water vs. No Sound	Flat vs. No Sound	Wave vs. Water	Wave vs. Flat	Water vs. Flat
Perceived bend angle	$\chi^2(3) = 14.59$, $p = .002$	$Z = -2.49$, $p = .0065$	*ns*	*ns*	*ns*	$Z = -2.81$, $p = .0025$	*ns*
Actual bend angle	$F(1.9, 26.5) = 4.65$, $p = .020$	$t(14) = -2.72$, $p = .008$	*ns*	*ns*	*ns*	$t(14) = -3.11$, $p = .004$	*ns*

Note. Nonsignificant comparisons are marked as *ns*.

FIGURE B2. Statistical Comparison of Sonification Effects During Physical Activity using the Kinect-based Device on Awareness, Performance, Motivation and Relaxation.

Effect of Sonification Paradigms on Exercising (Kinect Device)				
Measure	Friedman tests	Wave Sound vs. Active Listening	Wave Sound vs. Naturalistic Soundscape	Active Listening vs. Naturalistic Soundscape
Awareness	$\chi^2(2) = 11.17$, $p = .004$	*ns*	$Z = -2.81$, $p = .0025$	$Z = -2.20$, $p = .0014$
Performance	$\chi^2(2) = 4.67$, $p = .097$	—	—	—
Motivation	*ns*	—	—	—
Relaxation	*ns*	—	—	—

Note. Bonferroni correction was applied to multiple comparisons ($p = .0017$ corresponding to a significance level of $\alpha = 0.05$). Nonsignificant comparisons are marked as *ns*.

FIGURE B3. Statistical Comparison of Sonification Effects During Forward Reach with the Wearable Device on Awareness, Performance, Motivation and Relaxation.

		Effect of Sonification Paradigms on Exercising (Wearable Device)					
Measure	Friedman Tests	Wave vs. No Sound	Water vs. No Sound	Flat vs. No Sound	Wave vs. Water	Wave vs. Flat	Water vs. Flat
Awareness	$\chi^2(3) = 33.025$, $p < .001$	$Z = -3.24$, $p = .0005$	$Z = -2.96$, $p = .0015$	$Z = -2.40$, $p = .008$	$Z = -3.30$, $p = .0005$	$Z = -3.20$, $p = .0005$	*ns*
Performance	$\chi^2(3) = 32.819$, $p < .001$	$Z = -3.23$, $p = .0005$	$Z = -3.13$, $p = .002$	*ns*	$Z = -3.10$, $p = .001$	$Z = -3.21$, $p = .0005$	*ns*
Motivation	$\chi^2(3) = 25.935$, $p < .001$	$Z = -3.08$, $p = .001$	$Z = -2.83$, $p = .0025$	*ns*	*ns*	$Z = -3.07$, $p = .001$	*ns*
Relaxation	$\chi^2(3) = 18.892$, $p < .001$),	$Z = -2.54$, $p = .0065$	$Z = -2.53$, $p = .0065$	*ns*	*ns*	$Z = -2.54$, $p = .065$	*ns*

Note. Bonferroni correction was applied to multiple comparisons ($p = .008$ corresponding to a significance level of $\alpha = 0.05$). Nonsignificant comparisons are marked as *ns*.

FIGURE B4. Results from the Comparisons of the Effects Between Sound Conditions with and Without Target on Awareness, Performance, Motivation, and Relaxation.

Effect of Target Presence on Transferring From Exercise to Functioning (Wearable Device)				
Conditions	Measure	Flat	Wave	Water
Target vs. no target	Awareness	*ns*	$Z = -2.04, p = .041$	*ns*
	Performance	*ns*	$Z = -2.04, p = .041$	*ns*
	Motivation	$Z = -2.21, p = .027$	$Z = -2.04, p = .016$	$Z = -1.98, p = .047$
	Relaxation	*ns*	*ns*	*ns*

Note. Nonsignificant comparisons are marked as *ns*.

FIGURE B5. Results from Statistical Comparisons Between the Sound Conditions (Different Amounts of Information) Using the Wearable Device and Performing Movement Aimed Towards a Target.

Effect of Sonification Type on Functioning (Wearable Device)							
Measure	Friedman Tests	Wave vs. No Sound	Water vs. No Sound	Flat vs. No Sound	Wave vs. Water	Wave vs. Flat	Water vs. Flat
Awareness	$\chi^2(3) = 34.80$, $p < .001$	$Z = -3.32$, $p = .0005$	$Z = -2.96$, $p = .0015$	$Z = -2.57$, $p = .0065$	$Z = -3.22$, $p = .0005$	$Z = -3.22$, $p = .0005$	*ns*
Performance	$\chi^2(3) = 33.18$, $p < .001$	$Z = -3.23$, $p = .0005$	$Z = -3.13$, $p = .001$	*ns*	$Z = -3.10$, $p = .001$	$Z = -3.21$, $p = .0005$	*ns*
Motivation	$\chi^2(3) = 32.14$, $p < .001$	$Z = -3.22$, $p = .0005$	$Z = -3.13$, $p = .001$	$Z = -2.39$, $p = .008$	$Z = -2.99$, $p = .0015$	$Z = -3.20$, $p = .0005$	*ns*
Relaxation	$\chi^2(3) = 13.08$, $p = .004$	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

Note. For each type of measure, Friedman's test between the three conditions and planned pairwise comparisons using Wilcoxon (Bonferroni correction $p = .008$ corresponding to a significance level of $\alpha = 0.05$) are presented. Nonsignificant comparisons are marked as *ns*.