Musically Informed Sonification for Chronic Pain Rehabilitation: Facilitating Progress & Avoiding Over-doing

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ABSTRACT

In self-directed chronic pain physical rehabilitation it is important that the individual can progress as physical capabilities and confidence grow. However, people with chronic pain often struggle to pass what they have identified as safe boundaries. At the same time, over-activity due to the desire to progress fast or function more normally, may lead to setbacks. We investigate how musically-informed movement sonification can be used as an implicit mechanism to both avoid overdoing and facilitate progress during stretching exercises. We sonify an end target-point in a stretch exercise, using a stable sound (i.e., where the sonification is musically resolved) to encourage movements ending and an unstable sound (i.e., musically unresolved) to encourage continuation. Results on healthy participants show that instability leads to progression further beyond the target-point while stability leads to a smoother stop beyond this point. We conclude discussing how these findings should generalize to the CP population.

Author Keywords
Musically informed sonification; physical rehabilitation; auditory feedback
ACM Classification Keywords
H.5.2 User Interfaces: Auditory (non-speech) feedback

INTRODUCTION

Self-directed chronic pain (CP) rehabilitation is challenging and emotionally distressing [4]. In CP, that is pain that persists past the expected time of healing and it is not justified by physical damage [22], it can create anxiety towards movements that are perceived as threatening (e.g., stretching). It can be difficult to achieve progress due to fear of increase pain. At the same time, there is the danger of over-activity induced by the desire and personal expectations of progressing quickly which can cause set-backs and becoming bed-bound for weeks [15]. In this paper we explored how musically informed movement sonification can be used to invite progress during exercise, or discourage overdoing.

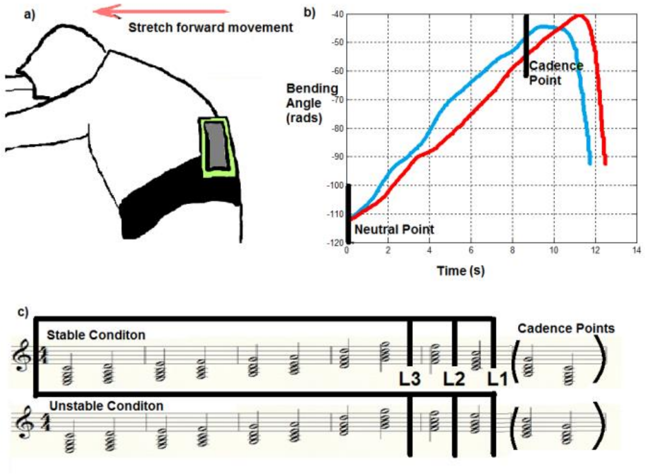

Figure 1. a) shows the stretch forward movement (trunk bend angle) tracked by a smartphone-based system. b) An example of the output recorded: the movement towards and past the cadence point for stable (blue) and unstable (red) conditions. This example illustrates the difference in amount of stretching beyond the cadence point. c) An overview of the sonification stimuli used, all ending on either a stable or unstable cadence point, with three lengths L1, L2 and L3 (derived by removing one or two chords from before the cadence point, followed by either the stable or unstable cadence).

Sound and visual feedback for rehabilitation has been used to provide rewards as it enhances the perception of moving (self-efficacy) [16, 24], enables a better control of the body with respect to trajectories/targets [25] and shifts the attention away from pain [9, 16]. Typically, the achievement of targets is rewarded through changes in the sonification, e.g., the ending of sound beyond the target, dynamically changing sound (increasing tone scales) to indicate progression [25, 16]. Deviations from the set targets (e.g., going beyond it) are signalled by an alteration of the sound, by stopping or by an auditory alert to signal wrong-doing [16, 24].

In this paper, we contribute a new method of sonifying target points based on the idea of harmonic stability. Musical harmony can be thought of as a series of tensions and relaxations: points of tension where the music feels as though it should continue (unstable) and points of resolution where the music feels concluded (stable) [1]. For example, in a

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pop song there may be a build in tension before the chorus, partly achieved through aspects of musical instability and which will often become resolved at the end of the chorus. This aspect of music has been shown to be understood implicitly by people without musical training, through day-to-day exposure [1, 23, 21, 14]. By exploiting the sense of agency over the heard sounds derived from the sonification of one's body movement (i.e., the feeling that the sounds heard are being produced by one's own body movement [18]) and the musical resolution obtained using harmonic stability levels, we aim to provide the perception that the level of resolution of the sonification is created by the person's internal decision to either conclude a movement or not. We investigate whether the target point of a movement (e.g., stretching forward), being stable or unstable, can affect the behaviour at that point. In particular, we explore the possibility of stable contexts to conveying the feeling that a movement is reaching an end, thus encouraging stopping, and unstable contexts for target points to producing the desire to continue. The novel contribution of this work is in the demonstration of the effect of harmonic structure when used in a sonification of movement. We aim to use this musical structure as part of an embodied interaction and whether the musical structure of harmonic stability is perceived as the conclusion of the movement.

BACKGROUND

Sound feedback for physical Rehabilitation

Sonification of movement has been used in many contexts: for optimisation, e.g., sports [13, 2], dance [3] or motor-learning [7, 17]. Several works have also investigated the use of sound feedback to aid rehabilitation. Wallis et al. developed a system for the rehabilitation of arm mobility in stroke patients that used musical sound feedback driven by movement within a given space [25]. The progression of the feedback was driven by the individual's movement. The ending of movement was incentivised by using harmonic resolution and an auditory alert to indicate completion. Undesired movement was indicated using other auditory alerts. This work shows the use of harmonic structure within a defined space to provide a rewarding end. However, it does not explore the uses of harmony to encourage continuation or how the harmonic resolution affects the movement.

Vogt et al. focus on helping people undergoing physiotherapy to better understand their body and movement [24]. The system used two scenarios, a woodland scene where layers of sound were added with movement, and one where movement drove the playback of a musical sample/text, with inhibitory sounds used to avoid deviation from the movement. Again this work used a definite end point, not allowing progression past a predefined point.

Singh et al. used sonification specifically to aid CP rehabilitation [16]. Each individual defined their own exercise space consisting of a neutral start point, a comfortable amount of stretching and a final target amount of stretch. The sonification used these points to space a melodic progression within the exercise space: an ascending melody marked the progression from the start to the comfortable point and from this point a descending melody marked the progression to the target point. Participants reported higher performance and self-efficacy with this feedback.

The work described above defined an end to the movement to inform an individual that they are moving outside of the given space through a change in the sonification. Sound feedback has also been shown to affect the perception of body appearance and/or the body physical capabilities (e.g., body strength) and these may have an effect on movement behaviour [18, 19]. These mechanisms exploit the concept of agency, that is the perception of the sound as direct sensory feedback of one's own action. Hence careful manipulations of sonification are perceived as consequences of one's own motor behaviour rather than externally imposed [6, 20]

Implicit music understanding

Musical stability can be thought of as how much a piece of music has concluded. Bigand demonstrated that this aspect of music is understood by people without explicit musical training, and that tonal factors are important for both musicians and non-musicians for determining the stability [1]. Sears' recent work on perception of cadence also demonstrates the ability of non-musically trained people to identify differing stabilities of cadences [14]. Cadences represent a specific way in which musical stability can be manipulated. A cadence consists of two chords used most commonly at the end of a musical phrase that define whether it either continued or concluded. The ratings for different cadences taken from Mozart's Piano Sonata No. 3, K. 281 were given by musicians and non-musicians. Sears' work showed that similar completion ratings were given by both musicians and non-musicians for a series of different cadences.

These works show that the understanding of musical stability and cadential closure are acquired to some degree implicitly without musical training. Using this understanding, we aim to create a musically-informed sonification which would allow better progression and discourage over-activity. Our approach is grounded in neuroscience theories of motor-to-sensory transformations showing implicit associations between sounds and movement (e.g., sound pitch and direction of movement) [8] and that sensory feedback is used to update motor predictions and implicitly biases the subsequent movements [27].

HARMONIC STABILITIES EFFECT ON MOVEMENT

Motivation and Hypothesis

This experiment investigates the use of stable and unstable cadences for defining the target point of a movement; for example, a set amount of trunk bending, as shown in Figure 1.a. Participants were given sound feedback driven by their movement and asked to use the sound to inform them that they have reached the target point. A stretch forward movement, often used in the rehabilitation of chronic lower back pain, was chosen for its past use as an example of an anxiety-inducing movement for people with CP [16].

We hypothesised that a target point sonified by stable cadences would lead to a more natural stop, whereas with unstable cadences a more prolonged movement past the target point would be observed (**Hypothesis 1**). We also hypothesised stable cadences would provide a stronger sense of reward and motivation than unstable ones (**Hypothesis 2**).

Materials

Our sonification is based on that used by Singh *et al.* consisting of a set of ascending tones followed by a set of descending tones ending at the final-target point [16]. The use of a simply shaped sound was considered important as it was easier to interpret while executing a feared movement, as such we used the same shape but added harmonic structuring. The target point sonification was based on the conceptual sonification design framework proposed in [12]. A set of six conditions was created: three stable (ST) and three unstable (UN). For the descending part, three different lengths were used: 3 chords (L1), 2 chords (L2) and 1 chord long (L3) for both ST and the UN of the sound, as shown in Figure 1.b. The reasoning behind the different length stimuli was to avoid learning bias, where participants would learn after how many chords the feedback stopped. The cadences were chosen following a validation study with 38 participants who rated the stability of six different cadences and different length stimuli. The unstable condition was left unresolved and participants returned to the initial position once they realised no more chords would be triggered.

Participants

A total of 21 healthy paid participants were recruited for the study (age=21-75, 14 female and 7 male). Four participants from the study were discounted from the analyses, three as they failed to consistently reach the final cadence point and one due to exceeding the range of the sensor. For this study we recruited from the general population, instead of any specific rehabilitation population, this was done for two reasons: 1) to ensure it would be safe to use within a rehabilitation context and 2) as there should be no difference in the perception of the sonification or its effect on movement between rehabilitation and non-rehabilitation populations. 13 out of the 17 participants were found to be below the mean score for General Musical Sophistication subscale of the Goldsmith musical sophistication index in the general population (81.58) [10], therefore we assume the effects seen are not due to musical training.

Experimental Design & procedure

To achieve the sonification, a smart-phone application was used: the phone was placed on the participant's lower back, via a support band, and used its integrated gyroscope to measure the bending of the trunk during the stretching forward which drives the sonification, it operated at ~50 FPS with minimal frame loss. First, measures of each participant's neutral position (i.e., standing up right) and a maximum stretch position were taken. The stretch space between neutral position and target point was then divided into 11 equal segments so that as the participant stretches the next chord in the sequence played. The final two chords of this sequence gave either a ST or UN target point within the stretch space (dependent on the length). Behavioural and self-reported measures were taken:

Stretch distance: The amount of stretch beyond the cadence point, as measured by the phone gyroscope, was used as a measure of how far participants continued to stretch before stopping to return to the neutral position.

Time of return: The time taken between the cadence point and the maximum amount of stretch before returning (the stretch distance) was used as a measure of the participants response time to the final cadence (i.e., how long it took them to realise they had reached the target point).

Self-reported measures: Measures of perceived stability, perceived motivation to continue, perceived amount of stretch and perceived reward at the target point were taken with 7-point Likert-type response items.

A randomised within-subjects design was used and consisted of 12 trials, including two repetitions of the six conditions. The participants were first introduced to the experiment and given a demonstration of the smart-phone application. They were instructed to stretch forward at a steady pace allowing each chord to sound and to use the music produced to inform them when they had reached the target point (i.e., the end of the feedback). After each stretch a questionnaire was used to collect the self-report measures. The study was approved by the ethics committee of UCL.

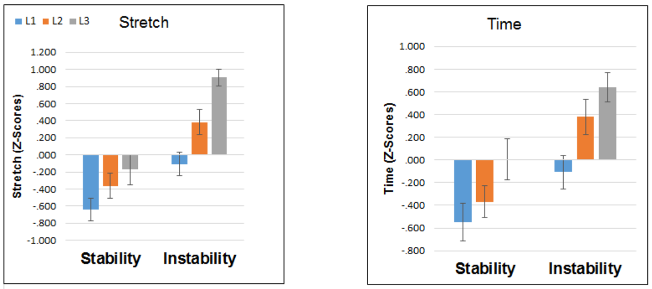
RESULTS

Behavioural data was normalised using individual z-scores. The trials were submitted to repeated measures analyses of variance (ANOVA) with stability, length and repetition as within-subjects factors, and musical expertise as between-subjects factor, followed by Bonferroni-corrected pairwise comparisons. Self-reported data were analysed with Friedman tests, followed by Bonferroni-corrected Wilcoxon signed rank tests. Results are summarized in Figure 2.

Stretch distance: Significant effects were found both for stability ($F(1,14) = 25.744$, $p < .001$, $\eta^2 = .632$) and length ($F(2,60) = 15.201$, $p < .001$, $\eta^2 = .503$), with no significant interaction. Bonferroni-corrected pairwise comparisons showed that people stretched more in L3 than in L1 ($p < .001$), and in L2 than in L1 ($p = .037$). No significant effect was seen due to repetition. *Participants stretched on average more in the UN and less in the longest condition L1.*

Time of return: Significant effects were found for stability ($F(1,14) = 13.917$, $p = .002$, $\eta^2 = .481$) and length ($F(2,60) = 8.000$, $p = .002$, $\eta^2 = .348$), with no significant interaction. A significant difference was found between L1 and L3 ($p = .006$). Again no effect of repetition was found. *Participants responded quicker to ST, and to the longest L1 vs L3.*

Self-reported measures: Wilcoxon signed rank tests showed no significant differences between the two repetitions for each item. Thus, the repetitions were averaged resulting in six conditions. A series of Friedman tests found significant differences for: perceived stability ($\eta^2(5) = 47.357$, $p < .001$), perceived stretch ($\eta^2(5) = 12.139$, $p = .033$) and perceived reward ($\eta^2(5) = 38.180$, $p < .001$), but not for perceived motivation. Subsequent Wilcoxon tests (the adjusted significance level was at p = 0.055) showed that STL3 was significantly less stable than STL1 (Z = -2.866, p = .004) and STL2 (Z = -3.005, p = .003). ST conditions were significantly more stable than their UN counterparts for L1 (Z = -3.209, p = .001), L2 (Z = -3.625, p = .001) and L3 (Z = -3.423, p = .001). For perceived reward, significant differences were found between STL1 and STL3 (Z = - 2.806, p = .005). ST conditions were found more rewarding than their UN counterparts for L1 (Z = -3.054, p = .002), L2 (Z = –3.160, p = .002) but not L3.Significant effects were not found for perceived stretch.



	STL1	STL2	STL3	UNL1	UNL2	UNL3
Stability	1(1-6)	1.5(1-5.5)	3(1-6.5)	5(1-7)	6(1-7)	5.5(3-7)
Motivation	4(1-7)	5(1-7)	4.5(1-7)	2.5(1-6.5)	3.5(1-7)	4(1-7)
Stretch	6(4-7)	5.5(2-7)	5(1.5-7)	5.5(2-7)	5.5(2.5-7)	5.5(1-7)
Reward	5.5(4.5-6.5)	5.5(3.5-6.5)	5(2.5-6)	4(1-6.5)	3.5(1.5-6)	4(1-6)

Figure 2. Experimental results: (top) mean (SE) stretch & time; (bottom) median (range) values for self-reported data for stable (ST) and unstable (UN) cadences of lengths L1-3.

DISCUSSION

The results show that, in music-based sonifications of movement, ST can be used to promote ending and conversely UN can be used to encourage continuation of movement after the target point. As hypothesized, we found that for UN there was additional movement after the cadence point and that for ST the time of return was quicker. Results also show that the length of the sonification prior to the cadence had significant effects on both stretch distance and time of return. Furthermore, ST endings were as expected more rewarding than UN. These results are in keeping with Bigand's suggestion that musical stability is implicitly understood [1]. They are also in line with previous neuroscience works on motor-to-sensory transformations showing that sensory feedback received on one's actions can implicitly bias subsequent motor behaviour [27] and constitute a novel contribution to this area of research in which there are only few studies looking at sound feedback [19]. These previous studies mostly used distorted versions of sounds that naturally accompany body movement. However we show that implicit associations between body movement and musical sound can also have an effect on motor behaviour. Results also suggest that the length of the sonification prior to the cadence point can modify movement behaviour, as significant effects of sonification length were found on stretch distance and time of return. This should be taken with caution. We hypothesize that it could be due to the knowledge of the maximum stretch so that as they stretched further they were more expectant of the ending.

Though our study was carried out with healthy participants, we feel these preliminary results can be generalised for a musically-informed sonification for CP rehabilitation. The key differences between this population and that with CP are pain on movement, and anxiety. Previous work has shown that self-calibrated sonification of movement can refocus attention from pain and anxiety to movement by providing an external focus [16] and sound/music can be used to manage anxiety and even reduce pain [11, 5]. Moreover, our approach directly mimics the verbal instructions of physiotherapists [15]: the UN cadence mimics their use of continuous tense during movement to focus on moving and encourage progress; the ST cadence mimics direct verbal instructions to specify targets and avoid overdoing.

The present results also show that ST endings were significantly more rewarding than those that do not reach musical conclusion, this is beneficial in terms of reducing overdoing. Self-efficacy is especially important in CP as it links to fear and anxiety of movement [26]. The importance of marking the end of a movement was also seen in Wallis et al. [25] for other kinds of rehabilitation.

At the same time, the UN cadence was perceived as less rewarding. However, in the context of rehabilitation, an UN cadence would be used to encourage movement past a point, then followed by a ST cadence at a final target to both resolve musically and reward movement. Naturally the next step will be to verify its use in this context.

CONCLUSION & FUTURE WORK

These results demonstrate how harmonic stability can be used to promote movement for a rehabilitation context. We demonstrate the application of implicit musical understood theory [1, 14] to create a musically-informed movement sonification. We show that endings of different stabilities can be used to either encourage movement or provide a definite end point and how these definite ends are seen as more rewarding. This work primarily focuses on the rehabilitation applications of this sonification; however, this could be used elsewhere, for example: motor learning/optimisation for sport/training, where sound feedback has already been shown to be effective in the past [7, 13, 2, 17].

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