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Altering body perception and emotion in physically inactive people through movement sonification

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Abstract— **Physical inactivity is an increasing problem. It has been linked to psychological and emotional barriers related to the perception of one's body, such as physical capabilities. It remains a challenge to design technologies to increase physical activity in inactive people. We propose the use of a sound interactive system where inputs from movement sensors integrated in shoes are transformed into sounds that evoke body sensations at a metaphorical level. Our user study investigates the effects of various gesture-sound mappings on the perception of one's body and its movement qualities (e.g. being flexible or agile), the related emotional state and movement patterns, when people performed two exercises, walking and thigh stretch. The results confirm the effect of the "metaphor" conditions vs. the control conditions in feelings of body weight; feeling less tired and more in control; or being more comfortable, motivated, and happier. These changes linked to changes in affective state and body movement. We discuss the results in terms of how acting upon body perception and affective states through sensory feedback may in turn enhance physical activity, and the opportunities opened by our findings for the design of wearable technologies and interventions in inactive populations.**

Keywords—sonification, emotion, body perception, physical activity, multisensory feedback, wearables, self-care technologies

I. INTRODUCTION

Physical inactivity is the fourth risk factor in health problems and global mortality. Globally, 31% of adults aged 15-64 years had an inactive lifestyle during 2008 and there are approximately 3.2 million deaths/year because of this problem. One of the aims of the World Health Organization (WHO) in increasing physical activity (PA) in people is to prevent non-communicable diseases [1], [2]. WHO guidelines emphasize that to encourage inactive adults to become physically active (i.e. moving from "no activity" to "some level" of activity), it is necessary to consider physical requirements, such as the need to increase the duration, frequency, and intensity of PA, together with emotional and psychological needs which may act as barriers to PA [2].

Supporting people to become physically active through technology remains an important challenge. Several commercial and research sectors, in the fields of Human–Computer Interaction (HCI), Affective Computing and others, have attempted to address this challenge by means of technologies. Many of those integrate sensing devices for PA tracking, allowing self-monitoring and setting PA goals; they often provide motivating feedback, mostly building on cognitive behavioural theories [3]. However, as highlighted by [4], these technologies present important limitations: while users may become more aware of their problems (e.g. physical inactivity or capabilities), they often are not able to act on them on their own, undermining changes in behaviour and increasing frustration. In this study we attempt to address some of these limitations (i.e. facilitate to act on physical capabilities and inactivity) by building on the complementary novel approach proposed in [5] that exploits bottom-up multisensory mechanisms related to body perception (BP). Grounded in neuroscientific research showing the *altering of BP* through sensory feedback [6]–[8], this work showed that the altering of the sounds that one's body movements naturally produce (e.g. footstep sounds) can alter BP (e.g. feeling lighter), as well as emotion and behaviour related to such perceptions [5]. Here we aim to investigate the possibility of evoking changes in the perception of body movement qualities (e.g. being flexible) by sonifying the movement rather than modifying the sound naturally produced by one's actions. In doing so, we also aim to investigate the emotional changes and movement patterns that such sonification and BP changes may trigger.

Our main contribution is a prototype and a user study testing the feasibility and potential of this novel approach to promote PA in inactive populations. Our second contribution is two gesture-sound palettes for two kinds of movements recommended in PA programmes to enhance physical condition (walking, thigh stretch), which act upon different BP (e.g. perceived agility, flexibility, tiredness) and that could help enhancing and motivating active lifestyles, as well as enhance emotional states related to one's BP.

The rest of the paper is organized as follows: we present the background and our contribution; then we describe the prototype and the gesture-sound palettes; and summarize our experimental protocol and results. We end by discussing the insights emerging from the results in relation to the design of technology enhancing BP and emotion to facilitate PA.

II. RELATED WORK

Technologies for physical activity (PA)

Various studies on wearable devices have explored novel ways to help people to engage in PA or have proposed prototypes to change sedentary behavior. Many of these studies have been looking at self-monitoring of PA. They have explored how wearable devices can encourage engagement in PA, using commercial devices such as Fitbit [9] or smartphones [10], which often integrate sensors of physiological activity or PA e.g., heart rate monitor, step tracker, accelerometers or pressure sensors. Sensor inputs are computed and accompanied by interactive apps aiming to help people achieving their PA goals through awards, challenges, or messages [11]. For example, a smartphone app that reminds users to move to avoid sedentarism [10].

The technologies above mentioned focused on ways of tracking activities (e.g. running) and understanding the best strategies to present data to long-term trackers (e.g. hourly or by goal) to increase awareness of PA and engage individuals in active lifestyle [10] or help them recover from motor issues [12]. However, it is still a challenge to achieve long-term adherence to PA in sedentary or inactive people [13]: while by using these technologies users may become more aware of their problems, they are often incapable of changing behaviour by themselves, as highlighted in [4]. Works focusing on psychological needs or barriers that prevent PA [14]–[17] have identified significant correlations between PA and barriers related to self-esteem, motivation, BP (e.g. proprioception), or affective states, among others.

In this work we propose to act on the psychological needs related to BP and affective states in inactive people as a way to change behavior and promote adherence to PA in this group. We build on prior studies using real-time audio feedback on movement to help the movement or to alter BP.

Audio feedback to facilitate sport and physical rehabilitation

An approach to assist therapeutic rehabilitation is to use sound to give feedback on body movements. This approach is known in HCI as *Interactive Sonification (IS)* and is defined as the use of sound within a human–computer interface to provide information about the interaction itself to helps refining the activity, in our case basic movements.

The use of IS to inform about movement start/end, or to accompany the movement, has been shown to be beneficial in sport activities as swimming, rowing [18], [19], or dance [20], in motor rehabilitation of upper or lower limbs [21]–[23] and in reconnecting with functional activity [17]. For example, a study with a wearable device for people with chronic pain showed that IS could be effective, motivating, informative, and attractive to PA; simple vs complex sound structures with information on body position were more effective in improving users' body awareness [16]. [21] showed that using unstable cadence at the end of the movement induces a desire to stretch further.

The abovementioned technologies have in common the use of sound as *sensory information* on body movement to lead or help the movement. There is much less work on sound as a source of *sensory alteration* of one's own BP. By manipulating the sounds produced by own body movements it is possible to alter BP and in turn the related emotional state and motor behaviour [5]. A recent work [24] describes how altered footstep sounds can change BP during exertion exercise. Note that for such changes to happen sound-feedback needs to be felt as generated by one's body [25].

In this work we aim to combine, for the first time, both approaches and use IS of body movement to alter BP, including movement quality, and emotional state. Related works used *metaphorical sonification*, e.g. of body weight distribution of the users walking on reactive surfaces [26] or of micromovements [27] to increase awareness of feet speed, rhythm, balance, etc., thus showing the potential of such body alterations for HCI - however, the focus of these studies was mostly on heightening the somatic awareness of the user [28] rather than evaluating BP change. By inducing the sense of being more capable of doing PA and bringing positive affect to one's body, we aim to act on the psychological and affective needs related to BP and impact on PA-related motor behaviour.

III. METHOD

A. Participants

26 participants (Age: Mean=22.08 years, SD=5.19, Range=18-44; 11 male, 15 female). Note that only physically inactive participants took part in the study. A pre-screening was conducted based on the International Physical Activity Questionnaire (IPAQ) [29] and on the number of hours/week dedicated to sport activities [30]. Out of 246 people screened, 26 people falling into the IPAQ low or moderate-low PA categories (<2772 METS/week) and doing less than 2 hours/week of sport took part. The study was approved by the local ethics committee.

B. Exercise selection

Our selection of movements is based on [31] guidelines to become more physically active. These guidelines recommend three programs - walking, strength (i.e. seat-to-stand), and flexibility (i.e., thigh stretch) - to gradually increase the amount of daily PA. We chose two movements from these programs - walking and thigh stretch. Walking was chosen because it is the most recommended exercise and considered natural and complete, as it covers building up strength, coordination, cardiorespiratory condition, etc. Thigh stretch was chosen because it involves the challenge of raising and stretching the foot and keeping control of the movement, and as so we consider its potential to build on flexibility, agility, sense of capability, etc.

C. Materials

Our prototype is a refined version of the one in [32]. It consists of a pair of shoes with integrated movement sensors and a specially developed piece of software implemented in Max/MSP (Cycling'74), which "sonifies" the sensor inputs. The software allows various gesture-sound mappings and recording the movement data to quantify user behavior.

The wearable prototype is composed of a wireless emitter with an Inertial Motion Unit (IMU) connected to two force sensitive resistors (FSR). The FSR sensors (1.75×1.5″) detect the exerted force by feet against the ground and are placed in the front and back of strap sandals, under the insoles, to protect them and to increase user comfort. The wireless sensor module is a BITalino R-IoT (v2 from Plux) embedding a 9-axis IMU sensor digitized at 16 bits. The data are wirelessly transmitted using the OSC protocol to a computer running Max/MSP. In this study the R-IoT was worn on the lower leg, attached to the ankle, see Fig. 1. The sound was fed back via digital wireless with analogue inputs closed headphones (Sennheiser RS220). The latency introduced by the use of R-IoT and wireless headphones was kept under 90 ms. After several pilot studies we considered that this latency was actually hardly perceived and does not affect the perception of the movement-sound coupling. As a matter of fact, the designed movement-sound mappings associate continuous movements to continuous sounds, lasting over the whole considered action, and as such the perception of where the sound must actually start is not well defined from a perception point of view, making the latency is acceptable. Note that this case is fundamentally different from the case of triggering sounds on specific discrete actions such as finger tapping or percussive-like actions.

Fig 1. (left) Front and back FSR, accelerometer and battery; Sandal with back FSR (right) walk and thigh stretch movement.

We developed mappings of sounds for two different movements, walking and thigh stretch, through the implementation of a descriptor-based concatenative synthesis [33] that plays and modifies recorded sounds using the library MuBu for Max. This technique consists in selecting and playing in real-time short sound samples previously segmented and analysed. It allows establishing various relationships between the sensor's values to specific sound characteristics such as the audio energy and the spectral centroid (associated to the timbre perception).

The use of sound samples as source material allows selecting specific sounds that evoke body sensations at a metaphorical level. Our aim was to elicit different BP (e.g. feeling more flexible or more agile) through the sonification. The included mappings are based on [32]. We tested various mappings in a pilot exploratory study with 9 participants including questionnaires on bodily and affective feelings, think-aloud and semi-structured interviews. Based on these inputs we designed with our team the mappings list below:

Walking exercise:

Mapping 1 "Can-crush": Inputs from front FSRs are mapped to an "aluminium can-crush" sample sound, in order to replicate the sense of pressing a coke can against the ground [34]. This sonification aims to study the possibility to elicit perceptions of having a stronger or heavier body, through the use of this metaphor. The FSR max value is used to select samples of varying mean audio energy (the lower the FSR value, the lower the audio energy).

Mapping 2 "Control-can": Inputs from the front FSRs are mapped to a "constant tone" sound with the same duration as the mapping 1, and with a constant pitch with a frequency of 440 Hz, which was considered a neutral sound with no metaphorical associations [35]. While Mapping 1 builds on a "Can-crush" metaphor, mapping 2 is used to control for the possible effect of simply hearing a sound while performing the same movement [5], [16].

Mapping 3 "Wind": Inputs from the front FSRs and accelerometers are mapped to a "Wind" sound, which plays a sample sound during the foot swing of a stride (the lower the FSR value, the lower the audio energy). This sonification aims to study the possibility to change BP in relation to speed, strength, movement "fluidity" - previous works with a similar sonification have reported that it leads to feelings of more expressive, fluid, and energetic movements [36].

Mapping 4 "Control-wind": Inputs from the front FSRs and accelerometers are mapped to a "constant tone" sound (440 Hz) with the same duration as the "Wind" sound. Mapping 4 is used as control stimulus for Mapping 3.

Thigh stretch exercise: Mappings 5-8 use as inputs the accelerometer and angle data when raising/lowering the leg.

Mapping 5 "Wind" plays a continuous "Wind" sound (pink noise) changing in frequency in response to the change in leg angle (from 220 to 3520 Hz). This sonification aims to build on BP of flexibility or fluidity, based on pilot testing.

Mapping 6 "Water" plays a continuous sound of water running and adds a "splash" sound at movement start/end [21], [22]. Similar to mapping 5, this mapping aims to build on perceived flexibility or fluidity, based on pilot testing. Moreover, we noted that Wind/Water gave feelings that the leg rises higher, being more capable, comfort, and agency over the sound. The acceleration value is used to select water splash samples of varying max audio energy (the lower the acceleration value, the lower the audio energy).

Mapping 7 "Mechanical" maps changes in angle with a gears sound. By adding extra information about angle changes, this sonification aims to enhance the sense of control/proprioception [16]. The angle value is used to select samples of varying mean audio energy.

Mapping 8 "Tone" plays a continuous tone during thigh stretch from start to end. It is used as control of Mappings 5-7, i.e. to control for the possible effect of simply hearing a sound while performing the same movement [18], [19].

D. *Experimental Design*

The study focused on two exercises: walking and tight stretch. For walking, there were five experimental conditions: "Wind" and "Can-crush" and their respective controls, "Control-wind" and "Control-can", as well as a "No-sonification" which served as baseline. For thigh stretch, there were also five experimental conditions: "Mechanical", "Water", Wind", "Tone" (Control) and a "No-sonification". During "No-sonification" in both types of exercises, the participant did not wear headphones and simply listened to the natural sounds produced during walking and stretching. The experiment was conducted in a quiet room, with a length of 9.3 meters, which was taken into account for the completion of the walking exercise.

E. *Measures*

As in [5],[6],[24] we hypothesized that changes in one's own BP may come together with behavioral and emotional changes, given the tight links between these dimensions: e.g. when perceiving one's body as lighter, one may feel more positive about this body and walk as if it were lighter, by accelerating and elevating the lower limbs [32], [33] or adopting an upright posture; this in turn may affect emotional dominance, as it is known to relate to upright posture [37]. On the contrary, perceiving one's body heavier may result in longer heel strikes, slower and less accelerated movements [38]. Changes may reinforce each other during the process. To monitor changes, these measures were used:

-Emotional state: Valence/happiness and arousal/ excitation scales of the self-assessment manikin (SAM) [39].

-Body feelings: A body feelings questionnaire, with 17 items (7-point Likert-type) allowed participants reporting their body sensations during each sound condition [5]. The first 7 items related to overall BP - they began with "As I was doing the exercise, I felt…" and then ranged from "Light" to "Heavy" (Heaviness); "Weak" to "Strong" (Strength); "Slow" to "Quick" (Speed); "Unagile" to "Agile" (Agility); "Unflexible" to Flexible" (Flexibility); "Not tired" to "Tired" (Tiredness); and "My heart/breath did not accelerate" to "Accelerated" (Heart/Breath accelerated). The next 7 items related to body movement – 3 items began with "I felt my movements were" and then ranged from

"Easy" to "Difficult" (Difficulty); "Uncoordinated" to "Coordinated" (Coordination); and "Not Fluid" to "Fluid" (Fluidity); 1 item was "I felt I was… of my movements" and ranged from "Not in Control" to "Control" (Control); the other 3 items ranged from "I felt capable/incapable of completing the exercise" (Capability); "I felt I could not tell/could tell exactly were my foot was" (Proprioception); and "I felt my muscle was" from "Not working at all" to "Working hard" (Muscles activity). 3 more items related to the sounds heard –and ranged from "Not produced" to "produced by me" (Agency); "Did not motivate" to "Motivated me to do the exercise" (Motivation); and from "Uncomfortable" to "Comfortable (Comfort)".

-Behaviour changes: Gait and stretch biomechanics measured both implicit changes in perceived body and the effects in PA. The sensors raw values recorded by the Max/MSP software, including back and front FSR, angle and acceleration (x, y, z) were analysed in MATLAB to extract the following parameters used to assess/quantify PA:
Walking exercise: maximum and mean heel and toe pressure applied on the ground (more pressure means more PA); heel-ground and toe-ground contact times and stance time, i.e. time interval between heel strike and toe-off events (the larger the contact time, the less PA);
Both exercises: For the leg up and down movements, we calculated peak angle (the larger the angle, the more PA; it also links to increase flexibility); time, velocity, acceleration and deceleration upward and downward (higher upwards velocity/acceleration link to increase in PA, while lower downwards velocity/acceleration link to higher force and control and thus increase in PA). Acceleration is calculated as the square root of the sum of the squares of the 3 axes.

In addition to these measures the International Fitness Scale (IFiS) was used to quantify the baseline participants' perceptions of their current level of physical fitness. The IFIS uses five 5-point Likert-type response items, ranging from "Very poor" to "Very good", to assess perceptions of general physical fitness, cardiorespiratory fitness, muscular strength, speed/agility, and flexibility [40].

F. Experimental Procedure

We conducted two experiments, focused on two different exercises, walking and thigh stretch, with their respective sound conditions. They followed a within-subjects design. Condition order was randomized to compensate for practice bias and avoid anchor effects of the initial value.

On arrival, participants read the information sheet and signed the consent form. Next, they filled in the IFIS questionnaire. Then, after being equipped with the shoes and instructed in all tasks, they performed the walking experiment. In each sound condition, they were asked to walk for one minute and soon after to complete the questionnaire that assessed their emotional state (valence, arousal) and body feelings (weight, control, heart/breath accelerated, strength, speed, agility, flexibility, tiredness, difficulty, coordination, fluidity, capability, proprioception, muscle, agency, motivation and comfort) for that sound feedback. Then participants performed the thigh stretch experiment. In each sound condition, they were asked to lift their right foot, hold it for 1 second with the right hand and release it, for 5 times, while the left hand rested on a wall to help keep balance. At the end of each condition they filled in the emotional state and body feelings questionnaires. The full experimental procedure took on average 60 minutes.

G. Data analyses

For questionnaire data, non-parametric Wilcoxon tests analysed the effect of sound condition on body feelings and emotion, using the standard normal distributed z-value and p-values to test significance. For the walking exercise we compared Wind and Can-crush sounds with their respective controls and with the "No-sonification". For the stretching exercise we compared all sound conditions with each other.

For the movement data we ran separate repeated measures analyses of variance (ANOVA) with the data for each of the movement parameters (maxFSR, meanFSR, timeFSR, stance time, peak angle, time up/down, velocity up/down, acceleration up/down), and with the within-subject factor sound condition. During the walking experiment one of the FSR sensors failed for 12 participants - we used data from the foot that worked well for these participants and calculated the mean of both feet for the rest of participants. Significance ANOVA effects (as indicated by F- and p-values, and eta square as effect size measure) were followed by planned paired t-test comparisons between the conditions of interest (with t- and p-values). The significance level was fixed at 0.05 for all statistical tests: a p-value ≤ 0.05 was used to reject the null hypothesis.

IV. RESULTS

A. Baseline perceptions of level of physical fitness

The median (range) IFIS scores for the different fitness scales were: general physical fitness: 3 (1-4), cardiorespiratory fitness: 2 (1-4), muscular strength: 3 (1-4), speed/agility: 3 (1-4), and flexibility: 2.5 (1-5). Note that in IFIS, 1 is "very poor", and 3 is "average" overall, participants considered their current physical fitness level to be worse than average. This confirms that the population sample fits our study focus, as we aim to enhance perceptions of physical fitness.

Effects of sound condition during walking

As shown in Table 1, when comparing the Wind and Control-wind, results showed that Wind gave higher feelings of being in control (z=-2.14, p=0.033), agency over the sounds (z=-3.42, p=0.001), and comfort (z=-2.51, p=0.012).

TABLE I. MEDIAN (RANGE) FOR SIGNIFICANT QUESTIONNAIRE ITEMS (7-LEVEL LIKERT, 9 FOR VALENCE AND AROUSAL) IN WALKING MOVEMENT.

Scales	Walking				
	Wind	***Contr-wind***	***Can-crush***	***Contr-can***	***No Sonif.***
Valence/Happiness	6(3-9)	5(1-9)	6(3-9)	6.5(3-9)	6.5(5-9)
Arousal/Excitation	4(1-8)	5(1-8)	5.5(1-9)	5(1-8)	4(2-7)
Control	6(2-7)	6(3-7)	6(2-7)	6(1-7)	6(3-7)
Heart Accelerated	4(1-7)	4(1-6)	4(1-6)	4(1-6)	4(1-7)
Flexibility	4.5(1-7)	4(1-7)	4(1-7)	5(1-7)	4(1-7)
Tiredness	2(1-5)	3(1-5)	3(1-6)	2.5(1-5)	3(1-5)
Proprioception	7(2-7)	7 (2-7)	7 (3-7)	7 (3-7)	7(2-7)
Agency	6.5(1-7)	2.5(1-7)	5(1-7)	6(1-7)	-
Comfort	4(1-7)	2(1-4)	4 (1-7)	4(1-7)	-

Comparing Wind and "No-sonification", participant felt more excited (z=-2.09, p=0.036), their breath/heart more accelerated (z=-2.07, p=0.039), and less tired (z=-1.99, p=0.046), although less happy (z=-2.138, p=0.033) with Wind. Comparing Control-wind and "No-sonification", participants felt their heart/breath more accelerated (z=-2.14, p=0.033) and less happy (z=-3.07, p=0.002) in Control-wind. Participants felt more flexible with Can-crush than with Control-can (z=-1.99, p=0.053). They felt more excited (z=-2.31, p=0.021) and flexible (z=-2.52, p=0.012) with Control-can than with "No-sonification".

The FSR data showed significant effects in heel-ground contact time ($F(4,96)=2.89$, $p=0.026$, $\eta2=0.107$); people spent more time on the ground in Control-can vs. Can-crush ($t(24)=-3.1$, $p=0.005$) and "No-sonification" ($t(24)=2.55$, $p=0.018$). Similar effects were found for stance time ($F(4,96) =3.29$, $p=0.014$ $\eta2=0.121$): there was an increase in stance time in Control-can vs. Can-crush ($t(24)=2.35$, $p=0.027$) and "No-sonification" ($t(24)=3.01$, $p=0.006$), see Fig 2. Note that more time in the ground means less PA, and may relate to the feelings of heaviness and tiredness [24]. There was a trend towards a significant effect in the downwards acceleration ($F(4,96)=2.1$, $p=0.087$ $\eta2=0.080$). T-tests showed less downwards acceleration in Can-crush vs. "No-sonification" ($t(25)=-2.32$, $p=0.029$) see Fig 3.

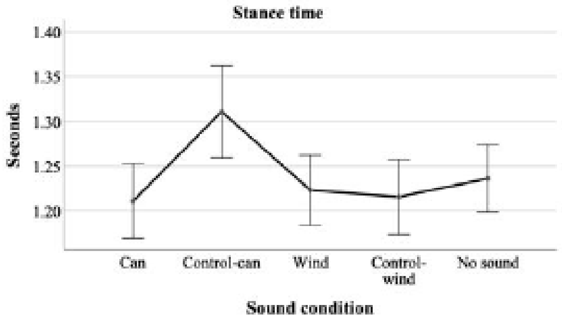

Fig 2. Mean (±SE) stance time by condition for "walking".

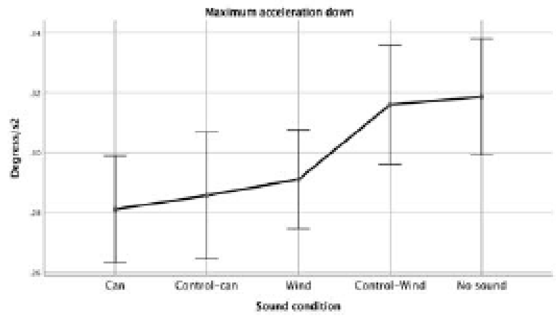

Fig 3. Mean (±SE) acceleration down by condition for "walking".

B. Effects of sound condition during thigh stretching

As shown in Table 2, in Mechanical vs. Tone participants had a higher sense of proprioception (z=-1.91, p=0.056) and agency (z=-2.0, p=0.045), but felt less comfortable (z=-2.3, p=0.021). In Mechanical vs. Water, they felt more agency (z=-3.31, p=0.001). In Mechanical vs. "No-sonification", they felt heavier (z=-2.06, p=0.040) and with their muscle working harder (z=-2.22, p=0.027). In Tone vs. "No-sonification" they felt lighter (z=-1.95, p=0.051), quicker (z=-2.099, p=0.036), and more fluid (z=-2.38, p=0.081). In Water vs. Tone, participants felt less tired (z=-2.18, p=0.029), more flexible (z=-2.36, p=0.018); lighter (z=-3.08, p=0.002), more comfortable (z=-3.59, p<0.001), happier (z=-2.56, p=0.010), and more motivated (z=-2.04, p=0.041). In Water vs. "No-sonification" participants felt less tired (z=-2.64, p=0.008), lighter (z=-3.67, p<0.001), quicker (z=-2.69, p=0.007), more agile (z=-2.35, p=0.019), more fluid (z=-2.34, p=0.019), and they found the exercise easier (z=-2.29, p=0.022). In Wind vs. Tone participants felt more motivated (z=-3.35, p=0.001), more agile (z=-2.11, p=0.035), more comfortable (z=-3.35, p=0.001), happier (z=-2.43, p=0.015), and less tired (z=- 2.04, p=0.041). In Wind vs. "No-sonification", participants felt happier (z=-2.01, p=0.044), more fluid (z=-2.04, p=0.042), lighter (z=-3.80, p=0.000), more agile (z=-3.19, p=0.001) and less tired (z=-2.79 p=0.005); more fluid (z=-2.04, p=0.042).

TABLE II. MEDIAN (RANGE) FOR SIGNIFICANT QUESTIONNAIRE ITEMS (7-LEVEL LIKERT, 9 FOR VALENCE AND AROUSAL) IN STRETCHING MOVEMENT.

Scales	Thigh Stretch				
	Mechanical	***Tone***	***Water***	***Wind***	***No-sonification***
Valence/Happiness	6 (4-9)	5.5(3-9)	7 (4-9)	6(1-9)	5 (3-9)
Arousal/Excitation	5 (1-8)	5(1-	4(1-7)	5(1-	4.5(1-7)
Heaviness	3 (1-6)	3 (1-	3 (2-	4 (1-	4 (2-7)
Control	6 (3-7)	6(3-	6(3-7)	5.5(2-	5.5(2-7)
HeartAccelerated	4 (1-6)	4(1-	4(1-5)	4(1-	4(1-6)
Flexibility	4(2-7)	4(1-	5(2-7)	4.5(2-	4(1-7)
Tiredness	3(1-6)	3(1-	3(1-6)	3(1-	4(1-6)
Difficulty	1 (1-5)	1 (1-	1 (1-	1 (1-	1 (1-6)
Fluidity	5(2-7)	5(2-7)	5(2-7)	5(1-7)	4.5(1-7)
Proprioception	6(4-7)	6(3-7)	6(3-7)	6(3-7)	6(2-7)
Muscles	5(1-7)	4(1-7)	3(1-7)	3(1-7)	4(1-7)
Speed	4 (2-7)	4.5 (2-7)	4 (2-7)	4.5 (2-6)	4 (1-6)
Agility	5 (2-7)	4 (1-7)	5 (2-7)	5 (2-7)	4 (1-6)
Agency	6 (1-7)	5(1-7)	6(1-7)	6(1-7)	
Motivation	4 (1-7)	4 (1-7)	5 (2-7)	4 (1-7)	
Comfort	4.5 (3-7)	4(2-7)	6(2-7)	4(1-7)	

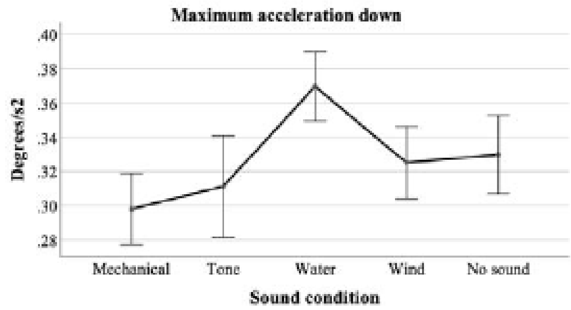

Fig 4. Mean (±SE) acceleration down by condition in "thigh stretching".

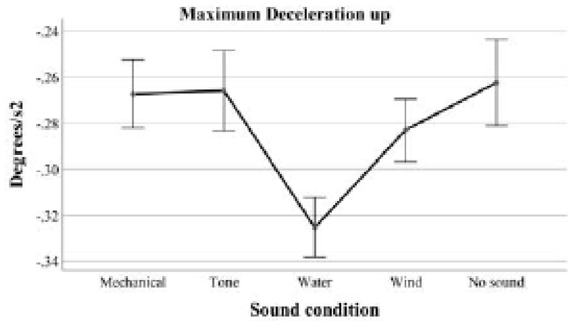

Fig 5. Mean (±SE) deceleration up by condition in "thigh stretching".

Analysis of the movement showed a trend towards significance for the time down ($F(4,88)=2.41$, $p=0.056$, $\eta2=0.099$). T-tests comparing all sound conditions revealed slower downwards movement for Mechanical vs. Tone ($t(23)=2.61$; $p=0.016$). Sound had an effect on downwards acceleration ($F(4,88)=4.1$, $p=0.004$, $\eta2=0.157$): T-tests showed higher acceleration in Water vs. all other sounds: Mechanical ($t(22)=3.83$; $p=0.001$), Tone ($t(24)= 3.92$; $p=0.001$), Wind ($t(24)= 2.93$; $p=0.007$) and "No-sonification" ($t(24)=2.04$; $p=0.053$), see Fig. 4. Water resulted in smaller deceleration up than the other conditions ($F(4,88)=3.82$, $p=0.007$ $\eta2=0.148$) (Water vs. Mechanical $t(22)=3.91$, $p=0.001$), vs. Tone $t(24)=4.1$, $p<0.001$, vs. Wind $t(24)=3.15$, $p=0.004$, vs. "No-sonification" $t(24)=3.11$, $p=0.005$), see Fig 5.

V. Discussion

This study aimed to investigate the use of movement sonification to change BP, emotional state and motor behaviour to enhance PA. We focused in home-based walking and thigh stretch exercises and investigated the effect of different movement sonifications. We observed effects of sound condition on the three dimensions aforesaid.

Walking exercise: We found that with the "Wind" sound, participants felt more in control of their movements and comfortable than in its control sound condition, and they reported feeling less tired than in the "No-sonification". This was despite the fact that with "Wind" they felt their heart/breath more accelerated and they felt less happy and more excited, than with "No-sonification". There were no significant differences in gait between the "Wind" and its control or "No-sonification", which suggests that while this sound led to changes in body feelings it did not disrupt participants natural walking. Our findings link to works using a related "wind" during spontaneous movements for autism therapy reported that this sound was rated as evoking more expressive, fluid, and energetic movements [36].

Further, participants felt more flexible in the "Can-crush" than in its control. Regarding gait, there were effects on the time spent in contact with the ground in the "Control-can", which means less PA, and may relate to feelings of heaviness and tiredness in this condition: this relation was indeed observed in studies that manipulated walking sounds to make them consistent with those produced by a heavier body [5], [24]. More related to our aim is the observed trend in less foot downwards acceleration in the "Can-crush" condition vs "No-sonification". Going back to gait biomechanics, downwards acceleration reflects in a reduction in the vertical load, this is lower applied force to hold one's own weight [41]. In this light, less down acceleration in "Can-crush" may link to higher force or PA.

Thigh stretch exercise: Results indicate relevant effects, in relation to our aims, for the "Mechanical", "Water" and "Wind" conditions. On the one hand, with "Mechanical" participants felt heavier and more tired than with "Water" and "Wind", which may relate to the fact that they also felt their muscles were working harder. Nevertheless, for this condition participants had a better sense of proprioception as compared to the "Tone". Regarding movement data, the downwards movement was slower for the "Mechanical" than for the control "Tone" and it was less accelerated than in the "Water" condition. This may link to the questionnaire results related to proprioception, agency or sense of building muscles – participants may slow down their movement as a result of being more aware of it or to increase the feeling of one's muscles being working harder. Previous works have found that simple sonifications that are informative of movement (such as our "Mechanical" sound informing of angle changes) are more effective for increasing awareness and performance of movement during physical rehabilitation [16]. Other works have found tone sounds increase awareness and performance e.g. in sports activities [18], [19], but note that, differently from our "Tone", they were informative as movement modulated the frequency of the tone. The fact that we only observed effects in performance in the downwards movement may relate to one needing some exposure to sound for the effect to build. Future work should study the effects of longer exposure.

On the other hand, with "Water" participants felt more flexible than with "Tone", and they also felt lighter and quicker than with "Tone" and "No-sonification". With "Water", as well as with "Wind", they felt less tired, more comfortable, more motivated, and happier than with "Tone"; and they felt more agile, less tired, found the exercise easier to perform and their movements more fluid than in the "No-sonification" condition. With "Wind" participants felt happier than with "No-sonification". Meanwhile, for the "Water" sound we found an increase in upwards deceleration and in downwards acceleration as compared to all the other conditions. These changes in behaviour may link to the observed feelings of being lighter and quicker than with the control "Tone", and of feeling more agile, less finding the exercise easier and their movements more fluid than in the "No-sonification" condition. Previous works using a similar "Water" sound for sonifying trunk bend angle during stretching movements for physical rehabilitation have found out that this sound is effective for relaxation and motivation [16]. Other works have highlighted that marking the start and end of movement (such as our "Water" sound does) results in more rewarding experiences, and builds on self-efficacy [21], [22]

Our approach exploits bottom-up mechanisms identified in neuroscientific studies, where sensory feedback allows changing BP [7], [12]. It aligns with works on sensory-motor transformations showing how sensory feedback on movement implicitly biases behaviour [20], [21]. Our work extends previous studies showing that real-time sound feedback on one's body can alter BP, change emotional state and behaviour [5], [21], [40]. While these previous studies have worked with altering naturally produced sounds, here, we used sonifications that evoke body sensations at a metaphorical level for altering BP. Previous works with sonification have shown how through sound feedback it is possible to lead movement or give information about it since start to end [16], [18]. They have discussed the possibility of using metaphors [33] but highlighted that for metaphors to be effective they need to be perceived as directly related to the performed movement [16]. These works have shown effects of movement sonification on emotional state related to BP that in turn facilitates movement, e.g., changes in fear, to feel safer and more comfortable during movement therapy [21]. Our study combines both approaches: we used movement sonification to alter BP in inactive people to support their psychological and emotional needs related to PA [15]. Through this approach, we aim to build on the user perceived physical capabilities and in turn facilitating changes in PA. By doing so, we respond to the call in [4] asking for tools to alter behaviour and decrease frustration.

To our knowledge, this is the first proof-of-principle study proposing movement sonification to alter BP, emotional state and behaviour in inactive populations. This work informs the fields of HCI and Affective Computing communities in relation to the design of technologies and interventions for PA. It is relevant to the field of Virtual Reality where sensory feedback in our case sound feedback can be used for users to "embody" a virtual body of different characteristics as one's own body [5].

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References

[1] K. González,et al., "Physical Inactivity, Sedentary Behavior and Chronic Diseases.," *Korean J. Fam. Med.*, vol. 38, no. 3, pp. 111–115, May 2017.

[2] *Global Recommendations on Physical Activity for Health*. Switzerland: World Health Organization, 2010.

[3] V. I. Kraak, M. Story, "A Public Health Perspective on Healthy Lifestyles and Public–Private Partnerships for Global Childhood Obesity Prevention" *J. Am. Diet. Assoc.*, vol. 110, no. 2, pp. 192–200, Feb. 2010.

[4] E. T. Kersten-van Dijk, et al., "Personal Informatics, Self-Insight, and Behavior Change: A Critical Review of Current Literature" *HCI.*, vol. 32, 268–296, Nov. 2017.

[5] A. Tajadura-Jiménez, et al, "As Light as your Footsteps: altering walking sounds to change perceived body weight, emotional state and gait." *Proc* ACM CHI 2015,

[6] A. Tajadura-Jiménez, et al, "Principles for Designing Body-Centered Auditory Feedback" in *The Wiley Handbook of Human Computer Interaction*, Chichester, UK: J.Wiley&Sons, 2017, pp. 371–403.

[7] M. Botvinick, J. Cohen, "Rubber hands 'feel' touch that eyes see" *Nature*, vol. 391, pp. 756–756,. 1998.

[8] A. Tajadura-Jiménez, et al. "Action sounds recalibrate perceived tactile distance" *Curr Biol.* 22, R516–7, 2012.

[9] L. M. Tang, J. Kay, "Harnessing Long Term Physical Activity Data—How Long-term Trackers Use Data and How an Adherence-based Interface Supports New Insights" In *Proc. ACM IMWUT.*, 2017.

[10]T. Grundgeiger, et al., "Combating Sedentary Behavior: An App Based on a Distributed Prospective Memory Approach," in *Proc CHI EA* 2017.

[11]C.-C. Yang, et al. "A Review of Accelerometry-Based Wearable Motion Detectors for Physical Activity Monitoring," *Sensors*, vol. 10, 7772–7788, Aug. 2010.

[12]A. Gupta, et al., "Designing pervasive technology for physical activity self-management in arthritis patients," in *Pro.c of PervasiveHealth '18*, 2018, pp. 1–10.

[13]D. Harrison, et al. "Tracking Physical Activity: Problems related to running longitudinal studies with commercial devices," in *Proc UbiComp 2014*, 699–702.

[14]S. Biddle, N. Mutrie, and N. Mutrie, *Psychology of Physical Activity*. Routledge, 2007.

[15]P. Rick, et al. "Identifying psychological factors to improve adherence to physical activity in the obese population" in *Proc. CBC conference,* 2019.

[16]A. Singh *et al.* "Go-with-the-Flow : tracking, analysis and sonification of movement and breathing to build confidence in activity despite chronic pain" *Human–Computer Interact.*, vol. 0024, pp. 1–49, 2015.

[17]A. Singh, et al. "Supporting Everyday Function in Chronic Pain Using Wearable Technology" in *Proc, ACM CHI '17*, 2017, pp. 3903–3915.

[18]D. Cesarini *et al.*, "Mediation : An eMbEddeD system for auditory feedback of hand-water InterAcTION while Swimming" *Procedia Eng.*, vol. 147, pp. 324–9, 2016.

[19]N. Schaffert, K. Mattes, "Interactive Sonification in Rowing: Acoustic Feedback for On-Water Training," *IEEE Multimed.*, vol. 22, no. 1, pp. 58–67, Jan. 2015.

[20]T. Grosshauser, et al., "Wearable sensor-based real-time sonification of motion and foot pressure in dance teaching and training," *J.AudioEng.Soc.* 60, 580–9, 2012.

[21]J. W. Newbold, et al., "Musically Informed Sonification for Chronic Pain Rehabilitation," *Proc,* ACM CHI 2016.

[22]G. Rosati, A. et al., "On the role of auditory feedback in robotic-assisted movement training after stroke.," *Comput. Intell. Neurosci.*, vol. 2013, 1-15, 2013.

[23]D. S. Scholz, et al., "Moving with music for stroke rehabilitation: a sonification feasibility study," *Ann. N. Y. Acad. Sci.*, vol. 1337, no. 1, pp. 69–76, Mar. 2015.

[24]A. Tajadura-Jiménez, et al., "As Light as You Aspire to Be:Changing Body Perception with Sound to Support Physical Activity"" in *Proc, ACM CHI* 2019, 1–14.

[25]F. Menzer, et al., "Feeling in control of your footsteps: Conscious gait monitoring and the auditory consequences of footsteps," *Cogn. Neurosci.*, 2010.

[26]F. Feltham, L. Loke, "The Slow Floor: towards an awareness of bodily movement through interactive walking surfaces" in Proc The Body in Design 2012.

[27]Y. Candau, et al., "Cultivating kinaesthetic awareness through interaction," in *Proc MOCO* 2017, 35–40.

[28]I. Bergström, M. Jonsson, "Sarka: Sonification and Somaesthetic Appreciation Design," in *MOCO* 2016.

[29]M. Hagströmer, et al., "The International Physical Activity Questionnaire (IPAQ): a study of concurrent and construct validity" *Public Health Nutr.*, vol. 9, 2006.

[30]D. Sanabria *et al.*, "The relationship between vigilance capacity and physical exercise: a mixed-effects multistudy analysis," *PeerJ*, vol. 7, p. e7118, Jun. 2019.

[31]N. Mutrie and A. Blamey, "Thinking about becoming more active ?," 2008, p. 24.

[32]A. Tajadura-Jiménez *et al.*, "Designing a gesture-sound wearable system to motivate physical activity by altering body perception," in - *MOCO* 2018, pp. 1–6.

[33]F.Bevilacqua, et al., "Designing action-sound metaphors using motion sensing and descriptor-based synthesis of recorded sound materials," in *RCEMI*, 2017, 11.

[34]B. Caramiaux, et al., "The Role of Sound Source Perception in Gestural Sound Description" *ACM Trans. Appl. Percept.*, vol. 11, no. 1, pp. 1–19, Apr. 2014.

[35]A. Tajadura-Jiménez, et al., "When Room Size Matters: Acoustic Influences on Emotional Responses to Sounds," *Emotion*, vol 10, 416-422, 2010.

[36]E. Frid, R. et al., "Interactive sonification of spontaneous movement of children-cross-modal mapping and the perception of body movement qualities through sound," *Front. Neurosci.*, vol. 10, no. NOV, 2016.

[37]Nikolaus F. Troje, *Understanding events : from perception to action*. Oxford University Press, 2008.

[38]S. Ko, et al. "Characteristic gait patterns in older adults with obesity—results from the baltimore longitudinal study of aging"*J.Biomech.* 43, 1104–10, 2010.

[39]M. M. Bradley and P. J. Lang, "Measuring emotion: The self-assessment manikin and the semantic differential," *J. Behav. Ther. Exp. Psychiatry*, vol. 25, 49–59, 1994.

[40]F. B. Ortega, et al., "Self-reported and measured cardiorespiratory fitness similarly predict cardiovascular disease risk in young adults," *Scand. J. Med. Sci. Sports*, vol. 23, no. 6, pp. 749–757, Dec. 2013.

[41]M. Kohle, et al.,"Clinical gait analysis by neural networks: issues and experiences"in *Proc. CBMS*, 1997.