Sonifying standing: An exploration of different mapping strategies of audio feedback for postural control

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***Abstract*— Maintaining balance during standing requires the exertion of right amount of torque to counterbalance the forces from disturbance. The human body can be modelled as an inverted pendulum that is inherently unstable, standing still without falling implies a control system that is continuously in action. The brain combines and integrates information from multiple sensory modalities to form a robust perception of the environment as well as the body states, which provides the necessary feedback to the control system. Furthermore, the brain is also capable of interpreting and utilising additional information detected by sensors and translated into signals for a certain or multiple sensory modalities. Movement sonification refers to a process where kinematic or dynamic information is represented by synthetic sounds. However, there are millions of ways one could map and translate movement data to sound parameters. In our study, a vowel based sonification system was developed focusing on audio feedback for postural control and several experiments have been conducted to explore different mapping strategies aiming to find an intuitive sonification method of the postural sway during standing. In experiment 1, the polarity of pitch change in front and back directions was investigated. Experiment 2 compared the continuous and discrete step scaling functions of pitch change. Two techniques of providing spatial information in sound were studied in experiment 3. The last experiment focused on the different combinations of timbre and pitch change in two dimensional space. As a result, the audio feedback system showed positive effects on postural control. Most subjects preferred pitch decrease as they swayed forward. The continuous scaling function was reported as more responsive despite that there was no reported perceptual difference between the two scaling functions tested in experiment 2. The panning technique was adopted after experiment 3 because more subjects found it easier to control comparing with binaural technique. Also, the non-individualised HRTF may resulted in perceptual differences among individuals. Lastly, more subjects thought that the choice of associating pitch change with front/back sway and timbre change with left/right sway was more informative than timbre change with front/back sway and pitch change with left/right sway.**

***Index Terms*—movement sonification, postural control, mapping strategies.**

I. INTRODUCTION

Walking through a room, reaching out for a cup of coffee, for a normal human being, being able to accomplish activities like these does not appear to be much of an achievement. The term ‘muscle memory’ refers to ‘the sort of embodied implicit memory that unconsciously helps us to perform various motor tasks we have somehow learned though habituation’ [1]. The actions like walking, reaching, or riding a bicycle don’t necessarily require the conscious reflection of how each procedure should be conducted. The body acts so automatically as if the movement commands just emerge by themselves. However, once examined closely, there are enormous complexities underlying any simple movement. To pick up the coffee cup on the table, our brain first has to figure out where the cup is in space, convert the coordination to body-cantered frame of reference, then specify one trajectory of possible ways in which the hand could reach that point, when moving the hand, flexion of joints and contraction of muscles have to be coordinated, the distance between the hand and the cup requires updating, finally grabbing the cup, only the right amount of grip force could counterbalance the weight of the cup properly. Any successful movement implies integration of the information gathered from the perceptual system and the outcome of the motor behaviour [2]. Even for rudimentary acts like standing still, a similar process is also constantly running without disturbing the conscious mind [3].

Our brain learns about the external environment as well as body states from our perceptual system. In a natural environment, almost all events generate stimulations to multiple sensory modalities. There is no single sensory signal that can provide complete information about the event under all circumstances. The brain combines and integrates information derived from multiple sensory modalities to form a robust perception. For example, the comprehension of a speech is improved with congruent visual and audio signals comparing with audio signal alone [4]. Not only the perception of certain event can be enhanced by adding the congruent natural sensory signals. The brain is also capable of interpreting and utilising the relevant information detected by artificial sensors and fed back cross different sensory modalities [5]. Vision and proprioception are mainly concerned when it comes to motor control and learning since many movements are naturally silent. Nevertheless, adding additional auditory information about the movement has shown positive effects on improving motor control and easing motor learning. Translating movement parameters into sounds is called movement sonification and this method has been applied in fields ranging from sensory substitution systems [6], sports practice [7, 8, 9], to clinical rehabilitation [10,11]. However, there are millions of ways one could map movement data to sound parameters. The association between these two dimensions still remains elusive. It is also shown that different mapping strategies yield different effects on motor control and learning. Overcomplicated or unnatural sound feedback may even hinder the learning of the motor task. [11, 12, 13].

Damages in the sensorimotor system due to illness or ageing usually result in difficulties in maintaining balance during standing [5, 20, 21, 33]. Studies have shown that providing concurrent audio feedback about postural sway can assist the subjects to maintain balance during quiet standing [32, 46, 54, 64]. Our study aims to develop a more intuitive sonification method for translating postural sway information into sound.

II. BACKGROUND

A. Mechanics of postural control

For us humans, 2/3 of our body mass is located in the area of 2/3 of body height above the ground. This implies that human body is an inherently unstable system. Even 'simple' as quiet standing requires a control system that is continuously acting. When a body maintains its balance during quiet standing, it is affected by the body weight acting at the body centre of mass (COM) and the vertical ground reaction force whose location is defined as the centre of pressure (COP). This pair of forces are equal in magnitude and opposite in direction, both will remain constant during quiet standing. To maintain balance is to keep the position of COM as close as possible to a reference position, typically 1-2 cm in front of the ankle joint. Body sway is usually indicated as the excursion of COM or COP. Assuming the body to be an inverted pendulum, pivoting about the ankle, the difference between the COP and COM is proportional to the horizontal acceleration of the COM,[14] information about balance control can be obtained from measuring acceleration of a reference point over the lower trunk with an accelerometer.[15] During quiet standing, a closed loop control system consisting of sensory feedback about updated bodily information and a feedforward model that makes predictions about the issued motor commands is continuously in action.[16, 17]

B. Sensory feedback for postural control

Maintaining balance requires the exertion of right amount of torque to counterbalance the forces from disturbance. Fast and accurate sensory information is key for the central nervous system (CNS) to remain informed about the progress of the motor task as well as generate state estimation about the positions and velocities of body segments.[18] Research from speech recognition found that the comprehension of speech is enhanced with both visual and audio cues. Moreover, when conflicting speech audio and video were played, subjects reported that the speech was neither perceived coherent with the audio nor the video content but something in between the two modes. This is usually referred to as the 'McGurk effect' and used to illustrate the fact that our perception is formed with integrated information from different sensory modalities. And this mechanism is proved to be able to reduce the noise from single sensory channel and resolve the perceptual ambiguity [19]. As the brain collects more and more information within or across modalities, a more robust estimate of the environment is formed, which enables us to act and react in various conditions [4]. Visual, proprioceptive and vestibular systems are three major sensory systems that contribute to postural control. Deviations of head orientation from gravity are detected by vestibular system, vision provides spatial information about the body and the environment and proprioception informs the CNS about the position and velocity of body segments as well as their contact with external environment. Cues from these sensory systems are combined to produce kinematic and kinetic information about body sway. Motor control mechanisms then generate an appropriate corrective torque according to this information. Patients with sensory loss of proprioception or vestibular system usually exhibit great difficulties in mobility and posture control [20, 21]. Moreover, for normal humans, the sensory system is able to flexibly adjust the weights of different sensory informations according to the availability or accuracy of the sensory channels, which ensures the optimal estimation about the body states in a variety of environmental conditions. Whereas deficits in the sensory systems result in lost of this ability [3].

C. Augmented sensory feedback for motor control

Acquisition of any motor skills, be it learning a sophisticated sports or re-learning basic motor abilities, includes the development of a parameterised motor program for feedforward control as well as the reduction of error and movement variability via sensory feedback loops [22]. During any kind of physical practice, the practician receives continuous sensory feedback about performance which can be used to make alterations and improve future attempts at the task [12]. According to the studies from multi-sensory integration, the CNS learns and operates optimally with multiple sensory modalities. Redundancy from multisensory stimulation is thought to be crucial for extracting and learning of the information. It is also showed improved learning effects from congruent multisensory training [23]. Furthermore, study showed that lost vestibular sensory information can be substituted with artificial tactile information, with training, patients can learn to appropriately interpret the information from artificial receptors and use the data as it is from the intact natural sense [21]. Sensory substitution is made possible with the ability of the CNS to modify its own structural organisation and functioning, which allows an adaptive response to functional demand. Not only does sensory substitution provides those with sensory loss an opportunity to restore lost sensory function, but also the immediate adaptation of the novel sensory signal offers insights into applying the same technology, namely the human-machine interface that relays the information from artificial sensors to the human sensory interface, in a broader context as augmented sensory feedback to enhance human sensibilities [5].

In motor learning or movement rehabilitation, extrinsic feedback is usually from a human instructor. With the development of sensing and displaying technologies, it is possible to provide augmented feedback by displaying movement-related information via various sensory modalities. These feedback strategies usually address the use of vision (screens, head-mounted displays), hearing (speakers, headphones), haptics (robots, vibrotactile actuators), or a combination of them [22, 24]. Among various choices of sensory modalities, this study focuses on exploring the use of sound as an augmented sensory feedback for postural control.

D. Sound as feedback for motor control

The experience of everyday listening usually remains unattended to the conscious mind. Unlike appreciating music, we hardly appreciate environmental sound in an analytical manner. However, we are actually constantly extracting information about the external environment and the body through the derived sound feedback [25]. The tapping sound reflects the material properties of the surface as well as the kinematic information about the motor behaviour, the greater the force applied to the surface, the louder the reactive sound. We also pick up cues about the walkers' physical property from his/her footstep sound. As a heavier body usually produces walking sounds with more energy in the low frequency components. By manipulating the auditory feedback from surface tapping or someone's own footsteps, not only the perception of the events is altered, but also the motor behaviours change accordingly [26, 27]. Our ability to extract information from sound in an unconscious manner makes it potentially an effective feedback for providing extra information without inducing cognitive overload. In addition, vision is usually involved in motor learning for monitoring the performance. Extra visual feedback can distract learners from the motor task and redirect their attention to the visual feedback task. And movements are largely silent, attaching audible sound to them increases feedback information bandwidth without intruding the natural sensory sources. Lastly, perceiving sound doesn't require a fix point of view and hence frees the body in movement execution. However, not any auditory feedback will improve motor learning process, it is difficult for learners to extract useful information from inappropriately designed auditory display and such audio feedback shows no improvements on motor behaviours [12].

III. MOVEMENT SONIFICATION

The term sonificaiton refers to the activity that uses non-speech audio to represent information, which 'seeks to translate relationships in data or information into sounds that exploit the auditory perceptual abilities of human beings such that the data relationships are comprehensible' [28]. Movement sonification refers to the sonification that encodes kinematic or dynamic information about movements. Studies have shown that movement sonification has positive impacts on movement perception and action, and its application in fields like sensory substitution, motor learning and physiotherapy [29, 6, 30].

A. Movement sonification for sensory substitution

For normal human beings, the information about the position and velocity of body segments are provided by proprioception and it is essential for maintaining the internal model in motor system [29]. For those who suffers from proprioception loss, the close loop motor control is no longer complete. Similar to aforementioned tactile-vestibular sensory substitution, the audio-proprioception substitution is also explored. Danna, J., & Velay, J. L. synthesised a rubbing sound that was associated to a correct handwriting velocity and its timbre varied according to the subjects' velocity profiles. When handwriting was too slow, the rubbing sound changed into unpleasant squeaking sound in order to warn the writers to increase their movement speed, and the pen pressure on the paper sheet was mapped to the amplitude, the greater the pressure, the louder the sound. The results from experiments showed improvements in the performance of both deafferent subjects and normal subjects [6, 30].

B. Movement sonification for motor skill learning

In addition to mimicking natural sound feedback in movement execution, Vinken, Pia M., et al. found that subjects were able to discriminate the artificial auditory representations of some everyday movements without prior knowledge about the kinematic-acoustic mapping and suggested that movement information related to continuous kinematic parameters can be transformed into the auditory domain [31]. As mentioned before, our brain operates optimally under multiple sensory stimulus. It is suggested that natural acoustic feedback plays an important role for athletes to acquire online information about their performance. During rowing, rowers can assess their performance from the splashing and flowing sound created by the interaction between the boat and water. Schaffert, N., Mattes, K., & Effenberg, A. O. mapped the data of the boat acceleration to the pitch of musical tones and fed back the sound concurrently with the rowing activity. As the boat acceleration increased, the tone pitch increased, and as the boat acceleration decreased, the pitch decreased accordingly. They found that the whole rowing team's performance improved significantly with the sonification. The synthesised sound about boat motion is regarded as an expansion of information presented in the auditory domain and can be integrated by the athletes without much cognitive efforts [7]. Similar results were also found in testing the perception and reproduction of countermovement jumps with additional sonification. In this case, the vertical component of the ground reaction force measured during jumping was mapped to the amplitude and frequency of sound as an electronically sampled vocal 'a'. The sound is played together with a video of the same jumping movement. Subjects were asked to assess the height of the jump as well as replicate the jump immediately after watching. The experimental results showed that the perceptual accuracy of the countermovement jump and the replicative performance both improved with additional convergent auditory information despite that some subjects reported that they didn't like the sound at all. This result again supported that the perception system is capable of extracting information from movement sonification and it is effective in using unconscious perceptual functions and unconscious control functions, which makes movement sonification a promising tool for assisting motor learning [8].

C. Movement sonification for postural control

As previously explained, human postural control entails that a feedback control system that constantly requires the updated bodily information from sensory systems and a feedforward model that makes predictions about the issued motor commands. Additional acoustic feedback about body kinematic information also showed positive effects on postural control.

The works by Dozza et al. examined the effect of audio biofeedback for the control of upright stance. In their system, the audio feedback is based on the medio-lateral (ML) and anterior-posterior (AP) trunk accelerations. A stereo sound consisted of two sine waves got louder in volume and higher in pitch as subjects swayed forward, louder in volume and lower in pitch when they sway backward, louder in the right ear channel and quieter in the left channel when they moved to the right, louder in the left ear channel and quieter in the right channel when they moved to the left. To avoid an overload of sensory information, a reference region was scaled within which only a low volume 400Hz sound was provided as reference for pitch change discrimination. This system has been proved to be effective in improving balance control in both patients with bilateral vestibular loss and healthy subjects. [32, 33]. They also found that the improved balance control wasn't induced by an increased stiffness in leg muscles as a passive response to the disturbance, but rather is caused by the brain actively changing to a more feedback-based control over standing posture [34].

What's more, in another study, the effects of linear and non-linear (sigmoid) coding of audio biofeedback for postural control were compared. The results showed that sigmoid-coded amplitude audio biofeedback reduced body sway more than linear coded amplitude audio biofeedback [11]. This result showed that different mapping strategies applied in the auditory feedback will yield different effects on motor behaviour and encouraged further exploration of other possible mappings between postural sway and sound feedback that may lead to even larger sway reduction.

IV. AUDIO FEEDBACK FOR POSTURAL CONTROL

Effenberg asserts that 'an almost endless amount of options are available to transform data into sound' [8], making a mapping decision that is effective in conveying movement information with sound is not an easy task. Study pointed out that different sound mapping strategies will affect users' performance in using auditory display for guiding movements. Since there is still no general guidelines for mapping data dimensions to auditory dimensions [35]. In order to design an effective sound guidance system that is able to guide users as precisely, quickly as possible and without overshooting the 'target', it is important to explore different sound strategies and then to evaluate them experimentally. An important principle of designing an effective sonification is the ability to communicate information with intuitive and easily learned auditory cues. Dyer, J., et. al. also proposed that when using sonification as concurrent augmented feedback for motor learning, it is possible that the sound may be internally simulated to further guide performance in absence with an intuitive, memorable action-sound mapping [12]. It is also suggested in a review about biofeedback for neuromotor rehabilitation that an appropriate biofeedback should not exhaust users' cognitive abilities and overload them with overly complex sensory information [24].

A. Vowel based sonification

The vowel based sonification has been gaining attention with the rationale that human auditory system is highly sensitive to vowel sounds [36]. Vowel based sonification allows for creating perceptually distant timber cues, for example, it is easy for us to distinguish whether a vowels is 'a' or 'i' as well as the gender or age of the speakers [37]. Taking advantage of the human's ability to differentiate concurrent vowels, this method is explored in representing complex and and multidimensional data [38]. Sonifying physical motion with vowel sound enables the listener to replicate the sound and to specify certain movement properties in motor learning activities [39]. What's more, vowel based sonification is explored in displaying auditory graphs [40] and other movement-related sonifications [41, 42, 43]. The listeners are also able to use their embodied knowledge to easily grasp vowel based sonification [39, 40].

A vowel sound can be synthesised with a source-filter model. This works by passing a pulse train as an excitation source through a series of formant filters whose characters correspond to the spectrum characters of the vowel to be synthesised. The frequency of the pulse train is perceived as the fundamental frequency of the vowel and different vowel sounds can be synthesised by changing the parameters of the formant filters [38, 39].

B. Spatial information in sound

In using multimodal biofeedback for task-oriented neural rehabilitation, audio feedback is regarded an effective source for temporal information whereas visual feedback works better for spatial information [44]. Our auditory system also has the ability to localise the sound source from its spectrum differences between two ears [45]. It is feasible that certain level of spatial information about body sway can also be provided through audio feedback. In Basta, D. et al.'s audio feedback system for vestibular rehabilitation, it consists of four speakers, which were placed left, right, in front and back of the subjects. When the angle velocity of their trunk sway exceeds the preset level, a tone is emitted from the loudspeaker towards which the subject had moved [46]. In designing the biofeedback system for balance training with balance board, Milosevic, M., and McConville, K. M. V. coded the direction of a balance board in the audio feedback by adjusting the interaural time difference and interaural level difference between the left and right channels of the headphone, so that the virtual sound source is in the direction of the balance board offset [47]. Some other sound spatialisation technique like panning is usually applied in sonifying physical motion since it is natural that movements in the right/left side of the body correspond to the sound panned to right/left [48, 49]. For providing body sway information in left/right direction, the sound also moves to left/right as subjects sway to left/right [32]. In this study, the spatial information in sound is given with the use of a non-indivisualised HRTF (Head Related Transfer Function) [50]. The exact mapping strategy is explained in later section. Because the non-individualised HRTF without tracking head movements used in our study can not provide accurate information about the sound source being from front or back, other sound dimensions were added for differentiating between this two directions.

C. Redundancy in sonification

Redundancy in sonification refers to that one variable in the data domain is mapped to several audio dimensions, for example, both amplitude and pitch increases as the data value increases. Angela and Tanja found that compared with mapping each sound parameter alone, combining several sound dimensions to convey information about the position of an object in a two dimensional space yielded best user performance in the object localisation task [51]. A study by S. Camille Peres and David M. Lane also showed that there was a benefit of mappings using two sound dimensions redundantly over using only one in displaying auditory graphs [52]. Kramer has suggested that increased complexity in sound would not only serve for the functionality of the sonification but also be subjectively pleasing to listen to since sounds from natural environment are usually complex in spectrum [53]. Another study also showed that when first exposed to audio biofeedback, the more information about body sway (direction and amplitude) coded in the feedback resulted in larger sway reduction [54].

D. Other issues in sonification

Despite the guidance listed above, there still remains ambiguity in associating movement related data to sound parameters. In the review of mapping strategies for the sonification of physical quantities, Dubus, G., and Bresin, R found that pitch is by far the most widely used auditory dimension in sonification applications [58]. However, how should pitch change correspond to postural sway. Is it more intuitive that the pitch increases as we leaning forward or the other way around? It is known that pitch perception varies among individuals [60]. How can the sonification accommodate the perceptual differences? What kind of spatial information is more effective in assisting postural control? Does the combination of sound parameters yield different perceptual experience? This list of inquiries could go on and on for a long time. In this study, a basic audio feedback for postural control was developed, upon which some questions proposed before were addressed with experimental work.

V. EXPERIMENTS

A. Basic audio feedback

The trunk accelerations in anterior-posterior (AP) direction and medial-lateral (ML) direction were measured as indication for postural sway. This is measured with an accelerometer attached to the subjects' lower back [55, 11, 15, 32]. To compensate the tilt of the accelerometer due to subjects' back curvature, standard Deviation (SD) and the average of the first 1000 measurements were used to calibrate the accelerometer and scale the audio feedback dynamic range [11]. Since spontaneous sway with small accelerations will always occur during natural stance posture. The reference region is defined as when subjects sway within the range of one SD above or below the average and is deemed no need for extra feedback information [11, 32, 33, 54, 55, 64]. The upper limits for the dynamics of the audio feedback in forward, left and right direction is ten times of the SD in respective directions. The limit for backward direction is 6.6 times the SD as forward sway is more tolerable. The data used to control the sound parameter is scaled to 0 - 1 as ratios between the accelerations exceeding the reference region and the amount of acceleration from reference region to the limit. The volume of the audio feedback gets louder following a sigmoid law as subjects sway towards the limit, which corresponds to the increased torque required for correcting posture and creates an urgent 'alarm' sensation [11]. The exact coding functions are consistent with those described in [32].

A vowel sound 'a' is synthesised and its fundamental frequency is mapped to subjects' trunk acceleration in AP direction, namely, forward and backward sway. Since human ear detect sound frequency on a logarithmic scale [56], the frequency change is scaled on an exponential scale and to keep the perceptual distance equal, the frequency of upper limit, reference frequency and the lower limit are 260Hz, 130Hz, 65Hz, similar to the frequency of middle C, bass C and low C. When subjects sway in the reference region a low volume 'a' with fundamental frequency 130Hz is play as an audio reference. When subjects sway forward/backward, the fundamental frequency of 'a' changes. As subjects lean towards left/right, the sound moves to the relative direction and the vowel transit from 'a' to 'i', These two vowels are chosen because they are physically distant from each other in the vowel chart by the International Phonetic Association and the transition from 'a' to 'i' also goes over an intermediary state which is close to 'e', this results in higher perceptual contrast [57, 60].

In the visual biofeedback system developed in [11], the spatial information about postural sway was provided by the movement of a red star on a coordination system, the x-axis of which is the trunk acceleration in left/right direction corresponding to postural sway in left/right direction and the y-axis is the trunk acceleration in front/back direction representing postural sway in front/back direction. As the subjects sway forward/backward the star will move up/down, sway to the left/right the star will move to the relative area of the screen. The reference region is represented by a green ellipse. In our audio display, the directional information about body sway is similar to the visual condition. Using the same coordination system the conditions where the sound position correspond to the sway direction, the azimuth of the sound position corresponds to the angle between the y-axis (up) and the line connecting the star and the centre of the coordinate. The sound is perceptually corresponding to subjects trunk position with respect to the reference region in a two dimensional plane.

B. Apparatus

The trunk acceleration data was sensed with an inertia sensor unit (InvenSense MPU-6050), which contains a 3-axis accelerometer and a 3-axis gyroscope. Only the acceleration along the subjects' anterior-posterior (front and back) and medial-lateral (left and right) directions was used in this study.

The accelerometer full scale range and the sensitivity is set to ± 2g and 16384 LSB/g. The sensor is mounted on the subjects' back at the height of L5 (same height as the navel position) using a Vlecro belt. This acceleration provides information about postural tilt with respect to gravity [15]. The data was lowpass filtered with a cutoff frequency at 44 Hz with an onboard digital low pass filter and recorded at a 100 Hz sample rate.

The accelerations were read with a micro controller board (Arduino Uno) and passed to a laptop (MacBook Air) by means of a USB cable. The sound feedback was generated with software Pure Data, which received the acceleration data from Arduino board via serial communication. Finally the sound output was delivered to the subjects with a pair of headphone (Sennheiser HD518).

C. Procedure

All subjects performed three (or four), 75s long trials standing on a foam mat with their eyes blindfolded to reduce the reliability of sensory cues from somatosensory perception under feet as well as to eliminate visual information. It is shown that additional audio feedback is most effective in postural control under such disturbed sensory condition [11, 32]. Two (or three) of the trials were different audio modes and one was control mode without any sound feedback as reference condition. Few marks were drawn on the foam to help the subjects keep their foot position across trials. The order of the trials was randomised for each subject. Each trial lasts about 75s. Trials were started 5s after the subjects were informed to be prepared. The first 1000 readings (10s) were used to calibrate the sensor and audio feedback dynamics. Prior to each trial with sound feedback, subjects had 30s to explore the audio feedback with the mapping strategy in the subsequent trial. After each trial or exploration, subjects were told to step off the foam mat and relax. Before the trials with sound feedback, each subject was instructed to keep the sound feedback as quiet and static as possible. They were also informed that when they stand still the sound would be in the ideal condition.

Accelerations from the trunk along AP and ML direction were collected and total accelerations were calculated afterwards. The trunk acceleration root mean square (rms) was post-processed for AP direction, ML direction, and for both directions combined. Root mean square of the acceleration was intended as an indicator of the subjects' sway area because it is highly correlated with the centre of pressure rms, which is traditionally used to quantify the stability of postural sway. To reduce the varieties among each individual, the rms percentage changes with respect to the control condition were also calculated [11, 34].

An interview was conducted after each subject finished all trials. The questions were asked are: a. Can you tell how the sound reacts differently to your movements between the two trials with sound feedback? b. Do you have any preference over the sound modes? c. Which modes do you think is more natural or intuitive?

D. Experiment 1: Polarity of pitch change

Very often the sound mappings in sonification are based upon common metaphors, for example, it is intuitive to associate a rising pitch with an increase in certain data dimension (e.g., temperature). However, there are cases that the data dimensions do not entail such metaphorical implication, the polarities of the pitch changing can be ambiguous, study showed that both mapping and polarity choices can affect reaction time and accuracy in monitoring tasks [59]. When designing a auditory representation of human movements, an embodied metaphor is usually applied, for example, a raising hand evokes a rising pitch [49]. In the audio biofeedback system developed by Dozza et al, the pitch of the sound was used to differentiating front and back sway, the pitch increases as subjects sway forward and decreases as they sway backward [32]. However, there hardly has any general impressions that rising pitch should associate with front or back.

To decide whether forward sway is more intuitively related to pitch increase or decrease, two mappings with opposite pitch change polarity were tested in this experiment. In mapping1, the pitch of the vowel sound increases up to 260Hz as subjects sway forward and decreases down to 65Hz as they sway backward. The polarity of the pitch change is reversed in mapping2, the fundamental frequency of 'a' decreases to 65Hz as subjects sway forward and increases to 260Hz as they sway backwards.

1) Participants: Five healthy subjects (3 males, 2 females) participated in this experiment. Average and standard deviation of age, height and weight of of the subjects were, 30.8 ± 7.9 years, 168.6 ± 11.6 cm, 61.2 ± 12.7 kg, respectively. 4 of them reported that they had musical training or experience. 1 is a dancer. All subjects indicated that they had no known neurological, hearing or balance disorders.

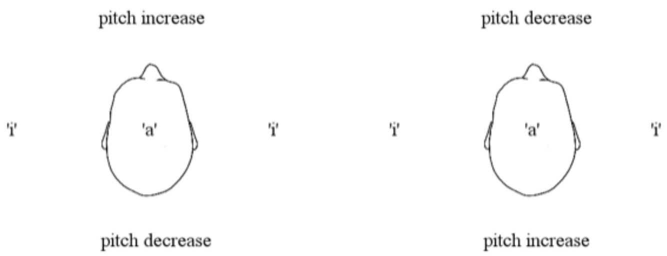
The data from the first subject is excluded as he reported that he didn't understand the tasks in the sound modes after the experiment. The experiment procedure was adjusted afterwards, the 30s of exploring sound and movements was added prior to each sound mode trials.

2) Results and discussion: It can be seen from Table I that both mappings induced reduction in the rms of trunk accelerations. The average reduction in percentage change induced by mapping2 is larger than mapping1 marked as the black bars in Fig 1.. All subjects indicated that they prefer mapping2, namely the pitch of the vowel decreases as they sway forward and agreed that this mapping strategy is more intuitive. Subject 1 said that the movement of tilting forward induces facing downwards so it makes sense to him to associate it with pitch going down and facing upwards naturally associated with pitch going up. Subject 4 reported that before the trial she had a preconception that leaning forward would be associated with pitch increasing and the forward - pitch decreasing pair first surprised her but then she found it actually easier to respond.

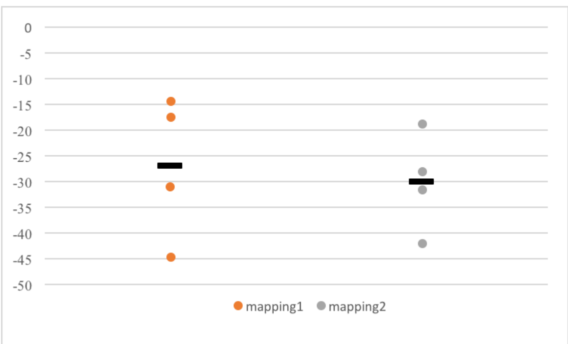
I. TRUNK ACCELERATION RMS UNDER DIFFERENT CONDITIONS AND PERCENTAGE CHANGE

	Control (mm/s^2)	***Mapping1 (mm/s^2)***	***Percentage change(%)***	***Mapping2 (mm/s^2)***	***Percentage change(%)***
Subject 2	263.1	145.4	-44.7	152.7	-42
Subject 3	170.9	146.5	-14.3	139	-18.7
Subject 4	222.6	153.4	-31.1	152.3	-31.6
Subject 5	191	157.7	-17.4	137.6	-28
Average	211.9	150.75	-26.88	145.4	-30.08

1. Mapping1 versus Mapping2



2. Percentage change of mapping 1&2 and its average



E. Experiment 2: Scaling functions of pitch change

Neuhoff, J.G., Knight, R. and Wayand, J. found that musicians and non-musicians showed great discrepancies in judging the pitch change and suggested that the changes should be sufficiently large to minimise the perceptual errors when using pitch as a dimension to represent a variable [61]. Because the kinematic or kinetic information of movements usually change continuously, when mapped to sound, the change is usually in the continuous manner.

After specifying pitch changing direction, different pitch changing scaling functions were compared. Mapping1 referring to the continuous mapping in aforementioned experiment was contrasted with a discrete scaling function in mapping2. Similar to the subdivision of the octave into semitones in Modern Western music [57]. The sway area exceeding reference region to the upper or lower limit is divided equally into 7 parts, the successive pitch intervals of which are 2, 2, 1, 2, 2, 2, 2 semitones corresponding to the major scales in Western music.

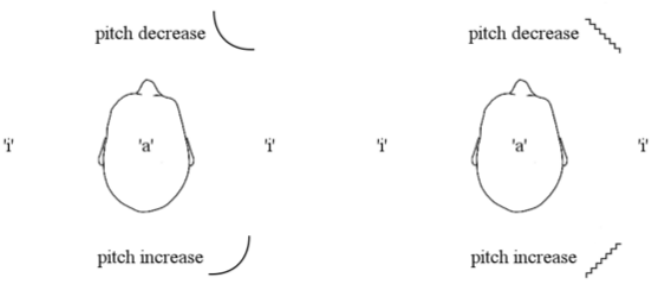
1) Participants: Five healthy subjects (3 males, 2 females) participated in this experiment. Average and standard deviation of age, height and weight of of the subjects were, 30.8 ± 7.9 years, 168.6 ± 11.6 cm, 61.2 ± 12.7 kg, respectively. 4 of them reported that they had musical training or experience. 1 is a dancer. All subjects indicated that they had no known neurological, hearing or balance disorders. All subjects participated in the first experiment.

2) Results and discussion: All but one subject swayed less with audio feedback. Subject 4 increased her sway in audio feedback trials and later reported that she noticed the reaction of the sound to her pelvis movement and she was experimenting with controlling the sound by adjusting her hip. Study also showed that subjects' movements at hip level were less restricted when practicing upright stance with audio feedback [54]. All subjects reported that they didn't notice much difference between two trials with audio feedback in this experiment but yet pointed out that they found the continuous scaling mode was more responsive and natural. This may be due to the rapid change in postural sway that didn't allow the transition to be perceptible. Subject 2 & 3 mentioned that they didn't notice the sound movements while subject 4 stressed that the standing task is quite demanding as the sound moves too fast in ML direction.

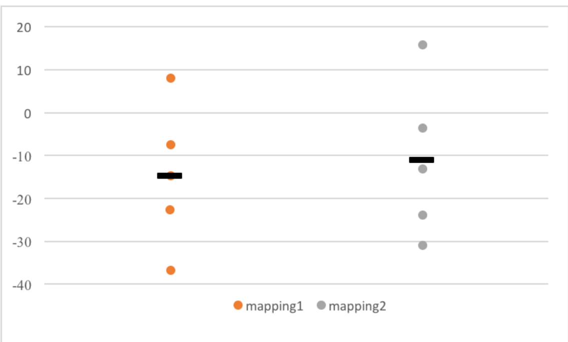
II. TRUNK ACCELERATION RMS UNDER DIFFERENT CONDITIONS AND PERCENTAGE CHANGE

	Control (mm/s²)	*Mapping1 (mm/s²)*	*Percentage change(%)*	*Mapping2 (mm/s²)*	*Percentage change(%)*
Subject 1	179.5	113.4	-36.8	124.1	-30.9
Subject 2	133.8	123.7	-7.5	116.3	-13.1
Subject 3	197.3	152.4	-22.7	150.3	-23.8
Subject 4	140.3	151.7	8.1	162.4	15.8
Subject 5	185.8	158.5	-14.7	179.1	-3.6
Average	167.34	139.94	-14.72	146.44	-11.12

3. Mapping1 versus Mapping2



4. Percentage change of mapping 1&2 and its average



F. *Experiment 3: Panning versus Binaural*

Because of the different reactions towards the spatial information coded in the audio feedback from previous experiments, this experiment was conducted to compare different sound spatialisation techniques. In addition to the non-individualised HRTF used in previous experiments, the sound got louder in the right/left ear channel and lower in the left/right one when subject swayed to the right/left direction, which is supposed to create a perceptual effect of gradual transition of the sound source to left or right as subjects move to left or right. Mapping1 indicates the results from this panning technique, mapping2 refers to the binaural technique with the HRTF.

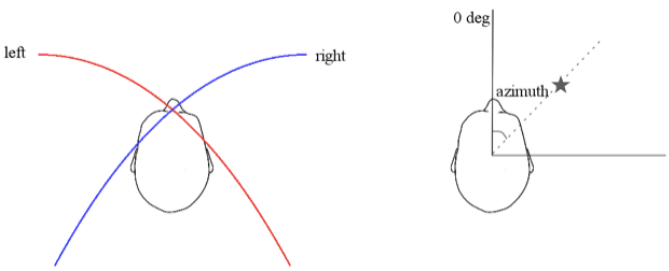
1) Participants: Five healthy subjects (1 males, 4 females) participated in this experiment. Average and standard deviation of age, height and weight of of the subjects were, 27.2 ± 4.5 years, 161.2 ± 5.8 cm, 53 ± 3.3 kg, respectively. 2 participated in previous experiments. All reported that they had musical training or experience. 3 had dancing training or experience. All subjects indicated that they had no known neurological, hearing or balance disorders.

2) Results and discussion: Except for subject 6 increased his sway with binaural mapping, all trials with audio feedback showed better results. There is no general preference over either mapping strategy. Subject 1 & 3 reported that the circular motion of sound in binaural mode is more natural to body movements. While subject 2, 4 & 5 prefer the panning mode and said it was more stable and easier to control for them. However, subject 2 reported that she didn't perceive any movements in sound during the trial with binaural mode. This may due to the individual difference in perceiving non-individualised HRTF [50]. It is interesting to note that all subjects referred to the panning mode as the volume change in respective headphone channel instead of the spatial inference about sound moving.

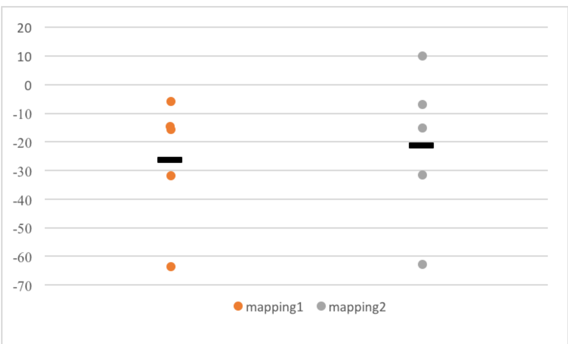
III. TRUNK ACCELERATION RMS UNDER DIFFERENT CONDITIONS AND PERCENTAGE CHANGE

	Control (mm/s^2)	*Mapping1 (mm/s^2)*	*Percentage change(%)*	*Mapping2 (mm/s^2)*	*Percentage change(%)*
Subject 1	170.2	115.9	-31.9	116.5	-31.6
Subject 2	299.3	109.2	-63.5	111.1	-62.9
Subject 3	199.4	170.2	-14.6	169	-15.2
Subject 4	244.8	206.3	-15.7	227.8	-6.9
Subject 5	173.7	163.4	-5.9	191	10
Average	217.48	153	-26.32	163.08	-21.32

5. Mapping1 versus Mapping2



6. Percentage change of mapping 1&2 and its average



G. Experiment 4: Mapping strategies for two dimensions

In designing sonification for stroke rehabilitation, Scholz, D. S. et. al. found that the learning curves were steepest when pitch was mapped onto the vertical axis and brightness onto the horizontal one compared with the other way around and hence concluded that the former is the most natural sonification [13].

To compare with the mapping strategy that pitch change corresponding to AP direction and timbre change corresponding to ML direction, a reversed mapping is made. When subjects sway forward, the vowel changes from 'a' to 'i', when they sway backward, 'a' changes to 'u'. In the vowel chart by the International Phonetic Association, 'i', 'a', 'u' happen to corresponding to front, central and back of tongue displacement [37]. Since the panning could be used to differentiate left/right directions, both pitch increasing and decreasing as the left/right sway towards the limit were also compared. In a word, Mapping1 is that AP sway correspond to pitch changing while 'a' transits to 'i' in ML sway. Mapping 2 & 3 are that the timbre change is associated with AP sway and pitch decreases/increases with ML sway respectively.

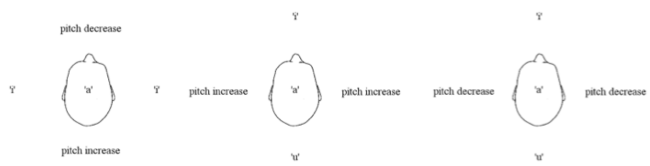
1) Participants: Four healthy subjects (1 males, 3 females) participated in this experiment. Average and standard deviation of age, height and weight of of the subjects were, 26.3 ± 2.9 years, 160 ± 6.1 cm, 50.5 ± 2.5 kg, respectively. 3 participated in previous experiments. All reported that they had musical training or experience. 3 had dancing training or experience. All subjects indicated that they had no known neurological, hearing or balance disorders.

2) Results and discussion: Subject 1, 2, 3 all expressed their preference over the mapping strategy that associates front/back movements with pitch changing and left/right movements with timbre changing. Subject 1 pointed out that this mapping is more informative while the other two mappings were more ambiguous. He was able to describe how the vowel changes in this mapping (pitch decreases as he leaned forward, 'a' transit to 'i' as he moves to right or left), but wasn't sure about the other two mappings. Study also showed that pitch changing is more informative compared with timbre changing [13], and in the case of this experiment, timbre changing was accompanied with panning in the left/right channels to enhance the perceptual effect. Subject 4 expressed her personal preference over mapping 3 because of the low frequency sound created a 'chanting' impression for her. The fact that she performed the postural control task better in this condition may due to that she was more engaged with the sound.

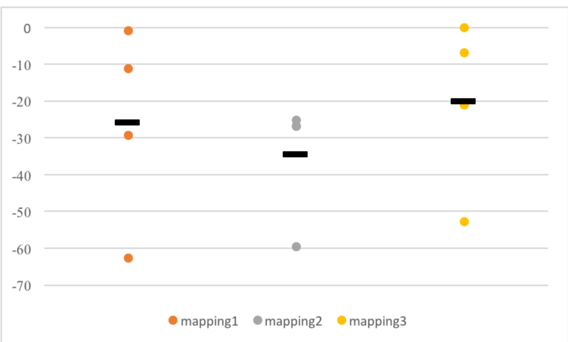
IV. TRUNK ACCELERATION RMS UNDER DIFFERENT CONDITIONS AND PERCENTAGE CHANGE

	Control (mm/s²)	*Mapping1 (mm/s²)*	*Percentage change (%)*	*Mapping2 (mm/s²)*	*Percentage change (%)*	*Mapping3 (mm/s²)*	*Percentage change (%)*
Subject 1	206.4	183.4	-11.1	150.9	-26.9	192.2	-6.9
Subject 2	416.4	155.3	-62.7	168.6	-59.5	197	-52.7
Subject 3	187.2	132.4	-29.3	137.1	-26.8	147.8	-21.1
Subject 4	158.4	157	-0.9	118.6	-25.1	158.5	-0.1
Average	242.1	157.03	-26	143.8	-34.58	173.88	-20.2

7. Mapping1 versus Mapping2 versus Mapping3



8. Percentage change of mapping 1&2 and its average



VI. General Discussion

Generally speaking, the audio feedback system tested in this study showed improvements in postural control. Falling usually occurs when the movements of position of COM exceeds the supportive base without prompt correction, hence the larger the sway area, the higher chance that the body would lose its balance. With the additional audio feedback, most of the subjects reduced their sway area indicated by the reduction in truck acceleration rms, which suggests that subjects were able to stay closer to the reference position defined before. Nevertheless, one subject still increased his sway in one trial with audio feedback. This may because of the fatigue after repeated trials of keeping balance standing on foam or the distractive environmental noises that interfered the perception of the audio feedback. In addition, it is important to give clear instructions about the additional audio feedback so that the users won't misunderstand the purpose of following the sound. Still, cares should be taken when using the augmented feedback to make sure that it provides positive assistance.

No participants showed any difficulties in learning the sound movement mapping and reported that the sound is annoying or disturbing. During interview, they were able to mimic the vowels when recalling the experience. Actually many of them found that the use of vowel sound was amusing. What's more, some participants expressed that the audio feedback made them notice more subtle movements that normally were ignored. One subject reported an impression that the sound came before she could sense the body movements. Studies also confirmed that augmented audio feedback can increase the awareness of movements and make it a useful tool for physiotherapy [62, 63].

On contrary to the mapping strategies in some existing audio feedback for postural control [32, 64], the general preference over mapping forward sway to decrease in pitch and backward sway to increase in pitch were found in this study. It is interesting to note that in the audio feedback used in aviation, the same accelerations (forward sway) measured about the movements of the airplane was mapped with decrease in pitch. As the term for this movement is referred to as 'nose down' [65]. Some subjects also pointed out that forward sway is more consistent with their idea of 'falling', hence the decreasing pitch made more sense to them. Again, the use of metaphor in sonification design yields more natural listening experiences [59]. However, whether the preferred or more intuitive sound mapping will yield better learning performance for balance rehabilitation still requires investigation.

Many movement sonifications were designed to take advantage of people's implicit and embodied understanding of music [66, 67], however, the use of major scale in this audio feedback system didn't outperform the continuous mapping between pitch and acceleration. As a matter of fact, the subjects participated in the second experiment didn't even notice the different scaling strategies. This may be caused by the nature of the movement task as the dynamic range of sound is rather narrow and subjects usually correct their sway rapidly.

Musically-informed sonification may be more suitable for exploratory movement training.

In our study, the postural sway information was provided with multiple sound dimensions. For example, the volume always increases as subject sway towards the limits signalling the danger of falling and the pitch changes in opposite directions to differentiate front and back sway. Study has shown that the perceived stimulus change is greater when pitch and loudness change in congruent directions comparing with incongruent directional changes [67]. We should note that though in each experiment the compared mapping strategies were targeted at one sound dimension, the interplay between multiple sound dimensions still exists. It remains unclear that the changes in the uninvestigated sound dimensions will alter the findings in this study.

This study also confirmed that sound perception is a subjective and contextual process [68]. It is impossible to come up with a universal sound design that could accommodate everybody's taste. Hence, allowing the sonification system certain freedom for customisation may be a promising solution.

VII. CONCLUSION

Normally the assistive audio technology is developed according to researchers' knowledge and experience. It is known that there is a large variability among individuals in terms of perceiving sound [68]. In this study, the sound design was evolved over experimental studies. The results suggested that certain movement-sound pairs are more preferred and the individual difference in sound perception should be considered. The characteristics of the movement task will also affect the sound output. It worth mentioning that in order to test the efficacy of the audio feedback, subjects in this study performed the balance task under deliberately disturbed condition, this may also influence the acceptance of the audio feedback.

As mentioned before, there are numerous ways to represent movement information with sound. The mapping strategies tested in this study only touched the tip of the iceberg. Future studies are encouraged to explore other possibilities. For instance, using the voice of both male and female speakers to create more distant perceptual cues in timbre or developing sophisticated HRTF to provide more accurate spatial information. Due to the limited subject sample size, whether the results can be generalised to larger public requires experiments with more subjects. Normally the audio feedback for postural control is used by patients with balance disorders in a rehabilitation context. Whether the results found in our study will apply to the practical situation still needs further research.

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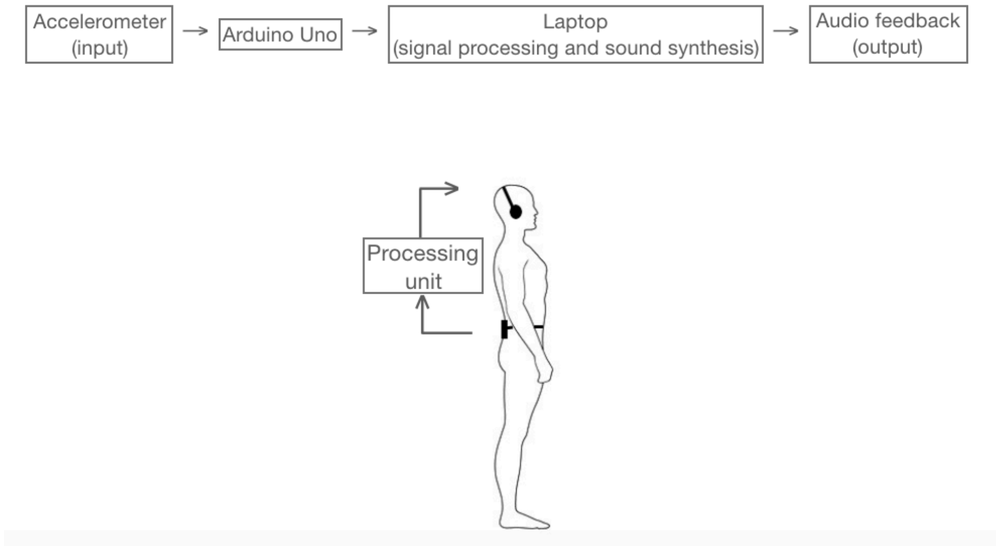
APPENDIX

1. Data flow diagram of the audio feedback system



2. One subject in experiment