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Principles for Designing Body-Centred Auditory Feedback

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Abstract

Our body can be seen as an anchor that tightly connects us with the surrounding physical world. Concepts of body-centred interaction have been successfully applied in virtual and augmented reality, however, mainly in the visual domain. Still, we interact with the environment through our body, and these interactions mostly always produce sounds. These sounds have information about involved movements, external objects, agents and also about our own body. In addition, sounds of our breathing or heartbeat constitute an important part of our body representation that can be called "sonic self-avatar". Current interactive multimodal technologies allow altering and feeding back body-centred sounds to the user in real-time. Such changes in auditory feedback often have a profound impact on self-body perception, triggering perceptual, cognitive and emotional changes. In this chapter we show how recent neuroscientifically and psychologically grounded insights can guide the design of new, enhanced interactive technologies for physical and virtual environments, objects and agents; forms of interaction and body expressivity; and for augmenting self-perceptions and facilitating movement and motor learning. We also discuss how new HCI applications grounded in these principles may be used to overcome psychological and physical barriers in people with specific health conditions. We end the chapter by listing open research challenges and suggesting some possible future research and innovation directions that would benefit from a body-centred sound design.

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Scenario

“Imagine yourself walking up the stairs. Suddenly, you hear someone rushing down the stairs from the upper floor towards you. Still not seeing the other person and just based on the footstep sounds, you can guess a number of things, such as the material of the staircase and the material of the stranger’s shoe soles. You can somehow know whether the person has a small or a big body, perhaps also know whether the person is a he or a she, and even tell something about his or her emotional state. Now think about the sound of your own footsteps and imagine that it suddenly changes: instead of sounding as usual, they now rather sound as if produced by a much smaller body than yours. Would you feel small and light as Alice in Wonderland after she drinks from the mysterious bottle? How do you think this would impact on your walking style or in your emotional state? And how do you think this event would impact on the perceived size of other objects and people around you or in the way you interact with them? Think about Alice and how the “little” door into the garden is not little anymore once Alice becomes small.”

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1. Introduction

For the majority of us, the feeling of having a body, moving it, experiencing its weight and the sense of touch when it interacts with other objects is so familiar that we do not usually think about it. Nevertheless, our body tightly connects us with the surrounding physical world. The example scenario above highlights a few of the phenomena related to this connection between our body and the physical (and possibly virtual) world. First, we interact with our surrounding environment through our body, and second, it is through our bodily senses, including audition, that we perceive the world surrounding us (Damasio, 1999; Tsakiris & Haggard, 2005). Auditory feedback often accompanies our interactions with physical and virtual objects, interfaces or agents. The scenario above demonstrates how a person can perceive various reality aspects just through footstep sounds. It can be information about the material of the ground surface (Giordano et al., 2012), the material of the shoes of the walkers (Giordano et al., 2014), or about the movements and the body of the walkers (Li et al., 1991; Pastore et al., 2008), including information about one's own body emotional and physical state (Tajadura-Jiménez, Basia, et al., 2015). The last point is especially important because our body posture often expresses our emotions, both intentionally and also unconsciously (Kleinsmith & Bianchi-Berthouze, 2013). In addition, self-body perception highly impacts our self-esteem and emotional state (Carney et al., 2010), forming a basis of self-identity (Giordano et al., 2014; Longo et al., 2008). Finally, the example scenario shows that one's body can be used as a "perceptual ruler" to measure the size of surrounding objects. Consequently, if one's body is perceived as smaller, by for example altering acoustic properties such as the reverberation time of the surrounding room, then external objects will be perceived as larger (like in *Alice in Wonderland*; van der Hoort et al. 2011; Linkenauger et al., 2011).

1.1 Body-Centred Interaction

The central role of our body in perception, cognition and interaction, has been addressed by philosophers (e.g., Merleau-Ponty, 1945/1962; Gallagher, 2005), psychologists (e.g., Niedenthal et al., 2005) and neuroscientists (e.g., Damasio, 1999; Damasio & Damasio, 2006; Tsakiris, 2010), and is often referred to as *embodied cognition*. This concept has also been applied in the context of Human Computer Interaction (HCI) and in the design of multimodal interactive systems. More than two decades ago Slater and Usoh (1994) introduced a "Body-Centred Interaction" paradigm that involves a number of components: a) inference about the state of one's body; b) body-centred feedback; and c) magical and mundane interaction. Through a number of insightful and seminal experiments, Slater and colleagues showed that one's own body, either physical or virtual, plays a primary role when perceiving and interacting in Immersive Virtual Environments (IVE) and it strongly influences the feeling of *presence* (i.e., "the sensation of being there", but also see more recent work on place and body illusions, e.g., Blanke et al., 2015). In this perception-action loop (also known as sensory-motor loop or sensorimotor loop), data sensed by our body lead to the perception and cognition of the external reality, which in turn guide our next bodily actions that influence the surrounding environment. This perception-action loop approach is reminiscent of the widely accepted neuroscientific theories of 'forward internal models' of motor-to-sensory transformations (Wolpert & Ghahramani, 2000). These theories state that motor actions planning and execution are adjusted according to the match between the sensory feedback received when performing actions (*afferent* inputs) and the feedback predicted based on the signals generated by the motor system (*efferent*

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copy). In the theories of 'forward internal models' the body takes a central place, because the predictions on the sensory feedback (including sounds) caused by our actions are based, among other factors, on the dimensions and configuration of our body through which we perform these actions. Similarly, in Slater and Usoh's view, presence in the actual or virtual reality occurs through our body becoming an object in that reality, and the perceptions of objects and agents are influenced by the way we mentally represent our bodies.

1.2 A mental model of our body guiding our interactions

Neuroscientific studies have repeatedly shown that our brain uses these body-representations, or mental models of the body, when we move or touch objects. Body-representations are indeed necessary for successful and smooth interactions with the environment (Head & Holmes, 1911–1912; Maravita & Iriki, 2004). They are continuously updated in response to sensory inputs received about the body (e.g., Botvinick & Cohen, 1998), but in a way can be considered *amodal* as they are not specific to a single sensory modality.

There are at least three different types of such mental body-representations. First, there are representations of the physical appearance of the body, such as its shape and size, often known as "body-image" (de Vignemont et al., 2010). Second, there are representations of the configuration and location of the different body parts in the space, often known as "body-schema" (Holmes & Spence, 2004; Haggard et al., 2006). Third, there are representations of the region of space immediately surrounding the body, often known as "near space", "peripersonal space" or "personal space" (Lourenco et al., 2011; Tajadura-Jiménez et al., 2011).

It is often the case that mental body-representations do not match exactly the actual physical appearance or configuration of the body. Most people experience some of these differences between actual and represented body, but sometimes the differences are extreme as in certain clinical disorders. Among such examples are *anorexia nervosa* which is characterized by distortions in body-image (Carruthers, 2008); some cases of chronic pain caused by the lack of awareness regarding one's body parts location in the space (i.e., proprioception; della Volpe et al., 2006); or distortions in the represented size of body parts and peripersonal space (Lewis & McCabe, 2010). Such distortions impact on people's way of engaging in interactions with the environment and with other people, and often also negatively impact on one's emotional state and self-esteem (Carruthers, 2008).

1.3 Altering representations of body and reality through sound interaction feedback

We described above how our perception of the environment and of our bodies is shaped by sensory feedback generated by our actions. For instance, we perceive the properties of the material of a surface, its roughness, hardness or coarseness, through the visual, haptic and auditory cues received when touching it (Klatzky & Lederman, 2010). Similarly, we perceive our body through the continuous stream of multiple sensory inputs: proprioceptive, vestibular, tactile, visual, auditory, etc. So what happens if sounds generated by our body actions suddenly change? Will we perceive differently our body, the object involved in the interaction, or perhaps both? Evidence suggests that all of these can happen due to the fact that our representations of the environment and of our body are not fixed and can be altered through sound interaction feedback.

Recent neuroscientific evidence suggests that object and body-representations are continuously updated in response to auditory cues, similarly to how they change through vision or touch. For instance, altering the frequency components of the sounds produced when touching a surface has been shown to change the perceived roughness of the touched surface (Guest et al.,

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2002). Similarly, altering the spectra and/or amplitude of the sounds produced when rubbing two hands together changes the perceived smoothness and dryness of the skin (Jousmäki & Hari, 1998).

The plasticity of these perceptions, together with the fact that current interactive multimodal technology allows altering these sounds and feed them back to the person, lead to many possibilities to change the perception people have of the world and of their own bodies. For instance, altering in real-time the heard sound of people's own footsteps has been shown to change their perception of their own body size (Tajadura-Jiménez, Basia et al., 2015). This possibility of changing the action sounds opens new avenues in the use and design of physical and virtual environments, objects and agents; forms of interaction and body expressivity; and even ways of augmenting one's self-perceptions, with a great number of potential applications in all possible fields ranging from clinical neuroscience to entertainment.

1.4 Body perception, sound and emotion

In this chapter we will often refer to emotional processes in relation to both body perception and sound. Indeed, sounds often elicit emotional responses in listeners as exemplified in our opening scenarios and as demonstrated by many studies on the impact of a broad range of sounds on emotional states (Bradley & Lang, 1999; Juslin & Västfjäll, 2008; Lenti Boero & Bottoni, 2008). Our sensory systems are responsible of keeping a constant margin of safety surrounding our body, and in this respect, the most basic function of the auditory system is to act as a warning system by eliciting emotional responses (e.g., Juslin & Västfjäll, 2008). Therefore, by hearing, we are able to monitor the surrounding environment in order to detect the presence of other individuals (or objects) and to obtain information about them (e.g., localization, size or material), their actions (e.g., direction or velocity) and, if needed, possible safe escape routes (Hermann & Ritter, 2004).

Emotional responses are triggered by the information gathered through the sound, and changes in one's body physiological state occur in order to get the body ready for action (e.g., Ekman, 1980; LeDoux, 1998; Levenson, 1994). While people such as James (1894) have argued that emotions arise from cognitive interpretations of these physiological changes in response to events, it is now accepted that emotions are psychological states characterized by behavioral, visceral and experiential changes (Seth, 2013). They impact on attention, cognitive and perceptual processes (de Gelder & Vroomen, 2000) and influence our judgments and decisions (Peters et al., 2006).

Emotional processes will either pull our body away from the sound source, in case of danger, or push our body towards the sound sources in case of feeling attraction towards them. This highlights the central role of body perception in relation to emotional responses to events, since one's body is taken as a reference frame in establishing one's position in relation to the objects, individuals, events, and situations around us and reacting emotionally to them (e.g., Damasio, 1999; James, 1890). Given that one's body perception may modulate emotional responses to sound, and that at the same time sound can also induce emotion and changes in body-perception, the interaction between these three aspects needs to be considered in a body-centred sound design.

1.5 Body-Centred Sound Design: Outline of this chapter

Although many of the ideas discussed in this chapter apply to all other sensory feedback, we focus on sound cues (and related sound design solutions) that provide critical information about body-centred interaction; this is a subset of sensory cues rather neglected in HCI. We

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selected recent research from multiple areas including virtual reality (VR), sports, health, rehabilitation, and art from the perspective of body-centred sound design and how such design is and can be informed by recent neuroscience and psychology findings. Thus, our focus is not specifically on technology or on sound synthesis (see section 1.6 for further reading suggestions), but rather on the top-down and bottom-up brain processes that can guide the effectiveness of sound-based body-centred interaction design.

In this chapter, we discuss how neuroscientifically grounded insights contribute to the design of new, enhanced interactive technologies. Section 2 starts by listing a number of interesting advantages of using sound for HCI applications and then focuses on how auditory cues can be used to enhance the perception of self by constructing a sound-based representation of one's own body, a sonic self-avatar, in mixed reality environments. The various types of cues for representing sonic avatars, like footsteps, heartbeat or voice, and for representing virtual space around the body (one's "safety margin" or near space), are discussed. In Section 3 we concentrate on examples of altering our body representation by sound to enhance positive emotions and facilitate movement and motor learning. In Section 4 we then present examples in which sound is used to alter the properties of objects being touched in order to also alter movement dynamics and emotional state. Finally, in Section 5 we discuss how new applications based on these principles can be used in rehabilitation and, in particular, to help to overcome physical and psychological barriers in people with specific physical or psychological conditions.

We deliberately decided to narrow the topic of this chapter to "***Designing Through Body-Centred Sound***" due to its emergent nature and actuality of embodied cognition themes. However, there are many thorough works that concern topics closely related to this chapter. For general **Sonic Interaction Design** we refer the reader to the book of the same title edited by Franinovic and Serafin (2013). A very inspiring treatment on the topic of **Music and Emotion** is offered in the article by Juslin and Västfjäll (2008) and the handbook by Sloboda (2010). The topic of music also closely relates to **Embodied Music Cognition**, including Action-based effects on music perception, and interpersonal synchrony and entrainment by listening to music or by playing music together with other people (Delaherche et al., 2012; Leman, 2007; Maes et al., 2014; Reidsma et al., 2014). For an overview of technologies related to **Virtual and Mixed Auditory Realities** and presence we suggest Larsson et al. (2010) and references therein. While we concentrated on sound in this chapter, our perception is multisensory and we invite interested readers to learn about **Multisensory Design** principles in the article by Soto-Faraco and Väljamäe (2012).

2. Self-representation via sound in mixed reality environments

According to the "body-centred interaction" paradigm introduced by Slater & Usoh (1994), having a representation of virtual body states, as well as having body-centred sensory feedback (e.g., visible parts of a virtual body), are crucial components for high presence responses and engagement in Virtual Environment (VE) and Mixed Reality applications. In this section we address some of the examples that concern such a virtual sonic body and acoustical surroundings.

2.1 Advantages of using sound for HCI applications

The use of sound offers a number of interesting advantages for HCI applications. First, it does not interfere with movement. Second, it can potentially inform the user of events outside of their visual field since audition has a 360 degrees-field of view. It has also been shown that one

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can create a space representation based on sensorimotor and auditory cues only (Viaud-Delmon & Warusfel, 2014). Third, the use of sound allows for the presentation of several streams of information (e.g., tactile and gesture) in parallel (Hermann & Ritter, 2004). And finally, it can provide a continuous flow of information, as audition never “turns off” in the same way that vision is blocked when shutting our eyes (Larsson et al., 2005), not mentioning the assistive technologies for visually impaired (Csapó et al., 2015). A further advantage of using sound is that the auditory system operates relatively well even in noisy environments, offering a high temporal resolution and a high sensitivity for detecting structured motion (e.g., rhythm; Hermann & Ritter, 2004). As a matter of fact, audition has been characterized as a change detector that responds to certain sound properties indicating a rapid change. It does so, by quickly orienting behaviour towards the changes that may signal potential threats (c.f. Juslin & Västfjäll, 2008); this response is faster than that observed for the visual system (McDonald, Teder-Salejarvi, & Hillyard, 2000). Hence, incorporating sounds that trigger intuitive, fast and accurate responses in users, might be beneficial for the design of systems where sound is used to convey alerts and warnings, such as vehicles, emergency systems in hospitals or working environments (for recent reviews see Roginska, 2013; Edworthy, 2013). Finally, from the point of view of aesthetics, sound is also a source of enjoyment and entertainment (Juslin & Västfjäll, 2008).

2.2 Sonic self-avatar

Our body produces many different sounds due to its own internal activity and to its interaction with the environment. Think for instance of the sounds produced by one breathing, yawning, chewing, walking or tapping on surfaces. These sounds are rich in information about one's body, its dimensions, its emotional state, the location of the body parts and the progress of the actions being executed. People do not pay attention to these sounds all the time, but they accompany us constantly, and can be considered a continuous “soundtrack” in our lives. People report that when these sounds are missing, for instance, when wearing earplugs, they have an altered awareness of their own bodies (Murray, Arnold & Thornton, 2000). Further, when hearing breathing or heartbeat sounds, people unconsciously tend to associate these sounds with their own physiological state, and these sounds have effects on the cognitive and emotional processes of the listener (Phillips et al. 1999; Tajadura-Jiménez et al., 2008). For instance, adding naturally breath intake sounds to synthetic speech seems to aid listeners to recall sentences (Whalen, Hoequist, & Sheffert, 1995). Similarly, listening to heartbeat sounds with fast or slow rate can respectively increase or decrease emotional arousal (e.g., Woll & Mcfall, 1979), as well as impact on participants' own heartbeat rate and recall of emotional events (Tajadura-Jiménez et al., 2008). Moreover, eating has been described as an emotional experience that involves “being aware of and listening to the crunch of each bite and noise of the chewing sound in your head” (Albers, 2003).

Without the sounds our body produces when interacting with the environment it would be difficult to coordinate apparently simple actions such as brushing our teeth, moving objects from one position to another, turning the car on or plugging in an electrical appliance. For instance, the motor behavior when touching a surface with the hand continuously “sculpts” the feedback sound, and vice versa, as we further explain in Section 4. As mentioned in the introduction, and further explained in sections 3 and 4, these sounds provide also feedback about the objects we are interacting with and about one's own body. For instance, the sounds produced when walking on a ground surface depend on the footgear and ground material, but also on the walker's weight and walking rate (Visell et al., 2009). Hence, these sounds can be used to enhance the perception

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of self in IVEs. Virtual reality research, as reviewed in section 1, suggests that presence in IVEs occurs through our body becoming an object in that virtual reality. It has been reported that seeing a self-avatar, that is seeing for example our virtual body from a first person perspective by looking down through a head-mounted display or by looking at a virtual mirror, increases presence in IVEs (Slater and Usoh, 1994; Dodds, Mohler, & Bühlhoff, 2011). Similarly, one could think of having a sonic avatar body, this is an avatar that is not visual but it is constituted by bodily sounds and interaction sounds and which represents one's body in these IVEs. As with the visual avatar, we now know that adding sounds representing our body moving in the IVEs increases navigation and interaction in those IVEs (Nordahl, 2006). Interesting examples of sonic self-avatars can be found in some audio-only games (see for instance www.blindsidegame.com).

Following this “body-centred interaction” paradigm, the addition of sounds representing one's self-motion, such as an engine-like sound added to the moving auditory scene, has been shown to significantly increase the sensation of movement in IVEs in a study by Våljamäe and colleagues (Våljamäe, Larsson et al., 2008). In this study, the engine sound, unlike other sounds in the moving virtual scene, was used as a stationary anchor, staying on the first person “point of hearing” (see Figure 1). This study also assessed mental motor imagery that refers to user abilities to imagine dynamic processes, including self-motion (Hall et al., 1985). It is common to separate motor imagery into visual motor imagery (visualizing the body performing a movement) and kinesthetic motor imagery (imagining the feeling that the actual body movement produces). The engine sound facilitation effect was significantly correlated with participants' kinesthetic but not with visual or auditory imagery, thus suggesting the relation of a first person perspective in the perception of the self-motion representation sounds. For a review of other auditory cues influencing sensation of self-motion see Våljamäe (2009).

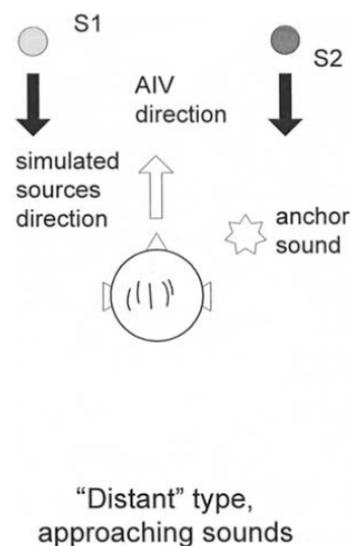


Figure 1. Having a sonic self-avatar in virtual immersive environments (left panel); schematic representation of auditory scene with the presence of the engine, anchor sound (right panel).

Further, when thinking about the constitution of a sonic self-avatar it is also important to consider the sound of one's avatar voice, as the acoustic cues of people's voices highly vary

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across individuals and are therefore very important in representing one's self, for example, in game applications (Wadley et al., 2014). There are voice acoustic cues that are usually good indicators of the age, gender and size of the speakers (for a review on salient cues in voice signals see Smith & Patterson, 2005). Hence, when constituting a self-avatar of a particular age, gender or body size, one could think about voice morphing techniques that manipulate people's voices, as they talk, and present the resulting sounds from a first person perspective (Deutschmann et al., 2011). Note that when people hear their own voice, approximately 50% of the sound energy they get is by air-conduction through their ears and the other 50% of the sound energy is transmitted through bone conduction (Pörschmann, 2000; Våljamäe, Tajadura-Jiménez et al., 2008). Hence, an effective presentation of the voice in this case may combine rendering of the voice through headphones (air-conduction) and through a bone-conduction headset.

Finally, in the already mentioned study on heartbeat sounds, it was observed that the effects of heartbeat sounds on people's emotional state are heightened when the sounds are presented from close distance to the listener, either by using headphones instead of far loudspeakers or by using vibrations to "capture" the sounds towards the listener (Caclin et al., 2002; Tajadura-Jiménez et al., 2008). This finding may suggest the importance of this first person perspective of bodily sounds for the constitution of a sonic self-avatar (i.e., for sounds to represent one's body in the environment), paralleling the findings showing the importance of seeing a self-avatar from a first person perspective. These findings also highlight different effects between presenting sounds in the near space (or peripersonal space) and in the space far from the virtual or actual body of the listener. We expand on research on these differences in the next subsection.

2.3 Peripersonal space and acoustics in Interactive Virtual Environments (IVEs)

We already mentioned that one of the types of mental body-representations is representations of the region of space immediately surrounding the body, often known as "near space", "peripersonal space" (also referred to as PPS) or "personal space" (Lourenco, Longo & Pathman, 2011; Tajadura-Jiménez et al., 2011). Neuroscientific and psychological studies have shown that our brains are specialized for the processing and integration of sensory information in the near space, as compared to the far space (e.g., Brozzoli et al., 2011; Rizzolatti et al., 1981). It should be also noted that spatial resolution and sensitivity of our auditory processing is different for the so called far-field (>1-1.5 meters) and the near-field, which is also reflected in different technological solutions to render acoustical events in a virtual space (e.g., Zotkin et al., 2004; see also Larsson et al., 2010, for more details and references).

In relation to external sound events and PPS, for instance, Neuhoff and colleagues (2009) demonstrated that the terminal distance of sound sources approaching one's body is underestimated and Tajadura-Jiménez and colleagues (2009) showed that the integration of sound and touch is facilitated for sound events near (versus far) the body. Several explanations have been offered for this specialization and for the importance of maintaining a representation of this space immediately surrounding the body, including the necessity of keeping track of objects located near the body in order to successfully interact with them (Chieffi et al., 1992; Moseley et al., 2012) but also for maintaining a margin of safety around one's body (Graziano & Cooke, 2006; Niedenthal, 2007).

There is also a tight link between PPS and emotion. Indeed, in the field of social psychology the term "Personal space" is often preferred over PPS and it is used to define the emotionally-tinged zone around the human body that people experience as "their space"

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(Sommer, 1959) and which others cannot intrude without arousing discomfort (Hayduk, 1983). Research on auditory-induced emotion has found that the spatial positioning of sound sources in relation to the listener's PPS might modulate the emotional responses to the sound. In particular, more intense emotional responses are observed in relation to unpleasant sound sources perceived to be approaching (Tajadura-Jiménez, Väljamäe et al., 2010; Ferri et al., 2015; Taffou et al., 2014) or close to the listener's body (Tajadura-Jiménez et al., 2008), or perceived as being behind the listener (Tajadura-Jiménez, Larsson, et al., 2010; Asutay & Västfjäll, 2015) as compared to sources that are far, static, receding, or in the front space. Furthermore, the acoustically perceived dimensions of the surrounding space around one's body can impact on the emotional responses to sound events (e.g., being in a small virtual room with a lion), as in a way they set the *context* in which events occur and therefore influence our interpretation of them (Tajadura-Jiménez, Larsson et al., 2010).

The presented evidence can be summarized in design principles, including that sounds in the near space (a) are preferentially and differently processed than those sounds in the far space, (b) have greater chances to constitute a sonic self-avatar and (c) can induce more intense emotional responses in listeners.

3. Altering body representation via sound to enhance body capabilities

In previous sections we already introduced the findings from neuroscience research that our brains use the available sensory inputs, including sound, to keep track of the continuously changing appearance of our body ("body-image), the configuration and position of our different body parts in space ("body-schema") and the space immediately surrounding our body ("peripersonal space"), as well as to keep track and adjust the motor actions (Botvinick & Cohen, 1998; De Vignemont, Ehrsson, & Haggard, 2005; de Vignemont et al., 2010; Haggard, Kitadono, Press, & Taylor-Clarke, 2006; Holmes & Spence, 2004; Lourenco, Longo & Pathman, 2011; Tajadura-Jiménez et al., 2011; Wolpert & Ghahramani, 2000). We also introduced the theories of 'forward internal models' of motor-to-sensory transformations (Wolpert & Ghahramani, 2000), which suggest that we predict the auditory feedback we should receive from our bodily interactions (e.g., the sound produced when tapping a surface with one's hand) by considering the motor commands our brains sent (e.g., the applied force, direction of movement) and the mental model of one's body dimensions and configuration. When the received sound feedback does not match these predictions, an update of the internal body models may occur, and this will also result in adjustments of the subsequent actions we perform. In this section we will briefly review the findings from neuroscience research on the effects of sound linked to body actions in the planning and adjustment of subsequent actions, as well as in the body image and body schema. We will then focus on the opportunities and challenges that these findings open for the design of technology in different contexts, including sports, health and rehabilitation. Recent HCI research, building on neuroscience findings, is starting to exploit the use of sound linked to body actions for enhancing the perceived body and its capabilities.

3.1 Action-related sounds are used to plan and guide own actions

Neuroscience research shows a tight connection between perception of action-related sounds and the brain motor commands for real or imagined action. For instance, hearing sounds produced when performing certain actions, such as tearing a paper into pieces, activates the same brain areas that would have been recruited when preparing to perform the same actions (Aglioti & Pazzaglia, 2010; see related work on *mirror neurons*, which are involved in action execution

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and action observation, e.g., Rizzolatti & Craighero, 2004 or Keysers, 2010. See also related work on *motor contagion* mentioned in the chapter entitled “Natural Human Robot Interaction” included in this handbook). Similarly, listening to sounds related to one's own actions can have an effect on the execution of subsequent actions. For instance, delaying the sounds produced by walking results in adjustments of one's gait (Menzer et al., 2010), and real-time alteration of the sound cues related to the strength applied when tapping a surface results in adjustments in the subsequently performed tapping movements (Tajadura-Jiménez, Bianchi-Berthouze, Furfaro, & Bevilacqua, 2015). The latter study also showed that emotional experience is affected by the congruence between tapping sounds and tapping actions. When hearing a *weak* tapping sound that did not match the sound predicted according to the applied strength of tapping, people felt less pleasant, more aroused and less able to tap as compared with a condition where tapping actions and sounds were kept congruent. Interestingly, in the condition where people heard a *strong* tapping sound, the mismatch with the tapping action was less evident and less unpleasant than in the *weak* tapping sound condition; in the *strong* condition participants felt able to tap and pleased with the sound feedback from their action, and they did not adjust their tapping behavior as much as in the *weak* condition. These findings demonstrate that people use body-related sounds to guide their own actions, which opens possibilities for technology to exploit these processes to facilitate and guide movement by using sound (Tajadura-Jiménez, Bianchi-Berthouze et al., 2015). Further, the tight link between auditory and motor areas in the brain extends to other types of sounds, such as rhythmic sounds, which are often used to entrain movement (Kenyon & Thaut, 2005; see also work on Interpersonal Synchrony and Entrainment by playing or listening to music, mentioned in the introduction: Delaherche et al., 2012; Reidsma et al., 2014).

3.2 Altering mental body models via sound

A few recent studies have shown that altering in real-time the action sounds made by one's body can have an effect on the perceived body size. For instance, altering the spatial location of the sounds that are produced when one's own hand taps a surface, so that the heard sounds originate at double the distance at which one is actually tapping, can lead to the perception of one's arm being longer than before (Tajadura-Jiménez et al., 2012; Tajadura-Jiménez, Tsakiris, Marquardt, & Bianchi-Berthouze, 2015), as well as to perform reaching actions as if one's arm was longer (Tajadura-Jiménez, Marquardt, et al., under review). Importantly, in order to observe a recalibration of the body-image and body-schema triggered by these effects, the spatial manipulations need to be kept within certain spatial and temporal limits. The sound location should allow for being perceived as coming from one's body, and the presented sounds need to be in synchrony with one's actions. Our work shows that presenting the tapping sounds at quadruple the distance at which one is actually tapping, or in temporal asynchrony over 300 milliseconds with one's action did not have effects on the perceived body size (Tajadura-Jiménez et al., 2012; Tajadura-Jiménez, Tsakiris, et al., 2015; see also Lewkowicz, 1996, 1999 for research on the multisensory integration window during which asynchronous stimuli in different modalities are perceived as simultaneous). Another study showed that altering the frequency spectra of the sounds one's body produce when walking, so that the resulting sounds are consistent with those produced by a lighter body, can alter the perception of one's body size and weight, so that one's body feels as being thinner and lighter (Tajadura-Jiménez, Basia, et al., 2015; see also Tonetto et al 2014). This study also showed that walking sounds making people feel thinner were connected to changes towards more active

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walking behaviors and more positive emotional states. These findings demonstrate that action related sounds can have an effect on people's body-image and body-schema, which again opens possibilities for technology to exploit these processes to make people more aware of their body or to make them feel in a different body.

3.3. Sound for sensory substitution or sensory enhancement of body perception

A body-centred design exploiting these findings could use sound, first, as a source of information about the *actual* body dimensions, position and movement – the use of sound in this context can be seen as a sort of *sensory substitution*. Several studies have validated the use of sound to give information that is normally channeled through touch. For instance, in the study by Boyer and colleagues (2015), a sound is heard when “touching” a virtual surface in the air. The actual curvature of the surface can be estimated through the auditory feedback when exploring the surface. While the average precision remains lower than published results using touch, this study showed that the auditory feedback could be effectively used to provide participants with subtle spatial information of a virtual object. Second, sound could also be used to provide altered information about the body dimensions, position and movements – the use of sound in this context can be seen as a sort of *sensory alteration* or *sensory enhancement*. There is a growing body of work supporting the use of sound in both contexts to increase positive body awareness and facilitate movement execution and engagement, as being more aware of one's body or feeling in a different body may impact in emotional state and in the planning of subsequent actions. For example, Boyer showed that sonification could enhance the accuracy in a visuo-manual tracking task (Boyer, 2015). As we already mentioned in the introduction, there is also a tight connection between sound and emotional state, which could be exploited in these applications (see section 1.4; Bradley & Lang, 1999; Juslin & Västfjäll, 2008; Lenti Boero & Bottoni, 2008; Tajadura-Jiménez et al., 2008, 2010a, 2010b), as well as the effects of auditory-induced emotion on motor behaviour (Leman, 2013). A body-centred sound design exploiting these findings could thus have applications in VR, art and entertainment contexts seeking to make people feel in a different body and to enhance body-related emotional state, but also applications in health and rehabilitations contexts seeking to increase positivity about one's body and facilitate action.

The use of sound as a source of information about the *actual* body dimensions, position and movement, has been shown to have positive effects in sports, dance, motor learning and rehabilitation contexts, such as enhancing body awareness and movement coordination, increasing motivation, reducing anxiety related to physical performance and enhancing the emotional state related to one's body (Grobhauser, 2012; Rosati et al., 2013; Schaffert et al., 2010; Singh et al., 2014; Vogt et al., 2009). For instance, sound feedback can facilitate motor learning by guiding movement by providing information such as the distance to a target posture (Sigrist et al., 2013), and can also improve self-efficacy (Singh et al., 2014). For a recent review on sensori-motor learning with movement sonification see the article by Bevilacqua and colleagues (Bevilacqua, Boyer et al., 2016). Section 5 is dedicated to work that has been done in the area of physical rehabilitation using sound as a source of physical information or to address psychological barriers. Much less work has been done using sound as a source of *sensory alteration* of one's own body perception. It was only recently that the possibility of altering one's own body perception with sound, to enhance physical performance, self-esteem and positive attention to one's body has been explored in the context of HCI. This is the case of the study that altered walking sounds in real-time to make people feel thinner and lighter, which showed that

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these changes in body perception made people walk “lighter” and induced a more positive emotional state (Tajadura-Jiménez, Basia, et al., 2015). Future research may consider applying similar body-centred sound design principles.

Finally, it is worth noting that the use of interactive sound feedback as a source of information about one's body has been experimented in performing arts, such as music and dance (Bevilacqua et al., 2011). The case of dance is particularly interesting since dancers are particularly trained to perceive their own body and space. For example, Viaud-Delmon and colleagues (2011) reported a study where a dancer experimented with an interactive system where sound and music were responding to her position and movements. This study evaluated whether such a system could alter dancers' perceptions associated with movements and extend their body space. The dancer in this study reported that the system helped to increase her physical awareness, and induced a change of her perception of the stage. In another study, Francoise and colleagues (2014) reported qualitative results, where dancers used an interactive system that was tuned to provide continuous auditory feedback to specific movement qualities. In this case, the sound was based on previously recorded vocalization of the dancers. They reported that the system tended to induce the exploration of different movement and modify their behaviors. In particular, the dancer felt that such a system could create a reflective space for movement learning. These studies clearly show that more research is needed in this promising area, to better establish how sound interactive systems could enhance body and movement perceptions.

4. Altering interactions with objects and multimedia interfaces via sound to enhance movement dynamics and emotional state

As already said, sound is of primary importance to inform us about our surrounding environment, both because of the omnidirectional nature of hearing and because the main function of the auditory system is to act as a warning system. Several types of listening have been proposed (Caramiaux et al., 2015), such as the *music listening* that focuses on elements such as pitches, timbre and rhythm, or *everyday listening focusing on events*, as proposed by Gaver (1993). In the case of a sound produced by a specific action, it has been shown that listeners have the tendency to describe the sound by the action itself (Lemaître et al., 2013). Moreover, we also perceive the size and material of the objects through the sound (Giordano & McAdams, 2006; Grassi et al., 2013; Klatzky et al., 2000).

4.1 A material perception - action loop during interactions with objects

The case of sound produced by objects through bodily interactions represents a specific case of body perception through sound. As our interactions with objects generally produce sounds, we constantly use the auditory feedback to adapt our movements as we touch an object to obtain information about its material. Interestingly, as in the case of our body perception, we are rarely conscious of how important are these auditory feedback mechanisms for our interaction through objects. For example, Cabe and Pittenger (2000) showed that users could successfully fill a vessel with water by using only auditory feedback. In this case the movement is continuously controlled through an action-perception loop (or vice versa, perception-action loop), where anticipation and adaptation come into play.

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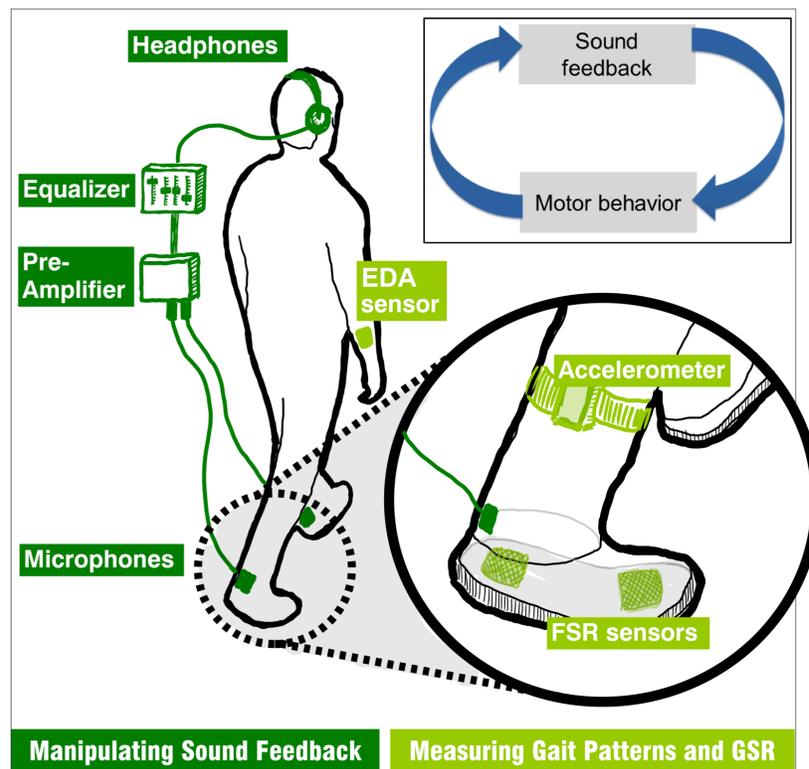


Figure 2. Bodily interactions with objects (e.g., walking on a ground surface) produce sound. The sound varies depending on the object material (e.g., ground material) and on the interaction (motor) behavior (in this case gait patterns), which continuously “sculpts” the feedback sound. The sound feedback is used to adjust the motor behavior, thus closing the action-perception loop shown in the subpanel on the top – right corner. The system displayed was used to alter in real-time the sound feedback resulting from walking and to measure the effects in estimated body size, gait patterns (measured with accelerometer and force sensitive resistors - FSR) and in arousal (measured by an electrodermal activity sensor – EDA). Figure adapted from Tajadura-Jiménez, Basia et al., 2015 © 2015 ACM, Inc. <http://dx.doi.org/10.1145/2702123.2702374>. Reprinted by permission.

The association between our actions on objects and resulted sounds is learned through our experience (Lemaître et al., 2015) and new associations can be learned. For example, the study by Cabe and Pittenger (2000) could lead to different results if different liquids causing different "filling" sounds, unknown to the participants, would be used. It has been also shown that the sound can activate motor representation of the movement. Several authors investigated movement that can be associated to sound or "sonic gestures". For example, Caramiaux and colleagues (2014) studied different movement strategies that users might use when asked to describe gesturally a sound while they are listening to it. In particular, they showed that identification of the action causing the sound favors the mimicking of the action.

The sound produced when touching an object can also be used to plan and execute subsequent movements. For instance, Castiello and colleagues showed that the speed of reaching-to-grasp movements (reaching towards an object) can be modulated by hearing, at movement onset, the sound that will be produced when grasping the object (as opposed to hearing the sound produced when grasping an object of a different material; Castiello et al., 2010). Several research studies also showed that the perceived floor material through sound

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feedback can influence the walking style (Bresin et al., 2010; Tajadura-Jiménez, Basia et al., 2015; Turchet & Bresin, 2015).

4.2 Changing sound feedback on object properties to alter movement dynamics

Similarly to the notion of affordance initially proposed by Gibson (1986) in the ecological approach of visual perception, several authors extended the notions of affordance to the interaction between sound and actions (Gaver, 1991; Godøy, 2009; Altavilla et al., 2013). Such notions of affordances have been used as design principles for the building of various interactive objects (Caramiaux et al., 2015; Houix et al., 2014), where the action and sound are coupled. Importantly, the use of multimodal interactive systems allows for designing the relationships between the actions and the sound feedback. The fact that we can easily, in a quantifiable manner, alter the audio feedback in response to the object manipulation opens opportunities to study our perception of the interaction (see Figure 2).

For example, Tajadura-Jiménez and colleagues described an interactive system that allows altering the perception-action loop between the touch of a surface and the sound produced through the action (Tajadura-Jiménez, Liu et al., 2014). In this study, the original sound of the touch was modified through digital sound processing, creating in turn the illusion of different surface textures such as grainy or smooth surfaces. We showed that by altering the sound feedback, both the touching finger movement dynamics and the material perception could be modified. This result is in line with the hypothesis that such an interactive system can modify the perception-action loop at the perception and motor levels.

Also emotion is intricate in this material perception – action loop. Changing the auditory information about motor performance or about the object of interaction may impact on how we feel about our motor capabilities or about being interacting with an object of particular characteristics. Using an interactive system, Tajadura-Jiménez and colleagues studied the influence of sound feedback to tapping either on a physical object (e.g., a table) or a virtual surface (i.e., tapping in the air; Tajadura-Jiménez, Bianchi-Berthouze et al., 2015). Similarly to the previous case, we show that altering the audio feedback related to the level of the tapping strength changes both the tapping behavior and the perceived hardness of the surface. Importantly, results obtained by using measures such as the Electrodermal Activity (EDA) and emotion questionnaires showed that the emotional state is also affected and should be taken into account. Summing the different studies indicates that the modelling of such perception - action loop between touch and sound is rather complex. Both the expectations we have about the experience of touching an object and the perception of the material as we touch the object influence *how* we touch it (Bianchi-Berthouze & Tajadura-Jiménez, 2014).

5. Initial learning from work in physical rehabilitation

In this section we discuss applications of the opportunities offered by the body-centred sound mechanisms discussed in the previous sections. Whereas from the previous sections, we have already acquired a flavor of the variety of areas of application, we focus here on a specific

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context of applications, that is, physical rehabilitation. Our selection is motivated by the fact that physical rehabilitation requires addressing many of the issues discussed above, that is, enhancing and remapping body perceptions and body capabilities as well as related emotional needs. We will review some specific work done in this field of physical rehabilitation discussing the opportunities, complexities and challenges brought by the use of a body-centred sound design and ubiquitous technologies, and the new questions and possibilities these technologies open to strengthen applications in many other fields.

5.1 Sound as physical information

Movement sonification (i.e., real-time auditory feedback of motion) is being increasingly used in the context of physical rehabilitation. Applications have emerged for example for recovery of movement post-operation, for reacquiring lost motor capabilities (Vogt et al., 2009) due for example to stroke (Wallis et al., 2007), or to facilitate movement despite pain and fear of injury (Singh et al., 2015). Sound is used here to enhance a feedback that is generally not visible or audible, that is the proprioceptive (kinesthetic) feedback. One of the main reasons for using sound as a form of feedback in physical rehabilitation is that it has been shown to facilitate sensory-motor learning (see section 3). In addition, sound can be played through portable speakers and/or headphones, and as it does not require fixating a display, it is suitable for any type of exercise and movement independently of the body configuration. This is even more important nowadays as physical rehabilitation is moving away from simple physical exercise dedicated sessions into functional activity. Hence, auditory feedback provided through wearable mobile devices becomes a suitable opportunity compared to visual feedback (Singh et al., 2015). Despite these interesting properties, extended experiments on movement sonification or wide clinical trials are still sparse.

Auditory feedback to guide movement

The initial use of sonification during physical rehabilitation aimed to inform the patients or the clinician that the movement deviated from a set trajectory. Maulucci and colleagues (2000) successfully showed that this use of augmented auditory feedback was beneficial for a rehabilitation task (in comparison to a group receiving no auditory feedback). In their work, no sound was heard when the movement trajectory of the tracked limb was kept within a defined margin, whilst changes in sound frequency indicated the amount of deviation of the movement from the ideal trajectory. In this case the auditory feedback can be considered as a gradual alarm whose sound characteristics informed about the importance of the problem and the need to attend to it (this type of feedback is generally formalized as Knowledge of Results - KR).

Given the positive effect on motor-learning, the use of sound feedback has been increasingly used to guide movement and enhance the perception of moving. Alterations of the sound are used to maintain movement within a desired movement trajectory and kinematic profile. For example, an increase in speed may be signaled by an increase in sound volume, whereas a deviation from a set direction may lead to a distorted sound or modified pitch. Using such a sonification, Boyer et al. (2014) showed that users could follow a specific velocity profile of the arm movement. Interestingly, most users were able to adapt to velocity profiles that changed over time, without being conscious of such shifts. Such a use of movement sonification

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could inform and help a person following a movement path and dynamics while discouraging from using compensatory movements, hence leading to a more effective therapy.

In the cases described above, other than guiding movement trajectory and its kinematics, sonification is used to enhance perception of target reaching. This is either indicated with a specific change in sound or by the ending of the sound. The sonification of reaching a target is considered very important as it provides motivation to cope with the challenging activity by having a clear and rewarding ending point (goal). Rewarding set targets has been shown to lead to increases in performance (e.g., Wallis et al., 2007; Singh et al., 2015; Newbold et al., 2016) and also to an increased sense of achievement and self-efficacy (Singh et al., 2014) even when performance did not change.

Calibration of movement path, acceptable deviation range and targets are set and adjusted by taking into account the physical capabilities of the person. As in the case of visual-based feedback systems (Kulic et al., 2015), the setting of these parameters is generally performed by clinical staff. However, as physical rehabilitation moves into self-management, researchers are investigating methods to facilitate either automatic calibration or a calibration that allows patients' exploration of their physical capabilities. An example is discussed at the end of this section.

Choice of parameters for movement-sound mapping

A question that is still open is the type of sounds that should be used to map movement (Dubus & Bresin, 2013). Indeed, there are several possible approaches to design movement-sound mappings. To be promptly used, even if the sound is simple, the information it carries needs to be intuitive (i.e., easily learned). Researchers have investigated how sound characteristics relate to movement characteristics. Following the review of related work by Bresin and Friberg (2013) showing that generally, vertical movement is more easily associated with increase in pitch, Scholz and colleagues (2014) investigated the perception of tone pitch and tone brightness in relation to vertical and horizontal movement in elderly. They found that the mapping of changes in pitch could be easily learned both in relation to horizontal and vertical movement, whereas brightness was more easily mapped to horizontal movement. These results show the importance of carefully selecting the sonification mapping and sound parameters for the mapping to be intuitive in a demanding and often anxiety-triggering task as those taken in physiotherapy.

In summary, different approaches reside in either sonifying the errors between the movement and "ideal" trajectory or sonifying the movement itself; the difference in effects between these two approaches remains unclear and asked to be explored widely. In this latter approach, the auditory feedback can be considered as enhancing body awareness, which could lead to a faster sensory-motor learning. Important questions remains on the different involved mechanisms: is the learning mechanism effective by enhancing the proprioception through sound or is the alteration of the expected sound that produced the movement correction? In all cases, the emotional response (beyond motivation and engagement) to the action-perception loop has been often eluded, but it seems important to consider it, even when using simple sounds, as discussed in the next section.

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Finally, sonification can support auditory-motor integration and hence does not only provide a form of sensory supplement when the proprioceptive system is dysfunctional but also, as suggested by Scholz and colleagues (2014), it offers a way to establish brain networks that transform sound into movement (e.g., Altenmüller et al., 2009). Instead, the alarm-like approach may be considered more useful during functioning where too much information would be overwhelming or not socially acceptable (Singh et al., internal report).

5.2 Sound to address emotional barriers

Whilst the above sonification frameworks aimed to compensate for limited proprioceptive feedback, to provide information about the quality of movement or to promote correct movement and a more engaging activity, emotional factors are also critical barriers to physical rehabilitation. Low engagement, low self-efficacy, low self-esteem, pain and fear of injury are some of the factors that affect the efficacy of physical rehabilitation and often lead to low adherence. Unfortunately, emotional aspects are often ignored in the design of physical rehabilitation technology.

Using musical and naturalistic sounds as metaphors

A particular approach aimed to motivation has explored the use of music instead of simple sonifications. Huang and colleagues (2005) created a virtual environment with both visual and auditory feedback and evaluated it with patients. They used general musical concepts that could potentially favor the user engagement. Further, the *Musical Stroke project* (Kirk, 2015; see also strokeproject.wordpress.com), with a strong user-centred design, focused in altering the sound feedback received during interaction with objects as a way to transform everyday objects in musical instruments. In this way, they could engage people who suffered stroke with their physical rehabilitation and enhance their motivation to perform the exercises they have been recommended to do. This work links to section 4, where we discussed possibilities of changing interactions with objects via sound as a way to enhance movement dynamics, which as exemplified here has applicability in the context of physical rehabilitation.

To make the sonification more intuitive and inviting, some researchers have also explored the use of metaphors (see for instance, Rasamimanana et al., 2011; Robby-Brami et al., 2014; Bevilacqua & Schnell, 2016). For example Vogt et al. (2009), make use of naturalistic sound to sonify the movement during shoulder physiotherapy. As the arm is moved upwards, the sonification changes from woodland sounds, to animals sounds, to the winds sound through the trees. The aim was to provide a more clear (even if gross) understanding of the position of the arm and, at the same time, a more aesthetically pleasant and relaxing experience.

The use of naturalistic sound was also investigated in Singh et al. (2015), where the phases of a movement are mapped into a path in a naturalistic environment (e.g., a forest) and changes in sounds reflect the reaching of a new landmark (e.g., a river, a herd of sheep). The skipping of one type of sound indicated that a phase of a movement had been avoided (e.g., the bending forward of the trunk during a sit-to-stand movement). The aim was again to enhance the sense of moving, to provide broad information of the movement quality and also to relax. Singh et al. (2015) results also showed that naturalistic sounds were relaxing and possibly more enjoyable; however, when sonification was used to understand one's body movement capability

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during pain or anxiety-triggering movement, the mapping between sound and movement aspects needed to be simple, i.e., easy to understand. Their participants showed preference towards a simple sequence of tone scales (as explained in the next subsection) rather than naturalistic sound or complex music, as they could better interpret the progression of their movement and the reaching of milestones in the simple sequence of tone scales.

Sonification to enhance the feeling of being capable (perceived self-efficacy) and confidence

The mechanisms discussed in sections 3 and 4 show that auditory feedback could be used to alter one's perception of body capabilities with possible emotion regulation effect and behaviour changes. Singh et al. (2014, 2015) set to explore this possibility. They investigated how movement sonification feedback should be designed to address various psychological barriers to physical activity rather than just the physical ones and motivation. In the context of physical rehabilitation of chronic pain, they have proposed and evaluated a sonification framework called *Go-with-the-flow* to address perceived self-efficacy, confidence in moving and fear of pain.

People with chronic pain often develop fear or anxiety towards movement that are perceived as threatening (e.g., stretching; Turk & Rudy, 1987). Rather than calibrating the sonification parameters to the physical capability of a person and to the expected movement profile, in the *Go-with-the-flow* framework the setting of the parameters reflects the psychological capability of a person in performing a movement. The *Go-with-the-flow* framework proposes the use of discrete tone scale to sonify progress of movement during the execution of anxiety inducing exercise.

As fear and lack of confidence in one's capabilities may deter people from engaging in a movement, the *Go-with-the-flow* framework proposes to sonify each phase of a movement according to its psychological demand. Rather than using biomechanical phases of a movement, the patient is asked to explore a movement and to split the movement into phases. For example, physiotherapists and people with chronic pain identify three phases of a stretching forward movement (see Figure 3): the first phase corresponds to the initial part of the stretching to the point where the person stops feeling comfortable stretching forward. The second phase is more challenging as anxiety kicks in even if the stretching is within a target set by the person. A third phase is the one beyond the target, i.e., where the person feels that the stretching is beyond his/her capabilities or state.

Figure 3. (Left). A smartphone attached to the back of the person is used to track the movement of the trunk and



provide real-time feedback. (Right) Sonification used to facilitate the stretching forward movement (Sing et al., 2014-2015).

In their work, Singh et al. (2014, 2015) showed that when using an increasing tone scale to sonify the first phase, people reported the feeling of having climbed a mountain and that when they reach the higher tone they feel a sense of achievement and they want to go forward. The

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increasing tone scale was used to provide a sense of increased challenge knowing that this phase of the movement was considered feasible despite the pain. The sonification of the second phase takes advantage of the emotional change and increasing coping capabilities created by the first sonification, and uses a decreasing tone scale to provide a sense of arrival and conclusion.

Finally, in order to further boost self-efficacy, the self-calibration aims to set the amount of reward to provide according to the set amount of stretching. Upon calibration (i.e., the setting of the maximum amount of stretching the person feels capable of), the step between the playing of two consecutive tones is automatically set on the basis of how much the person feels capable to do. For example, people that can stretch their trunks only for few degrees, will be rewarded more frequently (e.g., at every degree of trunk movement as they bend forward) than people that can stretch longer. In this way, despite the different capabilities, their stretch forward movement will be mapped over the same number of progressive tones. The faster rewards aim to enhance very restricted movement, producing a sense of “*worth doing and being capable*” (as participants reported). The slower rewards for the less restricted movement aim to provide a more clear sense of progress. In turn, this brings sense of control as the body travels a longer way and it is more challenged.

Control studies showed the benefits of such a structured and self-calibrated sonification in terms of increased self-efficacy, awareness, and even increase in physical performances. Participants also reported, that the simple sequence of discrete scale tone-based sonification was enjoyable despite its simplicity and, most importantly, it was rich in information and easy to map during a psychologically demanding movement.

Sensory substitution: using sonification structure to overwrite proprioceptive feedback

Discussion with physiotherapists and people with chronic pain raised the question of how to sonify movement targets. Two important issues emerged: how to avoid overdoing (stopping at set targets), and at the same time how to encourage progress when the physical capabilities are there. Building on the *Go-with-the-Flow* framework, and by taking advantage of the embodiment of sound, Newbold et al. (2016) proposed to use musically informed sonification to provide different levels of closure of the phrases of sonification. Using the concept of cadence, they investigated if a stable cadence would lead the body to naturally slow down as it approaches the target, whereas an unstable cadence would lead the body to want to continue to move passed the target (see Figure 4). They tested the different levels of stability and they show that stable cadences let people stop soon after the end of the sonification, whereas with unstable cadence, participants continued stretching forward for longer when the sound stopped. In addition, the change in speed profile was more sudden with unstable cadences. Self-report questionnaires also show that unstable cadences provided a sense of wanting to continue to move compared to stable cadences.

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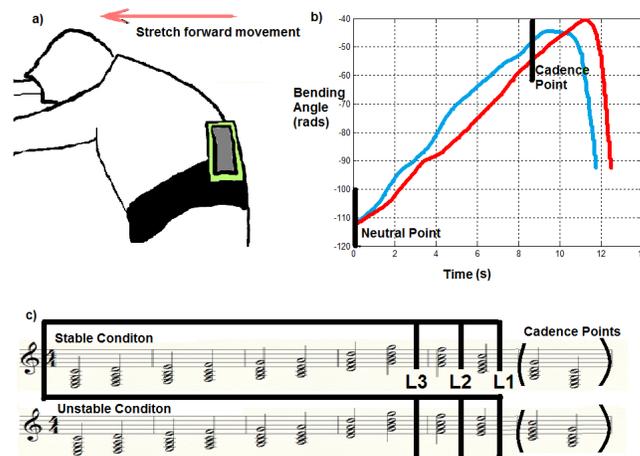


Figure 4. a) shows the stretch forward movement (trunk bend angle) tracked by a smartphone-based system. b) An example of the output recorded for one participant: the movement towards and past the cadence point for stable (in blue) and unstable (red) conditions. This example illustrates the difference in amount of stretching beyond the cadence point. c) An overview of the sonification stimuli used, all ending on either a stable or unstable cadence point, and the three lengths L1, L2 and L3 (derived by removing one or two chords from before the cadence point as shown, followed by either the stable or unstable cadence). Figure adapted from Newbold et al., 2016 © 2016 ACM, Inc. <http://dx.doi.org/10.1145/2858036.2858302>. Reprinted by permission.

Whilst music-based sonification and simple sonification have been shown to be effective and play different roles in supporting people during physical rehabilitation, an important concept emerges with respect to overcoming emotion. One could argue that in order for the feedback to be effective the sonification approach used needs to enhance the sense of agency so that the information is processed in a bottom-up manner and perceived as direct body feedback. This is particularly critical when the sonification itself aims not just to inform but to regulate critical emotional states. So possibly, this raises future research questions such as: what does the brain perceive as directly created by one's body? Or, what type of exposure does one require for the sonification to be perceived as a direct production of one's body action?

6. Conclusions and future directions

In this chapter we have summarized some of the mechanisms identified in neuroscience and psychology research. These mechanisms can serve as bases for better understanding users' experience of interactive technologies. Moreover, they can also serve as principles to design more effective sound feedback for these applications by adopting a body-centred approach. Below we summarize some of these principles and take away messages.

6.1 Summary topics important for future applications

Sonic self-avatar as representation of oneself. As shown in section 2 and other parts of this chapter, sounds constituting our sonic body can be instrumental for creating new experiences and shaping the mental representations of our body. A number of parameters, however, should

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be taken into account when creating a sonic-self avatar. These include the context (e.g., engine sound in the driving simulation), latency of the feedback (e.g., delay between the tapping action and the tapping sound in the body extension experiments), spatial location (e.g., the location of the heartbeat sound sources) and congruency with other sensory information (e.g., vibrations accompanying the engine sound).

Sensory enhancement and augmentation. As we showed, sound is often used to sonify the invisible - like hearing the body movement dynamics and its success in rehabilitation or sports, to amplify the feeling of one's own heart beating, to bring back the lost sense of touch in prosthetic applications, or to make one's footsteps really noticeable and instrumental to change one's body-representation and gate. Such auditory-based augmentation of our reality can only work in terms of provided sensory enhancement if conditions of time, space, intensity and context are respected (see next point). Cognitive load and attention demands should also be taken to account as a limiting factor of such sensory augmentation (e.g., Vazquez-Alvarez & Brewster, 2011).

Respecting thresholds in action – perception loops. It is not enough to sonify user's movement and actions but it is important to do so in a way that the user can intuitively incorporate the provided sound feedback into the existing action – perception loop. For example, in order for the sound feedback to be considered as being generated by one's body (i.e., feeling of agency) and therefore to have the possibility to produce unconscious adjustments in movement or in body-representations, certain threshold of deviations from the predicted sound feedback should not be trespassed. Thresholds apply to all temporal, spatial and intensity deviations. Specifically, if sound feedback is presented in large asynchrony with respect to the instant in which the action was generated, or if the sound feedback is presented too far away from one's body (e.g., outside the PPS), or if deviations in acoustic parameters (e.g., intensity of the sound feedback) are too large from the sound predicted based on the performed action, then sounds will not longer be perceived as produced by one's body, as found in the examples with tapping action and tapping sounds mentioned above.

Emotional design. Another take away message when designing applications is the necessity to think about sound design in a unifying way that joins physical and psychological aspects of the user experience, like in the case of rehabilitation. Emotional design brings, on the one hand, the necessity to consider user's emotional state (e.g., anxiety) and how it influences attention, cognitive and perceptual processes, which will affect how people perceive and react to the presented sound feedback. On the other hand, it opens possibilities of using sound feedback in a way that triggers specific intuitive responses in specific situations (e.g., alerts), relax the user in other situations, or interact with other processes in modulating body-representations. Sound design should consider the choice of parameters (i.e., intensity, source location, associated meaning) in relation to the emotional responses it can induce according to the context of use and users' individual psychological and physical circumstances.

6.2 Future outlook

The exponentially growing use of wearable sensors and computing, including various mobile, augmented reality devices like augmented glass, wristbands and smart fabrics, which

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allow for monitoring body motion and other physiological states of the body, inevitably invites to search for ways to convey such bodily information to the user. We briefly outline a number of potential applications that consider sound and body:

Sounding body / Sounding suit. A potential application would be one that offers the possibility of enhancing people's awareness of their body movement, body parts location and size by augmenting the sounds, or presenting new sounds, that the body produces when moving. A previous study has shown the potential of delivering intensive somatosensory stimulation of the whole body, by asking people to wear a custom-made neoprene diving suit, to improve body image in treatments of anorexia nervosa (Gruwald & Weiss, 2005). Another study has shown that people may feel their body as being metallic or 'robotized' if specifically designed auditory and vibrotactile feedback accompanies the flexing of the joints (Kurihara et al., 2013). Would it be possible to increase the positive awareness of one's body through a specifically designed sounding suit? And could such suit be used to enhance well-being of the general population and the population with clinical conditions, such as anorexia nervosa or obesity?

Having a sound system that raises awareness of one's everyday movement and aims at re-educating movements habits can have a strong therapeutic impact (Wang et al., 2014; see also Schiphorst, 2011). Indeed, the area of 'somatic movement education and therapy' is closer to therapy than to a classical dance (Eddy, 2009). The question here is the movement-to-sound mapping strategy and selection of appropriate spatio-temporal relationships for selecting the important body motion features. As the research of music, body and emotion is very wide, we refer to the reader to other references in Section 1.6 for topics such as of entrainment, group dynamics or sound metaphors.

Sonifying quantified self. An emerging movement of Quantified Self deals with person's daily life in terms of inputs (e.g., air, food) and one's performance (Russo, 2015). A good review of recent work on this area can be found in the chapter entitled "*The Quantified Self*" included in this handbook. Recent advances in wearable computing, such as sensor arrays for real-time analysis of body chemistry (Gao et al., 2016), provide users with various multi-channel data streams that are inherently related to our body and can fully benefit from body-centred sound design. In other words, how does your glucose level sound today? It would be interesting to see how such real-time audio-chemical loop may influence one's organism.

Body extension / Body swap. Our experiments are showing some apparent limits to the plasticity of one's body-representation. These limits might be related to the special processing of auditory information in the PPS (as opposed to the far space), or perhaps they have to do with one's body model not being totally plastic. For instance, there are much fewer reports in previous literature of sensory-induced body shrinkage illusions than of body expansion illusions (although see, for instance, Banakou et al., 2013; van der Hoort et al., 2011). Nevertheless, perhaps the observed limits have to do with the brief exposure to auditory feedback during the previously conducted studies. Would it be possible to further extend or shrink the body, or to have the experience of having a body of a shape and appearance very different to our actual body?

Sensory enhancement and magical experiences. Apart from benefits described in section 2.1, sound rendering technologies often offer an interesting solution like bone-conducted sound or narrow sound beams for personal experience using ultrasound loudspeakers (Olszewski et al., 2009). Such technologies can be used for creating unique or, as Slater and Usoh (1994) term them, magical experiences. For example, a simulation of hearing one's inner voice can be used as sonic-avatar based therapy for persecutory auditory hallucinations (Leff et al., 2014). The

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important question here is what level of technological simulation transparency needs to be maintained to keep the “the illusion of non-mediation” (Lombard & Ditton, 1997).

Sensory substitution systems. Sound has been used to provide missing visual or tactile input (e.g., Våljamäe & Kleiner, 2006). Both vibrotactile and auditory cues are also being used to indicate the location of objects approaching one's body in the absence of vision (e.g., Bird, et al., 2009). In terms of enhancing proprioception via sound, people with lost sense of touch use an audio glove (Lanzetta et al., 2004). It remains to be answered whether new brain networks are established when sound is used to provide a form of sensory supplement when the proprioceptive system is dysfunctional.

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