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# Co-Designing Sensory Feedback for Wearables to Support Physical Activity through Body Sensations

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Many technologies for promoting physical activity (PA) give limited importance to critical variables for engagement in PA, such as negative body perceptions. Here, we aim to address this gap by incorporating barriers and experienced body sensations into the design process for wearables and body-based devices thus expanding the design space for such technologies. We first report four co-design workshops with physically inactive participants (n=9); in these workshops, we explored tangible tools (i) to sensitize people to body sensations experienced when facing barriers to PA and (ii) to ideate how haptic and auditory feedback could transform body sensations to increase body-awareness and engagement in PA; results show several interactive sensorial patterns with potential to inform the design of body transformation wearables. These were validated through a follow-up workshop (n=13 participants) and reflections based on insights from a literature review. Our findings are significant for the design of ubiquitous technology to support and initiate PA in everyday contexts through a novel approach of transforming body perceptions/ sensations related to PA barriers. We contribute design inspirations and cards for identifying barriers to PA and to empower designers and researchers to integrate them early in the design process.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; *Empirical studies in interaction design*.

Additional Key Words and Phrases: wearables, sensory feedback, physical activity, embodied design methods

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## 1 INTRODUCTION

Physical inactivity is a major global risk factor of mortality [111], and contributes to many psychological and physical issues such as depression, cardiovascular diseases, diabetes or chronic pain [29, 111]. Many existing technological interventions designed to promote physical activity (PA) integrate activity tracking and build upon personal informatics and behavior change techniques (e.g. [69]). However, their efficacy may be limited due to overlooking some critical variables affecting PA, such as not considering barriers and facilitators of PA in their design or addressing them simplistically (e.g. motivational badges) [71]. Thus, traditional interventions ignore diverse barriers that people experience, including physical (e.g. medical status), contextual (e.g. work/studies) or psychological ones (e.g. low self-confidence or self-esteem) [71]. A more recent approach involves using sensory feedback to address barriers related to body perceptions or sensations. These barriers hinder PA adherence and engagement (e.g. lack of proprioception, feeling tired or heavy, not feeling comfortable with the body) [71, 77, 109]. While prior work has demonstrated the potential of sensory feedback **during** engagement with PA to alter body perceptions/sensations and facilitate PA [48, 50, 87, 92], no study has yet explored the potential of sensory feedback to affect body sensations **prior**, as a way to trigger and foster engagement with PA.

In this paper, we explore the design space of future wearable sensory technology to address barriers to PA by raising awareness of negative body perceptions associated with experiencing those barriers. We also use sensory feedback to address negative body perceptions and **initiate engagement with PA**, focusing on haptic and auditory feedback, due to their benefits in movement-based contexts [9, 75, 79, 84]. Following a Research through Design approach [27, 114], we first organized four design workshops employing embodied interaction methods [56, 63, 76, 110] with nine people who were identified as physically inactive. All participants were invited to participate in all four workshops and most of them did (Workshop 1 and 2, n=9; Workshop 3, n=8; Workshop 4, n=7). These workshops served to map barriers towards PA and identify associated body sensations. In them, we also explored haptic and auditory signals to raise awareness of these sensations and facilitate the transition from inactivity to activity by acting on them. These workshops yielded insights into somatic experiences of barriers and revealed compelling *sensory patterns* to enhance awareness of body sensations and prompt physical activation. We conducted a follow-up workshop with thirteen participants to validate sensory patterns for activation beyond the original context of physical inactivity and to develop a further understanding of patterns for physical activation in the general population. Connecting these patterns to insights from a literature review on body-centered sensory technologies for PA, we enriched and theoretically grounded our empirical results, proposing insights on their potential efficacy.

Our work contributes insights including:

- An understanding of how physically inactive people somatically experience barriers to PA (i.e. body sensations and impact on everyday life). Mapping and understanding such barriers can assist experts, such as physiotherapists, in treating, mitigating, and addressing these obstacles by providing a symbolic representation or language for discussion and communication. These insights help characterize this population in terms of how they experience different barriers to PA. This contributes to an understanding of how to design to address these barriers through technology. In our investigations, the focus was not on translating existing therapies but on exploring how different sensations evoked by interacting with different multisensory materials can help with enabling behaviors of PA. Thus, we contribute to the design of technology-driven multisensory experiences through wearable technology in this domain.
- Design inspirations through a set of sensory patterns (haptic and audio) for activation, developed and iterated with two different populations, and theoretically grounded in prior research. This contribution

is particularly valuable for designers working on various technologies, especially those leveraging users' multisensory experiences (e.g., wearables, virtual or mixed reality) to support PA.

Additionally, our work offers methodological contributions for researchers interested in addressing barriers to PA into their design and research processes:

- A novel set of *PA Barrier cards*, designed based on the items of the Barriers Questionnaire for PA (BQPA) [72] (see also [71]), serving as a tangible tool to identify and discuss barriers to PA during group sessions. Similar to design cards (e.g. the IDEO design cards [38]), these cards may allow designers access to, and articulation of, relevant knowledge for the design process.
- A novel methodological approach to incorporate barriers in the design process emphasising a somatic or body-based, first-person perspective. For example, we propose materialising barriers focusing on the body sensations felt when experiencing them. Further, we propose a somatic twist to traditional Interaction Design tools, like *personas* and *scenarios*. Regarding *scenarios*, we propose creating scenarios reflecting empirical material capturing the participants' descriptions of barriers as they are bodily experienced. The scenarios help contextualize barriers and reflect their real-world impacts for actionable and accessible design exploration. As for working with *personas*, we propose a novel embodied design activity, *Somatic Dress-Up*, which involves crafting one's body and 'dressing up' using external objects and diverse materials to embody a particular *persona's* sensations, which can help empathize with the *persona's* sensations and enact scenarios.

## 2 RELATED WORK

### 2.1 Sensory Feedback and Body Perception: Theoretical Underpinnings

Haptic and auditory signals are advantageous in PA contexts as they do not interfere with movements, allow users to maintain focus without the need for visual fixation [105], enable presentation of multiple streams of information simultaneously, and have demonstrated benefits in reducing perceived workload and enhancing performance [13, 32, 36]. These modalities are already used for movement guidance, correction, and motor performance improvement [9, 57, 84] (see recent overviews [75, 79]).

Moreover, neuroscience research highlights the contribution of both haptic/tactile and auditory signals to individuals' perception of their own body and actions [11, 91, 93–95, 100]. Recent studies have shown that auditory feedback can raise body awareness by providing information that may not be readily available otherwise [82] and transform body perceptions by altering the immediate sensory feedback from actions and movements [48–50, 87, 92]. Further, manipulating auditory cues in impact interaction sounds can result in alterations of perceived body part length [91, 93, 95, 97], full body weight and size perception [12, 20, 87, 88, 92], and perception of applied strength [96]. These changes in perceived body appearance and capabilities can also influence emotional states (e.g. inducing happiness [87]), and motor behaviors (e.g. movement velocity [91], strength [96], and acceleration [87, 88, 92]). Beyond natural sounds, artificial sounds synchronized with bodily actions can create illusions of changes in body perception, e.g. a rising pitch sound can evoke feelings of body lightness, speed, movement capability, and ease and motivation to perform movements [48, 50]. Moreover, movement sonification techniques with nature metaphors (e.g., wind, water) can positively influence various aspects of body perception, emotional state, and movement in diverse exercises, particularly for physically inactive individuals [49, 50]. The use of haptics to manipulate body perception has also been explored in soma design works in HCI. For example, the *Soma Mat* uses thermal stimuli to direct attention and raise awareness of different body areas [40, 55, 86]; *Soma Corset* influences the wearer's perception of their own body, leading to uncanny experiences and distorted perceptions [43]; and the *Breathing Wings* provides varied tactile feedback to help re-experience specific body parts [101].

Recent research shows the potential of combining both auditory and haptic feedback to alter body perceptions and sensations in the context of wearable technologies for PA [16, 57, 79, 99]. However, our understanding of these mechanisms and principles for designing sensory technologies to support such experiences and facilitate PA is still evolving. In the following sub-sections we review relevant prior work on sensory feedback in PA contexts resulting from a literature review that we conducted. We include insights on visual feedback because though it is not explored in our empirical work, it provides insights relevant for our work - as further elucidated in the Discussion. However, it should be noted that these studies have primarily focused on providing feedback **during PA engagement**. To date, no research has explored the potential of sensory feedback to address body sensations **prior to PA engagement**, as a means to trigger and promote PA involvement - a current gap that our contributions address.

## 2.2 A Literature Review of Body-Centred Sensory Technologies for Supporting Physical Activity

We conducted a literature review of body-centred sensory feedback for PA in HCI with the goal to derive concrete insights (revisited in the Discussion) for grounding and discussing the sensory patterns that we found in our own empirical work.

*2.2.1 Conducting the Literature Review.* We used the Association for Computing Machinery (ACM) digital library database [1] as ACM is considered the world's largest educational and scientific computing society [2]. The search string, in Figure 1, was constructed through group discussions and testing to ensure relevance. It covers both technology considerations (column 1) and use considerations (column 2). Our review aimed to cover literature related to PA and human body perception, specific sensory technologies, and studies with human evaluations. For technology considerations, we included keywords reflecting the technology type (e.g. haptic feedback, sensorial), the technology approach (e.g. soma-based design, first-person body) and the technology focus (e.g. what the technology had been designed for, e.g. somatic awareness). For use considerations, we included keywords to reflect different contexts of PA (e.g. exertion, general PA, sedentary lifestyle) and the impacts of the technology on body experience and physiology (e.g. bodily awareness, bodily sensation, physical capabilities). This initial search yielded 253 publications (Research Articles (183) + Short Papers (21) + Extended Abstracts (17) + Works in Progress (16) + Demonstrations (14) + Notes (2)) from 2006 to 2022. Article screening consisted of three steps. At every step, articles meeting any of the exclusion criteria in Figure 1 were excluded, and unclear ones were treated as included until the next or final step. The three steps were: (1) two authors read the titles and abstracts of all articles obtained through the search; 175 publications were excluded based on exclusion criteria. (2) The remaining 78 articles were read completely and discussed by two authors; 30 additional articles were excluded, resulting in 48 articles. (3) in 16 of the remaining articles, there were disagreements or doubts between the two authors and these were discussed among five co-authors to check if they should be excluded or not. After discussions, all 16 were excluded. The final corpus included 32 articles. Next, we summarize these by focusing on the effects of different types of feedback, including visual, haptic, and auditory feedback.

*2.2.2 Visual Feedback.* Our literature review highlights the extensive use of visual feedback in designing technologies for various physical activities and training. Visual feedback has proven effective in enhancing performance aspects, facilitating movement control and promoting body awareness [57, 58, 78, 105]. For example, it has been used to convey information on weight balance [112], muscle activity [42], posture [7] and heart rate [44].

Visual feedback has also been useful in addressing barriers to PA and facilitating body awareness by providing bodily information such as proprioceptive cues (e.g., posture, balance), influencing movements, and reducing fear and effort sensations, particularly in populations with specific challenges [57, 58, 78, 103, 104, 106]. For instance, simple visual feedback (e.g. green lights for fluid movements, red for jerky movements) influenced proprioception in children with mild sensorimotor challenges, and helped to reduce fear of pain (e.g. in the feet while walking

on a wire), or of effort during exertion (e.g. when holding a sit-up) [58]. Similarly, visual signals attached along the person’s spine enhanced people’s understanding of posture by providing clear visual accentuation of the overall shape of the spine [105].

Additionally, visual feedback offers detailed information about muscle activity providing real-time feedback during physical activities [42, 65]. For instance, the Fitback system [42] visually displayed changes in muscle activity (through abstract visualizations e.g., bars, circles and lines) to trainees while doing bicep curls. When this feedback was compared with sound feedback, trainees found that sound allowed them to focus more on the exercise at hand than visual feedback, similar to [7], in which mountain-bikers found the use of visual-directional feedback using colored light patterns, confusing and challenging to interpret. Thus, visual feedback is valuable in providing performance-related information (e.g. to correct or guide PA, see [105, 107] for a review), although it may require additional time for users to process and apply the feedback to their physical activities. Alternative forms of feedback may be more suitable for certain contexts where visual information may impede the activity being performed [7, 42, 105].

2.2.3 *Auditory feedback.* We identified a number of studies employing auditory feedback in the context of PA. Auditory feedback, similar to visual feedback, has proven effective in facilitating PA by providing detailed movement information that enhances performance, body awareness, and movement control through manipulating sound qualities such as pitch, volume, and duration [3, 58, 105, 112]. For instance, [105] explored using increasing sound volume in response to air passing through a tubular shape to enhance people’s awareness of their breathing

<b>1 - INITIAL SEARCH</b>	<b>Includes any of the following (in title, abstract, or keywords)</b>	<b>AND</b>	<b>Includes any of the following (in title, abstract, or keywords)</b>
	audio-based feedback, auditory feedback, auditory-tactile feedback, biofeedback, felt body, felt experience, felt sense, first-person body, first-person experience, haptic feedback, interocept*, lived body, lived experience, movement feedback, movement sonification, multisensorial feedback, multisensory, multisensory feedback, propriocept*, sensorial, sensory, sensory feedback, sensory stimulation, soma, soma design, soma-based design, somaesthetics, somatic awareness, somatic experience, somatic sonification, sonification feedback, sound feedback, tactile feedback, vibrotactile feedback		body perception, body sensation, body sensations, body awareness, movement trigger, movement activation, physical activity, physical activities, physical inactivity, physically inactivity, physically active, physical motivation, physical capability, physical capabilities, sedentary behavior, sedentary lifestyle, sedentary, embodied, embodiment, exertion, physical exercise, physical exercises, kinaesthetic, kinesthetic, motor activity, motor activities, physical training, bodily awareness, bodily sensations, bodily sensation, bodily perception, bodily perceptions
<b>Results: 253 publications</b>			
<b>2 - EXCLUSION</b>	<b>Presents at least one of the following</b>		
	The work is not related to physical activity (e.g. pregnancy concerns)		
	The work does not focus on human body perception (e.g. using sensory feedback to perceive virtual objects in VR)		
	The work does not specify a concrete modality of sensory feedback (e.g. generic movement feedback)		
The work does not include results from an evaluation with humans			
<b>Results: 32 publications</b>			

Fig. 1. Overview of the literature review strategy

during PA. In another study [3], dancers used auditory feedback to explore different movements, generating specific sounds; the auditory feedback helped to enhance their dance technique through replicating these sounds during repetitive practice. Further, auditory feedback has the ability to support PA by influencing body perception, for example using movement sonification to increase sense of speed and performance in speed skaters (e.g. [85]), alter body and movement perceptions of physically inactive people (e.g. [50]), transform perceived appearance or capabilities (e.g. [89]); increase proprioception and sense of control in daily life activities in people with chronic pain [80, 81] and in children with mild sensorimotor challenges [17, 57, 78, 104]. Auditory feedback has also been used as a strategy to encourage or halt movement, shifting focus from pain to sounds [64].

Other interactive art-based projects have used auditory feedback to enhance the perception of movement qualities in contexts such as choreographies of aerial acrobatic practices, allowing body expressions while composing music [52], and to shape bodily experiences in life dancer scenarios [54]. In this context, metaphorical sound design, incorporating natural or artificial sounds and musical elements, can aid in interpreting bodily information transmitted by sound (e.g. directionality) and facilitate the emergence of new bodily experiences. For example, the Slowfloor project associated the sound of water bubbling in a brook with slower movements during a walk, enhancing creativity and a sense of agency [25, 26]. Similarly, metaphorical sound feedback, like recorded water sounds for exerting the calf muscles and rustling leaves for shins, was used to facilitate kinaesthetic awareness of micro-movements [14]. In summary, auditory feedback has emerged as a promising, multifaceted approach serving as a facilitator for PA, particularly addressing psychological barriers related to body perception. Further exploration and investigation are needed to unlock its full potential in supporting PA, and particularly in addressing psychological barriers.

**2.2.4 Haptic feedback.** Our review reveals that haptic feedback is a versatile mode for delivering information during PA and the most commonly used types of haptic feedback in PA interventions include thermal [22, 40], pressure [41, 105], and vibration [5, 7, 8, 37, 57, 83, 84, 90, 99, 112]. In particular, vibrations have emerged as the primary modality for haptic feedback, commonly employed to provide information for correcting posture [7, 90, 112] or providing instructional cues [57, 90]. The use of metaphors in vibrational feedback has also shown potential to enhance movement quality and users' body experiences during PA. Metaphorical use of vibrational patterns can enhance movement quality during PA, such as simulating the sensation of being 'pulled' up or 'pushed' down for squat exercises [83, 84] which could be used to facilitate the same [90]. Furthermore, haptic feedback has demonstrated its potential to influence body awareness and other body perceptions. One notable example is the utilization of deep pressure feedback on the torso to enhance individuals' awareness of their breathing during therapy sessions [41].

Thermal stimuli, explored for directing attention to specific body parts [40], show varying sensitivities among individuals in body awareness exercises. Further exploration is needed to determine the optimal heat level, considering individual sensitivities to different body parts. Notably, participants reported perceived changes in weight and size of heated body parts. Additionally, some described the heat stimuli as being internal (i.e. a feeling inside the body), contrasting with external sensations like touch or vibrations.

In summary, this review highlights the potential of sensory feedback for conveying movement information and influencing body perception. Although promising for movement guidance, there's a lack of research on psychological barriers to body perception affecting PA engagement.

### 3 METHODOLOGY AND METHODS

Our work followed a Research through Design (RtD) [27, 114] approach, in which design methods and processes are used to probe and gain insights into particular situations. RtD as methodology focuses on generating design knowledge to inspire future possibilities and designs [114]. As such, it does not attempt to create generalizable knowledge as positivist or experimental science does. Rather, as other qualitative-leaning methodologies, it favors

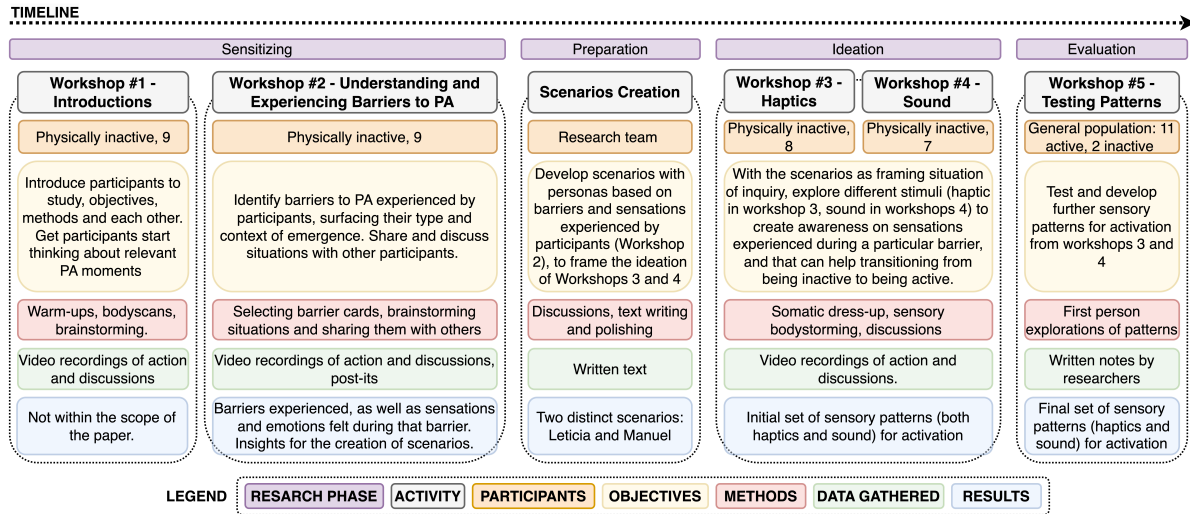


Fig. 2. Overview of our methods, with concrete activities, objectives, methods, type of data gathered and results.

a deep engagement with the research context and participants, eliciting rich and nuanced accounts [27, 114]. Thus, such research often features more variable, smaller sample sizes than experimental research [10, 35, 68], with RtD works ranging from studies with several participants (e.g. [106], 15 participants) to studies with few (e.g. [80], 4 participants).

This work is situated in the context of a larger project focusing on designing sensory wearable technology to alter body perceptions. We organized five workshops (2.5h each) in a room at University Carlos III de Madrid. We employed both traditional design methods (such as brainstorming and design cards), and embodied design methods [56, 62, 63, 105] that foreground movement-based and hands-on engagement, and enactment of situations. The workshops focused on i) **understanding** the target population, and supporting embodied explorations of their practices, barriers that hinder physical activities, and prompts for action they experienced (Workshops 1 and 2); ii) **designing**, through haptic and auditory outputs for creating awareness of body sensations that hinder PA, and encourage physical activation, i.e. haptic and auditory sensory signals to prompt action (Workshops 3 and 4); and iii) **testing** emergent signals (Workshop 5).

### 3.1 Workshops with Physically Inactive Participants

The first four workshops, with physically inactive participants, followed a similar structure. They started with a warm-up activity to prepare participants to engage with their own body, interact with others, and consider physical and contextual elements. Next, they participated in the main activities (interspersed with breaks), and the workshop concluded with a discussion. The workshops were co-facilitated by HCI design researchers including two experts in embodied design methods, two audio experts, and a psychology researcher. All workshops were video recorded. The recordings, together with materials that participants produced (e.g. body maps capturing the felt experience of users [102]) constituted the main data sources for analysis for this paper. For brevity, in this paper, we focus only on the results of the second, third, and four workshops; the first workshop mainly served to onboard participants, introducing them to the project and study objectives and to introduce, practice and explore our design approach and the (embodied) design methods we would use in subsequent workshops.



**Participants.** We recruited 9 participants (5 women, 4 men; mean age = 24.6 years, SD = 6.8, range = 18-33) using various channels including the participant pool at University Carlos III de Madrid, campus flyers, local distribution, and social networks, adhering to the university's ethical guidelines. Participants were identified as physically inactive using the International Physical Activity Questionnaire [31], which characterizes people's levels of PA. All participants exhibited *moderate* or *moderate-low* levels of PA ( $2700 > \text{METS/week} > 330$ ). Only one participant reported planning 2 hours of weekly PA [74]. To gain deeper insight into our participant sample, we explored what they considered to be the weakest areas of their physical condition. For this, we presented five cards developed based on the International Fitness Scale (IFIS) to our participants (see supplementary material - Appendix A for an index of supplementary material). The cards covered general physical condition, cardio-respiratory condition, muscle strength, velocity/agility, and flexibility [60]. Participants used the cards to identify aspects of their physical condition that they perceived as the weakest. Notably, each aspect was selected by three out of the nine participants, indicating that participants identified multiple dimensions lacking in their physical inactivity. All participants took part in Workshops 1 and 2, with eight and seven participants respectively taking part in Workshops 3 and 4. Participants gave explicit consent for use of pictures of them in publications. Next, we briefly present the methods employed in these workshops.

### 3.2 Body sensitizing

Workshop 1 introduced participants to the study's objectives focusing on exploring and eliciting "*energizing moments*" - instances of heightened energy and activation in everyday life, that may prompt PA engagement. Participants reflected on sensations and emotions experienced in various situations during guided activities. The workshop aimed to familiarize participants with project goals, facilitate introductions, and present methods/tools for future workshops, including warm-up exercises, bodyscan exercises, brainstorming, and the use of body maps. The analysis of the findings from this workshop is not relevant to the research question addressed in this paper.

*3.2.1 Exploring body sensations related to barriers to PA.* Building upon the reflective and sensitizing foundation of Workshop 1, Workshop 2 focused on identifying participants' barriers to PA and the context and their somatic experiences of these barriers. In groups of three, participants were given a deck of 61 Barrier cards (categorised into psychological (42 gray cards), physical (14 blue cards) and personal/contextual barriers (5 green)), created to represent potential non-demographic barriers based on the Barriers Questionnaire for PA (BQPA) [71, 72] (See Supplementary Material #1). Participants selected a maximum of five that were most relevant to each of them (Appendix B contains a Figure that illustrates Barrier cards).

They then individually brainstormed situations situation(s) in which they would face their most significant barrier, using post-its and guided by specific prompts: activities you are doing, where and when it occurs, other people involved, technological or non-technological objects involved, triggers and sensations. Participants shared the results of brainstorming in their small groups through enactment and verbal articulation, subsequently focusing on somatically replicating how the barrier felt in their bodies. Finally, they started exploring through enactment sensorial stimuli could address the barriers. This workshop paved the way for subsequent workshops.

**Scenarios.** Building on the previous activity, particularly the emerging contextual aspects and sensations reported and enacted by participants, five authors created two scenarios (see scenarios in Supplementary Material #2 and results in section 4.2) featuring two different personas and contexts. The scenarios helped participants to work empathically with relevant personas with similar sensations [66] while maintaining a certain distance from the target user, which can help by not having the participants have to disclose or expose aspects they do not feel comfortable with. Each scenario reflected representations and situations reported by participants based on fictional personas (Leticia or Manuel) in everyday contexts. To create them, five authors highlighted terms used by participants earlier to describe their sensations, which were grouped, and attributed to a persona. They then

inspired two different scenarios, using some of those terms. These scenarios were used in upcoming activities, i.e. for the somatic dressing activity in Workshops 3 and 4.

**3.2.2 Eliciting/Exploring Haptic and Auditory Signals for Physical Activation.** Building on insights from participants' somatically experienced barriers to PA in Workshop 2, Workshops 3 and 4 explored haptic and auditory signals respectively to create awareness of those sensations and to help transition from being inactive to being active by acting on those sensations. Both workshops had a similar structure and methodologies. For these workshops we brought in the scenarios, as well as a series of materials, objects and prototypes as physical ideation probes.

**Probes.** Sensory probes were used to help participants explore barriers and associated sensations somatically. Probes ranged from household items, playground, daily-life, office or items from sports shops (Figure 3). In workshop 3, focused on haptics, we provided probes with different material qualities for exploring a full range of tactile qualities such as humidity, roughness, temperature or elasticity (see Supplementary Material #4, for an inventory of the sensory probes).

In Workshop 4, focused on auditory signals, we provided haptic/tactile probes (which foregrounded interesting auditory qualities through their manipulation, e.g. pressing, tapping, rolling, or squeezing them). We included auditory probes, such as a wooden percussion kit, which could be used in combination with steel objects. We also brought some simple auditory technological probes (ATP), including recordable buttons -some with pre-recorded sounds-, iPods with an app that played sounds when shaking them (based on [59]), and various copies of a prototype, Soniband [49, 50], which integrates wireless inertial motion sensors (accelerometers and gyroscope) and sonifies movement. The sounds available through these ATPs were a mix of natural sounds i.e. existing recorded sounds and artificial sounds, including rhythmic and non-rhythmic sounds, bodily sounds (slow and fast), and instrumental sounds with increasing/decreasing pitch and intensity - (see description of the ATPs and sounds used in Supplementary Material #4, with an inventory of the technology probes and a folder of sounds samples).

**Workshop structure.** After being welcomed, participants engaged in warm-up activities aimed at familiarizing them with the provided prompts, encouraging exploration, and fostering group collaboration.

In Workshop 3, a **Somatic Dress-up** activity aimed to recreate the body sensations of the personas by exploring various sensory ideation probes [105]; activities involved "designing" and "wearing" the body, using available objects and prompts with different material qualities, so barriers could be physically manifested and experienced. Participants, divided into two groups, were assigned a scenario to work with (Leticia or Manuel in their associated context) (see scenarios in Supplementary Material #2). The process began with each participant selecting a



Fig. 3. Probes used in the Workshop 3 (Left), and probes in the Workshop 4 (Right).

particular sensation and using available objects and prompts to recreate and experience that sensation themselves. They were then guided to explore different body attachments, movements and movement qualities, and activities, refining their "somatic dress-up probe design" (i.e. the object(s) used to achieve the sought sensation). Everyone shared their design within each group, helping others experience it, and finally using their probe designs as inspiration (e.g. combining, mixing, discarding, etc. ), each group created a unified persona (Figure 4). Participants engaged in somatic enactment of their personas for approximately 25 minutes.

The dress-up phase consisted of full somatic dress-up in Workshop 3 and an abbreviated version in Workshop 4 ( starting with a participant from each group using the unified persona **somatic dress up** resulting from the previous workshop). Next, both workshops featured a **sensory bodystorming** activity[105] lasting approximately 40 minutes aimed at developing **awareness of the persona's body sensations** (e.g. feelings of tension or pressure) and exploring how to **transition from being passive to active**, by employing the probes. Participants used prompt cards (see quality cards in Supplementary Material #3) as in the previous phase to assist the "dressed-up" volunteer to explore different body locations, tactile/haptic/auditory sensations, and movements, and movement qualities, maintaining constant close connection with the persona they were "dressed up as". Ideas were tested iteratively as a group, with prompts refined based on feedback from the "dressed up" volunteer and fine tuning by the group. After bodystorming, participants used body maps [102] to represent effective sensations that worked well and associated artifacts that would elicit those sensations (see Body Maps in Supplementary Material #5, with a folder that contains the Body Maps for the scenarios of Leticia and Manuel from Workshops 3 (haptics) and 4 (sound)).

### 3.3 Testing Sensory Signals

In the final, fifth workshop, held during a science dissemination event, open to the general public at University Carlos III de Madrid, we experienced and refined sensory patterns for activation that originated from Workshops 3 and 4. 13 attendees participated, 11 categorized as physically active and 2 as physically inactive based on their responses to the IPAQ questionnaire. The workshop aimed to explore, iterate and concretize the sensory patterns for activation that emerged from Workshops 3 and 4, and better understand their potential. We divided participants into 4 groups, each focused on exploring a subset of either auditory or haptic patterns, generated using sensory probes from prior workshops alongwith a set of other sensory probes for introducing variations in these patterns. One of the authors facilitated explorations in each group, introducing participants to sensory signals, explaining what worked for physically inactive participants in previous workshops, giving prompts



Fig. 4. Enactment of the persona (P-Leticia: left and center; P-Manuel, right) through "somatic dress-up." Participants grouped together to "dress-up" one of their peers as the chosen persona, for which they used their individually explorations and "somatic dress-up probe design."

(using prompt cards from Workshops 3 and 4) to help participants explore what worked well for them - including prompting tweaks and iterations using different interactive patterns and body locations. Other researchers noted down the explorations and comments from participants, which became our main data source from this workshop.

### 3.4 Data Analysis

To uncover barriers experienced by physically inactive participants and how they felt (Workshop 2), we analyzed the video data [34]. We started by transcribing video data to text (e.g. conversations and main actions), focusing analysis on identifying commonalities among participants. We extracted initial sensory patterns from participant-filled body maps and also did a video analysis [34] of data from Workshops 3 and 4. This analysis served to complement and explain where patterns emerged from and why they worked. In Workshop 5, researchers' written notes served as the primary data source, guiding the analysis of how participants appropriated and adapted each pattern.

## 4 RESULTS ON UNDERSTANDING HOW BARRIERS ARE SOMATICALLY EXPERIENCED

### 4.1 Sensations and Emotions Felt When Experiencing the Barrier in Everyday Contexts

Participants individually identified the barrier most affecting their PA engagement, sharing real-life situations that illustrated how they experienced it and its impact. We highlight barriers and key takeaways below and offer empirical examples of how they manifest in daily life.

**Work/studies:** Three participants (P1, P2, P9) identified the contextual barrier 'work/studies' as their main barrier to PA engagement. They faced this barrier during everyday study routines when they were *actively engaged* (P1, P2) or *particular intense periods* like exams (P7) and deadlines (P2). These situations were often triggers to experiencing the barrier, alongside others such as the fear of failing a course, or feeling like they have not studied enough, if they decided to stop working or studying to engage in PA. For them (P1, P2, P9), the *physical setting* was central to experiencing the barrier: the office, library or university building, often settings where everyone is engaged in similar work or study activities. As P9 put it: "it is not the right atmosphere". Participants reported that when they experienced this barrier, they felt stressed (P2, P9), anxious (P2), and overwhelmed (P1). Some felt sad (P1) for not engaging more in PA, and they experienced feelings of insecurity and not being able to do things that they wanted (P1, P9).

**Routine:** Two participants (P3, P4) chose the psychological barrier of "routine" as their main barrier to engage in PA. Both of them experienced this barrier in their *everyday routines*, such as chores, or spending time with family and friends. P4 reported that they often filled up their week with things that needed to be done each day *leaving little or no time* for PA. P3 reported experiencing challenges in overcoming the everyday routine of commuting by car. At home they would be unlikely to engage in PA, favoring leisure activities, e.g. reading or watching TV. P3 further said that they routinely told themselves that there would be time later in the week to engage in PA (e.g. "it is still Monday" or "I'll do it tomorrow") – and hence effectively *postponing* doing PA. Both participants felt stressed when experiencing this barrier. P4 added that they often felt overwhelmed with their routines and P3 that they felt defeated, as if their routine had "won the battle against [them]".

**Planification, Intentions, Goals, Compromise, Willpower:** Two participants (P6, P8) chose "planification" as their main barrier to PA. P8 experienced this barrier *all the time*, morning or evening, summer or winter. P6 felt it especially in the moments when they were supposed to engage in PA. Both participants reported often putting off PA so they could stay at home, in bed or on the sofa, doing activities such as checking their phone or TV. P8 reported feeling the barrier more when alone, rather than when with others. P8 reported a lack of willpower and feeling lazy when experiencing this barrier.

**Stress:** One participant (P5) chose "stress" as their main barrier to PA. Their stress was triggered by factors of *everyday life*, such as work, home chores, or church duties. They always felt busy, even during holidays, and

that they had no time to engage in PA. On occasions when they had some free time, P5 admitted that they often preferred sedentary activities, such as checking their phone, internet, or TV, and that often their friends would propose plans that are more appealing than engaging in PA. P5 felt a myriad of negative feelings when experiencing this barrier, such as sadness, feeling small, feeling lack of control, feeling fat and insecure, and feeling that they did not know what to do.

**Priorization:** Finally, one participant (P7) chose “prioritization” as their main barrier to engage in PA. They recalled a situation they experienced in the last year of high school, where they had a personal trainer, but they often cancelled as they had a lot of exams. When they were experiencing the barrier, they felt tired, stressed with exams, and lazy.

## 4.2 Scenarios

We built scenarios around an everyday life situation of each of the fictional characters, Leticia and Manuel, as described in section 3.2.1. As in [66], scenarios were based on the barriers and sensations experienced by the participants; they were used for elicitation and to help participants imagine themselves in particular situations, rather than asking them to respond to a specific one that identifies or potentially embarrasses them. The persona Leticia is a 29-year-old professional who, due to her computer-based and sedentary work, has gained weight and does not find the time to exercise. Her sister teases her because of her weight, which stresses Leticia out, making her feel self-conscious. The persona Manuel is a 20-year-old undergraduate student overwhelmed by house chores, and his house-mate’s lack of care. This makes him feel exhausted and tired to engage in any PA. See Supplementary Material for more details #2.

## 5 RESULTS ON SENSORY PATTERNS (HAPTIC AND AUDIO) FOR ACTIVATION

Workshop analysis identified sensory inputs that participants found effective for activation. These inputs were further examined in a workshop with the general population, adding depth to their understanding and substantiating their impact on activation. Combining insights from both inquiries resulted in a collection of nuanced sensory patterns for activation, which are presented next. (note that in the Supplementary Material #6 it is possible to see and hear the audio patterns). To better ground and contextualize our results, we connect the patterns to works in our literature review (section 2).

### 5.1 Audio

*5.1.1 Pattern 1: A metallic sound that is produced by the rubbing of two metallic objects, located near the body. The sound is continuous (no specific attack and release), with a subtle periodic continuous change in frequency and volume, with the volume quite low. (Table 1).*

**Workshop P.Inactive:** Participants used this sound, playing in front of the person experiencing Leticia’s sensations (henceforth referred as P-Leticia). The sound produced by the rubbing of the two objects was constant, with nuances in timbre variation. Participants played it in front of their head, far from the body. These sounds activated P-Leticia.

**Workshop General Population:** One participant (P6) tried variations with different metallic objects. He placed a metallic straw inside of a metallic hexagonal cookie mold and rotated it to produce a sound that he described as “motors producing friction” (as if it had gears). He tried this on P7, behind and around her head, moving it from left to right. P7 responded to this sound with spasms across her whole body. She said the sound made her move, and it needed to have a rhythmic regularity and move from down to up. P6 tried this variation on himself and said that it worked better than the triangle in making him move, and that the sound needed to be behind, with a bit of distance and moving sideways.

Table 1. Summary of the auditory patterns identified and their effect on participants to guide future studies on stimulus design.

Pattern	Main characteristic	Pitch or Freq. range	Time evolution	Volume evolution	Body place	Potential effect	Methaphors evoked
1	Metallic sound	High	Continuous	Subtle changes	Near the body	To elicit physical activation	Rewarding sound in a game
2	Metallic sound	High	Continuous with speed variations	Crescendo-diminuendo	Continuous movement around the head	Sensations of surprise and curiosity	Rewarding sound in a game
3	Metallic sound, rattle-like	High	Continuous	Constant	Foot position	Enhance body awareness and movement experiences	Associations with confinement or imprisonment.
4	Percussive sound	Mid-low	Steady rhythm pattern	Constant	Chest level or near the ear	Sensations of activation, security and confidence	Being pushed or pulled, curiosity, dancing

**Relation and Contribution to Prior Work:** Prior work [50, 89] explored the use of a sound with a mechanical metaphor in the context of home exercises among physically inactive participants. This mechanical sound was described as discrete, resembling rusty gears and played continuously as the angle of movement increased/decreased. The sound helped coordination, movement fluidity and pacing. These effects differed for active participants in [50] who reported feeling their movements were less fluid and stiffer with this sound. Our workshop with the general population yielded similar findings regarding the associations of the gears sound. Here, we contributed to expanding on this concept by suggesting that the use of a continuous metallic sound produced by the rubbing of two metallic objects could activate physically inactive individuals. Similarly to the previous mechanical sound, the effect is likely due to participants associating this sound with a related action metaphor, which can elicit movements [47], but in which effects can vary across individual contexts.

*5.1.2 Pattern 2: A soft sound moving around the head, which is metallic, high pitched, bright, enveloping, clean, in-crescendo, with nuances in volume and speed, (Table 1).*

**Workshop P.Inactive:** Participants used a musical metallic triangle to activate the person experiencing Manuel's sensations (henceforth referred to as P-Manuel). They played the triangle around P-Manuel's head, increasing its volume and speed. They kept playing it for a while, in a continuous manner, and P-Manuel reflected that such a sound made them want to get activated. In one iteration, metal windchime sounds played in a similar manner (around the head) were more effective for activation, particularly to prompt standing up as the nuanced metallic quality evoked surprise and curiosity in the participant, especially P-Manuel. In other iterations, the metallic sound was found to be more effective for activation compared to other material qualities like wood.

**Workshop General Population:** Two participants (P6, P7) explored playing a metallic sound around the head by using a metallic percussion triangle. When P7 tried it on P6, he reported that when the sound was behind his head, it did not activate him but relaxed him. However, when the sound was in front of his head, it made him alert, as he associated the sound to that of water drops, and reported being repelled by the sound. P6 and P7 tried different variations: P6 played the triangle rhythmically at P7's foot level, and he then moved the object

slowly upwards, towards chest or head level, to then slowly separate the sound from the body. P7 reflected this made her feel safe and trust the sound, encouraging her to follow it - and hence prompting her to stand up. P6 said this variation also worked for him, but in a different way: when the sound was at his foot level, it made him alert, and when the sound separated from the body, it felt transparent and shiny, as if there were “diamonds” or precious rewards that he wanted to catch (as in videogames). Similarly, two participants (P10 and P11) explored the potential of the windchimes, trying to move it closer and further away from the body. P10 felt an urge to move, and said that the sound evoked a sense of curiosity if the sound came from farther away, but if the sound was too close it overwhelmed him. P11 closed his eyes and the sound evoked a feeling of tugging, especially if the windchimes were far away. In general, participants felt a sense of pulling if the sound of windchimes were close, and there was a feeling of being held by strings.

**Relation and Contribution to Prior Work:** Prior work [80] also explored the sound of the windchimes when using a wearable sonification device to support everyday activity for people with chronic pain. The windchimes sound played when people moved the trunk forward, which encouraged them to persist in their movement, and focused their attention on the sound, away from the pain. This finding supports our approach/pattern of initiating sustaining movement through the use of wind chimes, and more generally metallic sounds, evoking sensations of surprise and curiosity in physically inactive people, while the participants noted that these sensations were enhanced as the windchimes moved farther away from the person. Our work not only underscores the significance of this method but also extends its applicability to a broader context, highlighting the potential of metallic sounds, and their related metaphorical associations, to initiate movement in PA.

*5.1.3 Pattern 3: Rattle-like sounds, cluster of metallic sounds, with no clear overall pitch, located at the foot position and which are activated by the foot moving up and down. The sound recalls rattle instruments used in traditional dance, (Table 1).*

**Workshop P.Inactive:** Initially, participants played rattles around P-Manuel’s ankles, a sound of P-Manuel liked: *“I like something that is metallic”*. Participants attached the rattles to P-Manuel’s ankle, so the sound was produced by the movement of P-Manuel’s foot and leg going up and down as P-Manuel said this would make them feel activated, and *“when I [P-Manuel] control the ankle it is more interesting”*.

**Workshop General Population:** Two participants (P6, P7) explored wearing rattles on the ankle. For them, wearing the object did not elicit feelings of wanting to move. P7 associated the rattles to rituals in which other people wear and use them similarly. For P6, it elicited feelings of heaviness as he associated it to sounds produced by chains in jail. Due to time constraints, they did not try variations of this sound.

**Relation and Contribution to Prior Work:** In [85], sound feedback enhanced the experience of a professional speed-skater by sonifying foot movements. The sonification not only created a sense of increased speed but also facilitated the development of better technique through a continuous and rich flow of information. These findings are consistent with a previous study using a discrete sound resembling mechanical rusty gears, played continuously during body movement and gradually changing in frequency and speed [50]. In that study, physically inactive participants reported experiencing sensations of heaviness and movement control, attributed to metaphorical associations evoked by the sound, reminiscent of machinery, chains, and heavy objects. These sensations were associated with strength and seen to support PA. Our findings corroborate previous works included in our literature review that focus on providing sound feedback for specific body areas, such as the lower limbs, legs, ankles, or feet, to enhance body awareness and movement experiences [50, 85]. Thus, our findings contribute to the understanding of how sound influences movement and participant engagement, emphasizing the significance of specific sound patterns, their associations, and the control participants have over them.

*5.1.4 Pattern 4: Percussive mid-low-pitch sound, with no resonance, played at a steady rhythm and following a specific pattern, located at chest level or near the ear, (Table 1).*

**Workshop P.Inactive:** Participants used a cardboard box and a wooden cylinder as drums, employing drumsticks to play them, maintaining a steady rhythm and intensity, resulting in a combination of low pitch and high pitch sounds (see figure in "Sound patterns" in Supplementary Material). They played this makeshift wooden drum at chest level and upper back, with better results in front of the chest for P-Manuel. For P-Leticia, they tried playing the box around the left ear. The sounds evoked a sense of activation in both P-Leticia and P-Manuel. P-Leticia reflected this was because it evoked a sense of security and confidence within her chest.

**Workshop General Population:** Three participants (P8, P9, P12) explored playing the cardboard box with drumsticks around the body. P8 experimented with the box on his head, in a lying position, and said that the sound there evoked a sense of curiosity. P9 tried out the same position as P8, and reported feeling as if the sound source was pushing him. When P12 tried it, he said that the sound prompted a desire to dance, and that he felt his heart rate increase. Yet, he felt his heart rate decrease if the volume of the drum was lower. While playing a small drum, P9 experienced a feeling of going "*faster*" or "*pulling*", especially in the legs or chest. Additionally, two other participants (P13 and P14) who used a small drum and a drumstick reported experiencing a sensation of pressure originating from the upper back and pushing their chests forward. They generated a fast, constant rhythm by alternating low and high-pitched sounds through kicking on two distinct sections of the drum: the top skin and the outer wooden part. On a large drum, P5 reported having a sensation of "*an impulse to move*" mostly by putting the drum behind the head, with the intensity of moving proportional to the volume of the drum sound.

**Relation and Contribution to Prior Work:** These sound characteristics resemble those employed for movement sonification in a study [64]. [64] aimed to enhance the perception of movement by manipulating the musical harmony upon reaching the target point of the movement. They explored the effect of unstable and stable musical structures, where unstable sounds created a sensation of ongoing movement, while stable sounds conveyed a sense of conclusion. The constant rhythm with a distinct tone at the end aligns with the characteristic of stable sounds. The research work [64] emphasizes that sounds with a stable ending foster a feeling of stability, encouraging to keep moving. Here we contributed to expanding our understanding of how in the case of physically inactive individuals, this particular sound quality evokes a sense of security or confidence within the chest. While [64] highlighted the effects of stable and unstable musical structures, we focused on the constant rhythm of a distinct tone, aligning with characteristics of stable sounds. Our contribution lies in uncovering the potential of steady, percussive sounds to evoke sensations of activation, curiosity, pushing, dancing, and an increased heart rate among participants.

## 5.2 Haptics

**5.2.1 Pattern 1:** *Slow, but gentle and decisive punctual stimuli that start grouped together at the top of the head and then split into multiple flexible prongs and run down the scalp from the crown towards the ears and neck then back up again (akin to a scalp massager). (Figure 5.)*

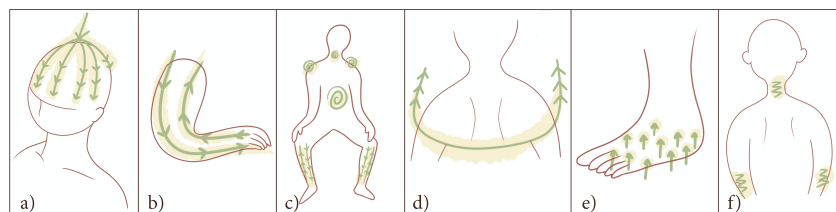


Fig. 5. Visual depiction of the six haptic patterns that emerged.



**Workshop P.Inactive:** Participants used a scalp massager tool on P-Manuel, moving it up and down their scalp in a continuous manner. P-Manuel liked the sensation as it relaxed them when it was going down, and at the same time made them feel the need to rise up.

**Workshop General Population:** Two participants (P2, P3) explored this pattern. When one was sitting down, the other repeatedly performed on him a smooth and continuous movement up and down the head with a head massager tool, then they switched places. P3 reflected that this haptic experience helped him stand up, especially when the massager was going up, given that he could feel the pull upwards. However, P2 said that for him this was a sensory input that would *accompany* the movement of standing from the chair, but it would not work as a trigger alone. They also tried the same haptic input on the knee. This time, P3 felt no effect in terms of being pulled to stand up. P2 however felt that in the outwards part of the movement of the object on the knee he could feel the pulling, and that again it would work for him as accompaniment to his standing up. He emphasized though that only the pulling would work, because it felt like something "detaching from the body" (P2).

**Relation and Contribution to Prior Work:** Prior works in our literature review reinforce the validity of this pattern [41, 83, 84, 90], for instance, [83, 84] discusses the utilization of pull and push metaphors in vibration feedback and multimodal feedback. Additionally, [90] explored the effectiveness of a waistband with the pull metaphor through vibration feedback, which assisted participants in upward movements. They described experiencing an inner drive to move, which facilitated their movements. Our contribution extends this research by exploring the application of haptic feedback, specifically the scalp massager tool, to evoke sensations of relaxation and upward pull, offering new insights into how haptic stimuli can influence movement and motivation.

5.2.2 *Pattern 2: A gentle, flexible, and light sensation moving up and down different body parts. (Figure 5.b).*

**Workshop P.Inactive:** Participants used a duster of artificial feathers on P-Manuel, moving it up and down on their arm, first in quick and short strokes, then in slow, delicate strokes that tickled P-Manuel. The latter evoked a sense of activation in P-Manuel, who experienced it as a gentle, flexible, light, and breezy, feather-like caress up and down the arms from wrist to shoulders, which felt cool on the skin and produced tingling.

**Workshop General Population:** Two participants (P1, P4), using a duster, decided to experiment with a similar sensation, now up and down from the nape to the back. Taking turns, one participant helped the other in experiencing the gentle and slow movement of the duster from between the shoulder blades to the top of the head. Both participants agreed that this sensation served as a trigger to initiate standing up, and it also accompanied their movements when transitioning to a standing up position. These movement dynamics (gentle, upwards movements) prompted experimentation with other objects: P1 and P4 tried it with a plastic scratcher, this time on the frontal part of the torso, extending from the belly button to the Adam's apple. Both participants expressed that this technique helped trigger their standing up movement. Additionally, they replicated the same movement dynamics using the scratcher on their calves, slowly moving from the ankle to the knee. In both instances, both P1 and P4 agreed that it compelled them to stand up. Lastly, two other participants (P2-P3) experimented with the same movement using another scratcher, moving it upwards from the lower back to the nape. P2 found that this sensation served as a supportive accompaniment to his standing up movement but did not function as a standalone trigger. In contrast, P3 stated that it effectively served as a trigger for him to stand up. Both participants agreed that the sensation worked best, whether as an accompaniment or trigger, when the scratcher's trajectory was longest along the back and when the movements were performed slowly.

**Relation and Contribution to Prior Work:** Prior work in our literature review [90] explored how to support PA and proposed travelling vibrations to evoke sensations of being pulled up and down. Both Patterns 1 and 2 in our study build on the concept of travelling tactile stimuli to initiate or accompany movement. Through Pattern 2, we contribute by extending prior work through incorporating light touch feedback as an alternative to vibration, serving as a trigger to encourage standing up. Additionally, Pattern 2 encouraged exploration of new body areas (e.g. a spatula on the head), and experimenting with e.g. sitting on the floor instead of a chair.

5.2.3 *Pattern 3: Continuous ice-cold temperature sensations applied to the body statically (e.g. belly or arms, shoulders and neck) and/or dynamically (e.g. up and down the shin of the legs). (Figure 5.c).* .

**Workshop P.Inactive:** Participants used cold bags on both P-Manuel and P-Leticia: small off-the-shelf manually activated sports patches, used to treat muscle fatigue or lesions, on P-Manuel's neck and arms. Both these locations were found by P-Manuel to trigger activation. In P-Leticia's case, they placed them on their hand, on the low back and their lower extremities (feet, calves, legs), leading to a sense of activation when cold stimuli were applied to the lower extremities and moved up and down. The same level of activation was not observed when the cold stimuli were applied to the hands or lower back.

**Workshop General Population:** Two participants (P1, P4) tried the cold bags on various parts of their bodies while seated. They applied cold touches to the outer parts of their arms, providing small touches starting from the elbow and moving upwards. Both participants reported that this approach effectively facilitated standing up. Additionally, P1 and P4 applied the cold bags on the region expanding from the abdomen to the chest. They tried both applying discrete cold touches and dragging the cold bag up to the chest. While both methods were found to be useful for standing up, the effect was less pronounced with discrete touches, and both methods were less effective compared to the cold bags on the arms. Subsequently, P2 and P3 were introduced to this concept. P2 and P3 decided to explore the use of cold bags on their shins, which proved to be effective as a trigger for standing up.

**Relation and Contribution to Prior Work:** Prior work explored the use of heat and cold as design material. For instance, [40] explored how hot and cold stimuli could enhance body awareness in different exercises by directing attention to various body parts (e.g. arm, leg, or along the spine) as part of a body awareness exercise. The findings indicated that hot stimuli were more effective in guiding body attention and aligning with positive experiences. The cold stimuli captured brought complete attention to the specific body part, but did not align with the goals of the body awareness exercises. In contrast, our contribution lies in the practical and potential application of cold stimuli, which serve as triggers for the standing-up movement and help in identifying the body part that can trigger activation.

5.2.4 *Pattern 4: A slow and progressive elastic force around the back (scapula) and arms (back and side) that pulls you upwards and forward. (Figure 5.d).* .

**Workshop P.Inactive:** Participants placed a rope made of elastic fabric around P-Manuel's shoulders and gently pulled it. This action created a gradual and progressive sensation of being lifted up from the seated position. P-Manuel reported feeling as though they were being pulled from the back and upwards, which facilitated their ability to stand up from the chair.

**Workshop General Population:** Two participants (P2, P3) experimented with the elastic band: one passing it through the other's armpits while seated. This created a sort of harness for the standing participant. Both participants expressed that the sensation of being pulled to stand up served as an *accompanying* sensory input to their standing movement, but they noted that it was not as effective as a trigger to initiate the standing motion.

**Relation and Contribution to Prior Work:** In our literature review, various works explored the use of pressure in specific body functions, for instance, [41] explored the use of shape-shifting interactive materials to support deep pressure therapy on and around the torso to promote breathing awareness. They used "pillows" or "pneumatic pads" that could be inflated and deflated on the shoulder, lower back, and neck. The study examined pressure feedback in symmetrical and asymmetrical modes, both in synchronous and asynchronous patterns. While this previous work focused on pressure and its effects, our contribution was in expanding upon it by incorporating the concept of symmetrical back pressure applied to the back muscles. This proved beneficial in triggering and accompanying participants' standing up movement, particularly for physically inactive individuals.

5.2.5 *Pattern 5: Alternating direct and sudden pricking sensations at different points on the sole of the feet (Figure 5.e).*

**Workshop P.Inactive:** Participants grabbed a massage bar equipped with rolling balls with spike-like protuberances, often used as equipment to relax. They placed them below P-Manuel's feet, so their soles were in contact with the spikes, and made the bar roll slowly. P-Manuel mentioned that the sensation of the pricking points on their soles evoked a sense of activation, and fostered the need to rise up.

**Workshop General Population:** Two participants (P2, P3) explored the perception of tiny spikes on their feet using a massage roller with spiked protrusions. Stepping with their bare feet on the roller, and gently rolling it back and forth, both expressed that the sensation of spikes on their feet could prompt them to stand up. However, they reported discomfort due to a tickling sensation, leading them to stand up and discontinue the experience: "*it is not good, I do not want to have it, which makes me want to leave*".

**Relation and Contribution to Prior Work:** The use of spike-like protuberances as a form of texture to support body awareness and control has not been explored in the literature we reviewed [105]. However, there have been some investigations into the use of other tactile textures. For instance, [105] employed the use of a bean bag and a bag of marbles to support body awareness and body control in yoga, as the bags would ground the person in various poses. The bean bag was preferred for its adaptability to the shape of the foot and its stable composite, making it suitable for poses requiring a firm stance. This contribution extends the current understanding of the effects of tactile sensations in movement initiation. Our contribution shows the potential of tactile sensations, even those that may induce discomfort, as triggers for movement and activation. It offers insights by highlighting how spikes on the soles of the feet can trigger physically inactive and active people to stand up and engage in physical activities, enhancing our understanding of how tactile feedback can influence them in the context of PA.

5.2.6 *Pattern 6: Intermittent short buzzes of vibration that are applied to both the neck and various "bony" areas of the joints. There are two options: 1) vibrations applied simultaneously to different body areas (aka synchronously); and 2) faster vibrations interweaving with one another. (Figure 5.f).* .

**Workshop P.Inactive:** Participants used an off-the-shelf massage tool and a vibrating ball to administer vibrational stimulation on specific areas of P-Leticia's body that were "bony" (that is, that only a thin layer of skin covered the bones, such as the nape, elbow, or knees). The massage tool and vibrating ball (which vibrate continuously) were applied in short, repetitive touches, effectively giving P-Leticia the feeling of vibration buzzes. First, the participants administered the vibration buzzes simultaneously across different areas and subsequently alternated between them. The proximity of the vibration to the bone resulted in P-Leticia being able to feel them intensely. In both cases, P-Leticia reported feeling activated by the vibrations.

**Workshop General Population:** Two participants (P1 and P4) engaged in an exploration using the two vibrating objects to generate upwards movements on different parts of the body while seated. They applied the objects on each side of the torso, from the hips to the armpits, as well as on the the back, from the middle back up to the nape, with one object placed on each side of the spine. They further experimented with various interactive patterns: 1) *continuous and synchronous*, in which both objects vibrated and were simultaneously moved upwards along the torso; 2) *intermittent and synchronous*, in which both objects vibrated and were placed on the body, then removed, in short touches progressing up the torso simultaneously; and 3) *continuous and asynchronous*, in which the vibrating objects were placed on the body and then removed, in short touches progressing upwards but in an asynchronous way (that is, when the left object was in contact, the right one was not, and vice-versa). Both participants reported that all versions effectively triggered their desire to move, but in particular those stimuli on the back. P2 and P3 who also tried these patterns, agreed that these types of sensory input effectively triggered movement. However, P1 and P2 preferred the intermittent/asynchronous version, while P4 and P3 preferred the intermittent/synchronous version.

**Relation and Contribution to Prior Work:** Our literature review showed that vibration feedback has been used to facilitate coordination [37], guide movements, or correct posture [5, 83, 84]. For instance, to facilitate

multi-limb coordination, particularly in coordinating wrist and ankle movements in different drum beat patterns [37]. Additionally, in [5], vibration was used to assist in correcting wrong posture during physical activities; they present a set of full-body vibrotactile patterns for both lower and upper body postures. However, it is crucial to be cautious when considering the placement of haptic feedback [23, 41]. As exemplified in [41], the use of deep pressure feedback with asymmetrical pressure applied to the neck resulted in negative experiences among participants, evoking sensations akin to "having a snake wrapped around my throat". This cautionary insight prompts us to reconsider the application of asymmetrical vibration feedback specifically on the neck and instead explore alternative body parts. Notably, our contribution focuses on the specific application of vibration to bony areas and explores various vibration patterns and their impact on movement initiation and activation. It seems that intermittent, short-vibration buzzes administered simultaneously or alternately to different body parts hold promise in prompting individuals to rise and be more active. This novel exploration offers valuable insights into the potential of vibration stimuli as triggers for movement and engagement, enhancing our understanding of the sensory-motor mechanisms behind.

## 6 DISCUSSION

### 6.1 Design Inspirations and Directions

Through our explorations, we identified 10 sensory patterns (four auditory and six haptic) perceived as facilitating PA. Emerging from two workshops that explored sensory stimuli and are supported by relevant prior works, these patterns offer initial insights and starting points for further investigation. Initially identified by physically inactive participants in Workshops 3 and 4 and refined and concretized by general population in Workshop 5, these patterns show promise in activating and engaging individuals in PA. We present them as valuable design inspirations for future sensory technology design. Next, we discuss overarching characteristics and design directions pertaining to auditory and haptic sensory stimuli in transitioning from inactivity to PA. These insights, summarized in Table 2, stem from our analysis of the presented patterns.

#### 6.1.1 Design Inspirations Based on Sound Patterns. .

**Use of metallic sounds.** During Workshop 4, our probes encompassed a range of materials; however, we note that three of the auditory patterns (1, 2, 3) that emerged incorporate "metallic" sounds, prompting a consideration for the potential of such sounds to facilitate PA. The sounds in each of those patterns have distinct characteristics and elicit different effects on individuals: Pattern 1 has slow periodic changes in timbre, created by rubbing two metallic objects together, characterized by continuous variations and non-harmonicity, triggering reactions like pulling away or even moving with spasms. Pattern 2 is a percussive sound, possibly resembling a musical tone or a bell, its rich harmonic content evoking surprise and curiosity. Pattern 3 comprises a cluster of metallic sounds, typically played rhythmically, reminiscent of instruments used in traditional dance.

**Sounds moving around the body.** Patterns 1 and 2 involve moving sounds positioned at a distance from the body, with the specific spatial pattern and evolution playing a significant role. In Pattern 2, the sound trajectory generated trust and confidence in the sound, which, in turn, motivated participants to follow it. Thus, pattern 2 serves as an **external focus of attention**, a strategy often employed in contexts where individuals engage in exercise [53, 70, 113] or physical rehabilitation, for instance to focus on sounds instead of pain [64, 80]. The sound trajectory also introduced a **sense of playfulness and discovery** for one of the two physically inactive participants in Workshop 5. This sense of playfulness is known as a catalyst of joy and facilitate PA [57, 58].

**Sonification of a body part.** Pattern 3 (rattle-like sounds created by the foot moving up and down), differently to other sound patterns, described a sound created and controlled by one's own movements. Movement sonification has been used to bring awareness to movement [82] and to encourage continuation or conclusion of it [64] but we show it can also trigger movement initiation and transitioning to activity. Pattern 3 aligns with and extends literature exploring sound feedback to support movement in specific body areas, such as lower limbs, feet, and

ankles **during** PA [49–51]. For instance, [51] used an ankle band to provide sound feedback (water and wind sounds) based on the angle and pressure of foot, for movements in exercises such as step-ups, walking, leg-lifts and thigh stretches. Results revealed that such sonification positively impacts perceptions of body strength and muscle-building **during** PA. Furthermore, sounds rising in pitch accompanying one’s foot movements [51] or arm [48] also facilitate feelings of speed and of “being pulled” by the sound easing movement [48, 49].

**Sounds with musical structures.** Musical structures can be leveraged to create sensations of movement stability (through structures with stable endings) or movement continuation (with unstable endings) [64]. For Pattern 4, we observed how the specific musical structure, featuring a distinct ending, elicited a sense of security or confidence within the chest, along with a sensation of being propelled by the sound in physically inactive participants in both workshops. Moreover, this musical structure is associated with perceived changes in heart rate induced by the sound. Sound characteristics such as periodicity, tempo, and rhythm have been shown to elicit physiological arousal [4], similar to sounds that increase in loudness inherently acting as warning signals [6]. Here we see how these characteristics have the potential to facilitate physical activation.

**6.1.2 Design Inspirations Based on Haptic Patterns. Multiple punctual stimuli moving up and down on the body:** Patterns 1 and 5 utilized punctual stimuli moving up and down the body, specifically on the head and feet of participants. This prompted participants to rise and stand up, acting as a trigger for some and as an accompaniment for others when transitioning from inactivity to activity. Previous research has identified vibrational patterns that generate sensations of being pulled or pushed by sound, facilitating movements similar to squats [90]. Our study introduces an alternative promising feedback approach in a similar direction. When designing such feedback for the feet, it is crucial to consider adaptability to the foot’s shape and stability, ensuring suitability for poses requiring a firm stance [105].

Table 2. Connections of the identified (4 auditory & 6 haptic) patterns with physically inactive participants and the Design considerations based on the potential to evoke feelings of activation, see extended version in Appendix C

Design Inspirations Audio (DI)	Audio Patterns (AP)				Design Inspirations Haptic (DI)	Haptic Patterns (HP)					
	AP1	AP2	AP3	AP4		HP1	HP2	HP3	HP4	HP5	HP6
DI1: Use of metallic sounds	X	X	X		DI5: Multiple punctual stimuli moving up and down on the body	X					X
DI2: Sounds moving around the body	X	X		X	DI6: Cold stimuli moving up and down on the body		X	X			
DI3: Sonification of a body part				X	DI7: Using force to move people					X	
DI4: Sounds with musical structure				X	DI8: Vibrotactile structures for stimuli distributed on the body		X				X

**Cold stimuli moving up and down on the body:** Within Pattern 2, a variant introduced stimuli inducing a cooling sensation on the skin, tested on the arms and nape of the neck. The stimuli moved up and down the body, generating a tingling sensation. Similarly, Pattern 3 applied cold patches on various body parts, including the neck, upper extremities, chest, back, and lower extremities. Similar to Pattern 2, effective activation sensations, particularly prompting standing up, occurred when the cold stimuli moved vertically on the chest or lower extremities. Previous research has explored the use of cold stimuli to draw attention to specific body parts [40]. Our study shows that cold stimuli, especially when moving vertically along the body, can activate participants for PA and trigger standing-up movements. Future research should investigate if cold stimuli are perceived as originating inside the body, similar to heat [40], and if such internal sensations are more instrumental to address barriers to PA related to body perception, as opposed to the external sensations created by touch or vibrations.

**Using force to move people:** Pattern 4 proposes applying force on participants using elastic strings to initiate movement, instead of focusing on eliciting body perceptions or sensations to prompt PA. While acknowledging this approach may be considered a last resort, as addressing psychological barriers related to body perception is key for sustainable behavior change [71, 72], implementing such feedback poses challenges in wearable technology integration. An alternative solution could involve employing soft robotics and shape-shifting materials, like pneumatic pads that inflate and deflate, to apply deep pressure on specific body areas [41].

**Vibrotactile structures for stimuli distributed on the body:** Vibrations are by far the most widely used haptic feedback within the context of PA according to the literature. They have been primarily used for guiding movement, aiding coordination, or correcting posture [5, 37, 83, 84]. Pattern 2 proposes a gentle touch that creates a path from the wrists to shoulders, or exploring with a scratcher on the calves moving from the ankle to the knee; while Pattern 6 proposes delivering vibrational feedback to various areas of the body, such as the nape, joints, and both sides of the spine, administering short buzzes intermittently to create various patterns (synchronous or asynchronous). This aligns with a recent study [94] which proposed using distributed vibrotactile stimuli on the body with specific haptic patterns to evoke different bodily sensations (e.g., feelings of heaviness or strength) through material associations. However, the effects of these stimuli on physical activation have not yet been tested. In our findings, we observed that short-vibration buzzes simultaneously or alternately applied to different body parts show promise in encouraging individuals to rise and become more active. Importantly, our review cautioned against placing haptic feedback on the neck, suggesting exploration of other body parts instead [41].

*6.1.3 Sound and haptic feedback with metaphorical associations.* We highlight that participants' reactions were not solely based on the low-level properties of sounds (e.g. pitch range, timbre and temporal structure) or haptic feedback (e.g. pressure, temperature) but also on the metaphors they evoked [15, 28, 39, 47, 48]. In particular, sounds could elicit movements based on the perceived actions producing them or trigger metaphorical associations. Specific examples included perceiving a high-pitched metallic sound as rewarding in a game and windchimes triggering memories or mental imagery. This may explain why some sounds led to different reactions among participants. Pattern 3 evoked feelings of heaviness, possibly due to associations with confinement or imprisonment. Previous research [50] shows that discrete mechanical sounds, such as those resembling rusty gears with gradual changes in frequency when played during movement, foster feelings of movement coordination and fluidity, and help individuals maintain pace, particularly those who are physically inactive. In contrast, windchimes induce feelings of relaxation and redirect the focus of attention away from the body towards an external source [80]. Previous works [50] also found that metallic sounds resembling mechanical gears can foster feelings of heaviness, similar to those reported in Workshop 5. This metaphorical heaviness, associated with heavy objects, in the context of physical activity (PA) may evoke feelings of strength. An example integrating auditory and haptic feedback is a study using pre-recorded sounds from a robotic arm as auditory and vibratory feedback during exertion, potentially leading to associations of being robotized and supporting repetitive movements. [46]. Finally, [94] suggested haptic patterns incorporating material metaphors (e.g. rocks) to induce sensations

to alter body perceptions, such as feelings of heaviness or strength. Our findings emphasize the importance of considering top-down effects of sounds and haptic stimuli with metaphoric associations, as they can evoke additional meanings that impact perception [73, 98].

*6.1.4 Technology roles.* One important aspect to consider in designing sensory signals for PA engagement is the role of the technology itself. Participants in our work viewed the sensory patterns as playing different roles. For example, in relation to the haptic signals, participants differentiated between sensory inputs that would *accompany* the standing up motion that a person does on their own; and a sensory input that would *trigger* the standing up motion, and in general participants preferred the triggering effect as a way to activate. Participants also described different effects that the auditory patterns had on them, such as creating curiosity or providing confidence. Thus, sensory technology for PA can have different roles, adding to related works which suggest particular roles, such as technology as a co-supervisor [82], empowering [57], increasing body and movement awareness [106], or altering body perception [50]. Future work on the identified patterns is needed to articulate what role they can play in prompting PA. Further, most prior work has focused on the process of supporting PA *during* moments of performing PA (e.g. [7, 65, 85]). In contrast, we focus here on the transitional moments *prior* to engaging with PA, moving from inactivity to activity. Other works have tapped on these transition moments through approaches to increase motivation of PA by facilitating movement (e.g. [50, 80, 90]). Our work contributes an alternative approach focused on sensory feedback to change body perceptions.

*6.1.5 Implications for Wearable and Ubiquitous computing.* This paper contributes to the wearable and ubiquitous community by addressing the potential and constraints of auditory and haptic feedback approaches, as in [16, 19], where the focus is on understanding user needs, such as perceptions of healthiness, to generate personalized music. This emphasis on user needs aligns with our research on integrating audio to transform body perceptions and emotional well-being in a health context. Our paper is a valuable resource for ubiquitous community members, for exploring alternative sensory modalities to enhance PA. The paper discusses research and development in the field [23], focusing on patterns and design considerations, like exploring haptic and audio elements for wearables. Examples shared offer practical insights for future research [69] and innovation in multisensory feedback design [23], addressing changes in body perception and emotional wellbeing through ubiquitous devices.

## 6.2 Methodological Reflections, Limitations and Future Work

In this paper, we made an explicit effort to report the methods followed aiming to assist other researchers interested in designing to address barriers to PA and to support awareness and activation. We found the methods particularly useful to make barriers accessible and actionable for participants and researchers and helping to move discussion from an intellectual and intangible plane, to a more visceral, and tangible one; further, we could explore, engage, and smoothly switch between first-, second- (social), and third- (such as observations from the outside, e.g. researchers; and interaction with objects) person perspectives. Particularly noteworthy was the somatic dress-up activity, in which physical ideation probes were used to sensitize and explore particular sensations felt by another person (a physically inactive persona), to create "somatic dress-up probe designs," i.e. proposals of how certain feelings and sensations of the target persona would translate to one's body. These were collectively explored and served to inspire and bring to life the personas that two of our participants enacted, dressing up with the iterated somatic dress-up probes. Our observations showed that while the resulting dress-up of the two personas were likely an exaggeration of what "the real" Leticia and Manuel would be and feel, they helped participants explore these sensations and target them sensorially. They helped barriers to become tangible and separate entities from the self, while still being embodied, allowing for addressing them through individuals' own experience, while still acting collectively and creatively. Consequently, it allowed exploring the design space for sensory wearables to promote PA in a more accessible way.

However, others need to try our approach and in more contexts. For this, we contribute both the Barrier cards and the scenarios (Supplementary Material), as well as the somatic dress-up activity.

Our work has several limitations. First, our limited sample size needs to be expanded in future work. This will help validate and/or refine the sensory patterns. Similarly, our methods (in particular the somatic dress up) need to be applied in other projects and contexts to better understand their potency. The sensory patterns were elicited by physically inactive people and iterated by participants from the general population. However, further testing with physically inactive participants is essential, and we are developing prototypes for this purpose. Our results should be taken as tentative until future work has engaged both with the patterns and the population. Additionally, exploring contextual factors and moments that foster or hinder PA is crucial [69]. Notably, our work yielded more haptic sensory patterns than auditory ones, similarly to prior work on co-designing sensory feedback [90]. This discrepancy may arise from participants' comfort with ideating using haptic rather than auditory signals due to a lack of auditory technical expertise. Finally, our literature review was restricted to ACM as the major venue for computing publishing [2], potentially missing other relevant works connecting to our sensory patterns. We did not aim for a full-fledged literature review of sensory technologies for PA, but rather as grounding for our empirics - which our ACM search yielded. We acknowledge the need for future systematic reviews to thoroughly cover the design space of sensory technologies for PA. Lastly, a more extensive literature search is needed to map out the space, engaging other databases.

### 6.3 Novelty and Contributions

Our work presents several contributions. First, we provide novel insights into how physically inactive people somatically experience barriers to PA (i.e. body sensations felt and impact on their everyday life). This extends empirical prior work investigating barriers to PA from a theoretical standpoint [71, 72]. Further, we contribute a novel set of Barrier cards for PA, a tangible tool for identifying and discussing barriers to PA that others can use in their own research and design processes. We demonstrate the use of the cards with physically inactive participants. We also contribute a set of sensory patterns, integrating auditory and haptic signals, and design inspirations that can guide the design of future wearable and ubiquitous technologies to trigger PA activation. We connect these patterns and inspirations to prior work, explaining how they align, extend or challenge it, in the results and the first subsection of the discussion. Together, they contribute to prior work on sensory stimuli for PA (e.g. [7, 8, 25, 26, 37, 41, 57, 58, 83, 84, 90, 99, 105, 112, 112]).

Methodologically, we contribute a novel approach to technology design for PA involving acting on body perceptions and sensations related to barriers to PA engagement and adherence, through novel embodied design activities (e.g. somatic dress-up) contributing to embodied design methods and approaches (e.g. [62, 63, 105, 110]).

More broadly, our work contributes to prior HCI work to foster PA (e.g. [18, 21, 45, 61, 108, 115]) with two distinctive foci from prior work: 1) a focus on using sensory feedback to act on body perceptions as a way to address barriers to engagement in PA, instead of e.g. personal informatics [24, 30, 33, 67]; and 2) a focus on supporting the transition phase of moving from being inactive to active - instead of focusing on supporting people already engaged in PA (e.g. [50, 57]).

## 7 CONCLUSION

This study explores an innovative approach to designing technologies for PA by leveraging multisensory feedback to address barriers related to body perceptions, such as tiredness and heaviness. To our knowledge, no study before this has explored the potential of sensory feedback to affect body sensations to trigger and foster such types of engagement with PA, thus opening the design space for future wearable sensory technologies. We contribute insights on how barriers to PA are experienced, and inspire sensory patterns to foster feelings of activation and to support PA engagement. We argue that our research and findings are significant for the design of



ubiquitous technology to support PA among people who struggle to engage in PA in everyday contexts. Current interventions often overlook critical variables, limiting efficacy. Our novel approach focuses on body perceptions and sensations, aiming to transform barriers and initiate PA engagement. These insights may guide multisensory wearable technology design for PA. Our work also introduces methodological innovations, like tangible Barrier cards and the Somatic Dress-Up approach, to empower designers in addressing barriers somatically.

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## B FIGURE OF PARTICIPANTS USING THE BARRIER CARDS



Barriers cards and participants identifying which one is related to them.

## C TABLE 2 EXTENDED

Design Inspirations Audio (DI)	Audio Patterns (AP)				Design Inspirations Haptic (DI)	Haptic Patterns (HP)					
	AP1: A metallic sound that is produced by the rubbing of two metallic objects and that is located near the body.	AP2: A soft sound moving around the head, which is metallic, high pitch, bright, enveloping, clean, in-crescendo, with nuances in volume and speed.	AP3: Rattle-like sounds, cluster of metallic sounds, located at the foot position and which are activated by the foot moving up and down.	AP4: Percussive mid-low-pitch sound, with no resonance, played at a steady rhythm and following a specific pattern, located at chest level or near the ear.		HP1: A punctual stimuli that start grouped together at the top of the head and then split into multiple flexible prongs and run down the scalp from the crown towards the ears and neck then back up again.	HP2: A gentle, flexible, and light sensation moving up and down different body parts.	HP3: Continuous ice-cold temperature sensations applied to the body statically (e.g. belly or arms, shoulders and neck) and/or dynamically.	HP4: A slow and progressive elastic force around the back (scapula) and arms (back and side) that pulls you upwards and forward.	HP5: Alternating direct and sudden pricking sensations at different points on the sole of the feet.	HP6: Intermittent short buzzes of vibration that are applied to both the neck and various “bony” areas of the joints.
DI1: Use of metallic sounds	X	X	X		DI5: Multiple punctual stimuli moving up and down on the body	X				X	
DI2: Sounds moving around the body	X	X		X	DI6: Cold stimuli moving up and down on the body		X	X			
DI3: Sonification of a body part			X		DI7: Using force to move people				X		
DI4: Sounds with musical structure				X	DI8: Vibrotactile structures for stimuli distributed on the body		X				X