Toward Iconic Vibrotactile Information Display Using Floor Surfaces

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Abstract

This paper presents our preliminary research on haptic displays integrated in floor surfaces. We emphasize potential roles for the latter as vibrotactile communication channels that might be seamlessly integrated in everyday environments. We describe the interactive floor component that is the platform for our research, and an application we have developed to support the design of vibrotactile icon sets for display with the device. The results of a preliminary evaluation of this display method are presented, and future directions for this research are described.

1 Introduction

Tactile feedback is playing a widening role in computing applications in everyday environments, and holds special potential for improving interaction in the mobile computing domain, where attention is frequently at a premium, input devices are often small, and visual display opportunities are limited. However, the possibility of haptic interaction with artifacts or surfaces in our existing environments – such as architectural elements, transit points, or public furniture – has garnered less attention to date. The ubiquitous role that such features, including floor surfaces, play in the negotiation of our surroundings points to the possibility that they may be positioned to take on a more significant future role in haptic computing.

The research described here is motivated by the idea of exploring the latent potential in the use of floor surfaces for information display. Such surfaces are notable, from a haptic standpoint, as being among the few that are universally accepted as touchable, and with which we are most often in contact (albeit, frequently through our footwear).

1.1 Floor Surfaces as Situated Vibrotactile Displays

Recent years have seen growth in interest in haptic information displays for people in everyday environments. Most work in this area has addressed tactile displays for handheld or wearable information appliances. However, haptics has long found a role in the design of passive information displays in public spaces, notably on urban walking surfaces, where tactile ground surface indicators – passive haptic cues provided via patterns of bumps or other textures – are used to demarcate locations or paths of interest for visually impaired people or in situations in which low-lying features, such as stairs, may not be visible.

In a similar vein, many everyday ground surfaces could be profitably augmented with active displays of vibrotactile information to demarcate a location, event, condition, or process of interest. Such displays might find roles that are complementary to those that haptic displays for mobile devices have been developed for. Some simple end-user scenarios may be helpful to guide the discussion:

- A visually impaired pedestrian in an urban environment is traveling on foot and by public transportation. At a noisy urban crosswalk she receives timely information, in the form of a vibrotactile cue supplied near the curb, indicating the location and state of the crossing (figure 1.1). She reaches a building lobby, and locates the elevator. While ascending to her destination, she receives a vibrotactile cue from the elevator floor, indicating the floor number that has been reached, and instantly knows when to disembark.
- A dense crowd of pedestrians in a stadium is quickly approaching the turnstile exit. They cannot see the turnstile locations (the crowd is thick, and the lighting is poor), but vibrotactile indicators underfoot provide them with cues as to the direction of the nearest turnstile.

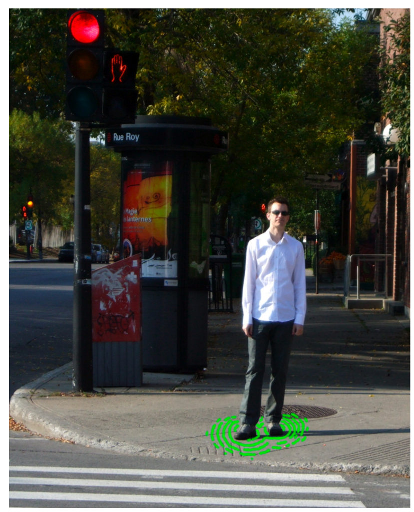

Figure 1: A possible end-user scenario: A crosswalk at which pedestrians receive vibrotactile cues (represented in green) indicating both the location of the crossing, and the state of the signal.

2 Background

This project concerns vibrotactile information display to the foot via ground surfaces. We briefly review prior research in the areas of vibrotactile display, vibrotactile communication design, and haptics for the feet.

Diverse applications of vibrotactile displays have been proposed, in contexts ranging from aeronautics to web browsing. The engineering simplicity of many vibrotactile haptic devices relative to their force-reflecting counterparts has led to a shift in research emphasis toward matching displays to human capabilities and application contexts. The lightweight nature of these displays has made it possible to experiment with the presentation of such information to virtually any area of the skin, including the finger, hand, forearm, chest, abdomen, waist, back, forehead, and feet. As tactile sensory capabilities vary considerably by body location, an accounting

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of the location dependence of different aspects of tactile sensation is needed. Fortunately, many of the relevant issues have been reviewed in recent literature [11].

The design of vibrotactile communication systems for the transmission of information via touch has been studied by many researchers. In the 1950s, Geldard systematically investigated this topic, addressing problems such as display design relative to sensory capabilities and stimulation method, and stimulus set design [6]. He successfully trained several users in the understanding of a tactile language composed of 45 distinct symbols. Various authors have since approached the problem of developing design guidelines for the creation of vibrotactile symbol sets, based on combinations of perceptual, cognitive, and heuristic criteria, together with methods for their evaluation (see [15] for a review). Prior research in this area that has substantially informed our present work, as reviewed in section 4 below.

Although tactile sensation in the foot has been less studied than that of the hand, the foot has long been acknowledged as one of the most sensitive parts of the body to vibrotactile stimulation [28]. Moreover, its sensory physiology is broadly similar to that of the hand, including the same types of tactile mechanoreceptors as are present in the glabrous skin of the hand [22]. The main differences include typically much higher activation thresholds for the foot (by a factor of approximately eight [12]), and larger receptive fields (by a factor of approximately three [12]). Functional differences include the greater prehensile dexterity of the hand, the larger and more sustained forces that the feet are subjected to during locomotion, and the systematic differences in the types of activities that are performed with the hands (e.g., grasp, manipulation, and fine exploration) and the feet (e.g., stance, balance, and self-motion).

A wide range of interfaces for the feet have been previously engineered for human machine interaction (e.g., foot controlled transcribers, dental equipment, sewing machines) and human computer interaction (including foot controlled computer mice, sensing floors and shoes), but little work in these areas has aimed to profit from the integration of active haptic feedback in the interface.

A major area of recent research has concerned the engineering of locomotion interfaces for virtual environments (recently reviewed by Iwata [10] and Hollerbach [9]). However, research in this domain has predominantly focused on the challenging problems of stable, high-fidelity force-reflecting haptic interaction, with the aim of enabling the design of omnidirectional virtual walking experiences. The display of vibrotactile information underfoot for the purpose of increasing immersion for locomotion in virtual environments has only recently begun to be addressed [13]. Vibrotactile feedback via environmental surfaces has been integrated within simulation and entertainment systems (as, for example, in the vibration of vehicle simulator pedals or cockpits), but we are not aware of any systematic evaluations of the use of such displays as distinct communication channels.

Vibrotactile communication displays for presenting discrete, information-bearing stimuli to the soles of the feet, have received limited attention to date. Shoes for presenting informative stimuli to their wearers via integrated vibrotactile displays have been addressed by a few prior researchers [18, 25]. Ferber et al. investigated the design of tactile cues to aid tasks involving a force-feedback exercise machine, such as the maintenance of a target exercise rate [5]. A body of prior research has also addressed haptic feedback in the automobile cockpit (e.g., Enriquez et al. studied communicative feedback from car steering wheels [3]). Hayward and Rovan developed prototype floor tiles and in-shoe vibrotactile stimulators for providing additional feedback during computer music performance [17]. We are not aware of prior work on the design of vibrotactile information displays for pedestrians via the actuation of floor surfaces. Due, in part, to the modest technological requirements, it seems plausible that related devices, such as in-floor warning signals, have been the subject of past experimentation or invention, but we are not aware of any prior work of this nature.

3 Interactive Vibrotactile Floor Component

The floor component used in our work has been described in more detail in earlier publications [27, 26]. This device has been designed with the aim of enabling interactive vibrotactile information display to pedestrians standing or walking upon it. It is assumed that pedestrians are wearing their accustomed footwear. No special equipment need be worn in order to use the device.

In addition to actuating components, force sensing capabilities have been integrated to enable stimuli to be displayed in an interactive way, contingent upon the presence or movements of the individuals walking upon it. In separate work, we have used this interface to interactively synthesize the vibrotactile signatures that would normally be generated by walking on natural materials, such as snow or gravel [27, 13].

The device is designed to be simple to build, and to be adaptable to existing floor construction methods. The prototype, shown in figure 2, has been constructed from readily available, inexpensive materials. The tiles of the prototype shown are rigid polycarbonate of dimensions $30.5 \times 30.5 \times 1.25$ cm. Other prototypes have used plywood tiles. The tiles rest on a rigid substructure (constructed from aluminum extrusion in the model shown). An inertial motor type vibrotactile actuator (Clark Synthesis model TST-silver, single-unit retail price less than US$100) is rigidly attached to the center of the underside of each tile. A personal computer generates the vibrotactile signals in real time (described in section 4). These signals are output via the digital to analog converter of a computer audio interface, and sent to an amplifier that drives the actuators. To support display applications in which a stimulus is supplied contingent upon a user stepping upon the active area, force sensing has been integrated in the device. One force sensing resistor (Interlink model 403) encased in foam rubber 0.5 cm thick is positioned under each of the four corners of each tile. A microcontroller digitizes the force data (with a resolution of 10 bits and sampling rate of 250 Hz) and transmits it via a serial USB link to the computer.

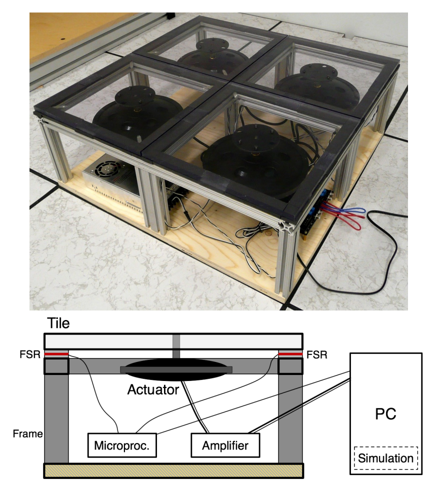

Figure 2: Top: 2×2 tile interactive floor prototype, showing the tile surface (polycarbonate sheet), vibrotactile actuator, force-sensing resistors, structural frame, and associated electronics. Bottom: Diagram of the same, including the PC running the software application.

4 Vibrotactile Icon Design Software: Parametrization and Synthesis

Vibrotactile icons can be defined as symbolic cues, in the form of temporally discrete vibrotactile stimuli, that are provided by a computational artifact to inform a user about some object, place, event, or process of interest.

For a given display device, one question of research interest has been how to design such stimuli to most effectively make use of the tactile communication channel relative to the capabilities of the device and human perceptual apparatus. Prior researchers have formulated this goal through different inter-related problems, including that of maximizing information transfer (measured in bits per displayed stimulus) [19], that of creating the largest perceptually distinguishable stimulus set [14, 21], or of designing the largest set that can be separately identified at an acceptable average error rate within a task context of interest.

The design of such stimuli is frequently accomplished via a parametric representation of the family of vibrotactile signals from which the stimuli will be drawn, together with a method (heuristic or otherwise) for determining the parameters of those stimuli that are actually used. We adopt a musically-motivated design paradigm that has been introduced in prior literature on vibrotactile icons, where it has been evaluated positively. This approach views stimulus as composed of a short-time structure akin to a musical note (with a duration of perhaps 500 ms or less), and a longer time structure consisting of a motif or musical pattern composed of the note-like entities [7, 1, 24]. Parameters for describing a short-time signal of this type have often been borrowed from those that are employed within musical signal processing and sound synthesis. They can include variables such as fundamental frequency, harmonic content, waveform shape, amplitude temporal envelope, and duration. Other, psychophysically-inspired characteristics such as roughness (often specified as an amplitude modulation) or spectral centroid are also used. Longer time patterns are typically specified in terms of structural arrangements of such notes, characterized according to musical features such as rhythm, dynamics, and tempo [24, 1, 21]. Such structures may last one second or longer for each stimulus. The parameter ranges to be used can be limited by sensory and psychophysical considerations. Briefly, vibrotactile displays are often designed primarily to target the Pacinian corpuscles, which are cutaneous tactile receptors with a maximum sensitivity around 250 Hz and usable bandwidth of only a few hundred Hertz. Thus, the usable frequency bandwidth is much narrower than in audition, for which such parametric representations were first developed. Other constraints can be determined from perceptual effects such as temporal masking, dynamic range, and temporal event sensitivity, as reviewed in recent literature on vibrotactile display and interaction design [11, 7].

Spatial encoding is another interesting degree of freedom that is often used for design [20, 23]. The floor display discussed here is limited in this respect resolution, although it can be used to present distinct signals to each foot, at each location of a distributed floor area, or in response to each temporal footfall. Here, we ignore these degrees of freedom, and focus on the design of stimuli for an area of floor surface that is actuated in a spatially uniform way.

Additional considerations arise from the distinctive nature of the area of the skin that is used for display – in our case, the feet. Apart from the sensory differences mentioned in section 2, the design of such displays is complicated by the potential mobility of their users, and consequent variation in contact conditions between the user and the display. This has implications for application design in real world settings. Furthermore, in realistic settings, differences in vibrotactile transmission due to variations in users' footwear may be significant. Such issues are not addressed here, and in the preliminary study we have conducted (section 5), participants remained stationary on foot throughout, and all wore identical shoes.

4.1 Haptic Icon Designer

In order to explore the design of vibrotactile stimuli to be presented through a floor surface, we developed the Haptic Icon Designer application shown in figure 4.1. The application allows a designer to specify short-time, "note"-like stimulus properties, through parameters controlling fundamental frequency, duration, harmonic content, roughness (amplitude modulation depth), and amplitude temporal envelope (specified as a piecewise linear function). Harmonic structure is generated via a nonlinearity applied to a sinusoidal signal of the specified fundamental frequency. A sum of Chebyshev polynomials is used to design the nonlinearity, since in this representation, the amplitude of the nth harmonic frequency component of the signal (i.e., the nth multiple of the fundamental) is controlled by the corresponding polynomial coefficient [16]. Together with the real-time frequency spectrum display, this allows the designer to ensure that the stimulus lies within the target frequency band (centered on 250 Hz).

The interface allows to specify longer-time structures using a musical phrase metaphor, including rhythm, duration, note amplitude (accents), repetition, and duration. These phrases are designed within a "step sequencer" paradigm that is commonly used in digital music composition. The time domain of a single phrase is quantized into 24 steps. (The actual synthesized stimulus is continuous in nature.) Notes can begin at any step and possess durations given by integer numbers of steps (length of the blue bars shown in the interface). Only a single note is able to play at any time. The amplitude of each is specified at its onset. The duration of the entire phrase is specified in milliseconds, and the phrase may be repeated an arbitrary number of times. Notes within an icon's rhythmic pattern differ only in their amplitude and duration, so that all possess the same frequency characteristics. This is a significant constraint, but greatly limits the number of parameters that must be specified for each icon.

Once specified, the icon, or set of icons, may be saved in parametric form (in xml format) via the application. Icons may be interactively recalled as required for a given experiment or demonstration. The numerical parameters may be browsed (using a separate window) if desired.

The same application interface is used to perform real-time synthesis and to initiate playback of icons via the floor device. We have, in addition, made use of this capability to implement interactive demonstration scenarios in which, as a pedestrian steps onto the tile surface, he or she is automatically presented with a vibrotactile icon. In this case, an adaptive footstep onset detector is used to identify a step onto the surface of the tile. Such a mode of interaction is relevant to potential end user scenarios such as the vibrotactile crosswalk indicator described in section 1.1.

5 Preliminary Evaluation

The goal of this pilot experiment was to investigate the extent to which vibrotactile icons can be effective for information display via floor interfaces. Concretely, the aim was to examine the identifiability of a set of icons designed using the approach described in section 4. An initial set of twelve stimuli were specified using the Haptic Icon Designer. Each possessed a distinct rhythmic pattern of between two and five notes, repeated three or four times, with one accented note at the beginning. The duration of each icon was between 1.4 and 2.4 seconds. In addition, each icon was assigned a distinct roughness, fundamental frequency, and a frequency spectrum with most energy near 250 Hz. An informal pre-test was used to eliminate four of these stimuli that seemed too similar to the others, leaving eight icons to be used in the experiment.

The experimental design was similar to those used in prior research (e.g. [8]), although in this preliminary study, we only measured identification in a single condition. The experiment was guided by two working hypotheses: The first was that the musically-inspired method used to design the stimuli would allow participants to identify 8 different icons after a short period of training, mirroring the success that such design techniques have found in

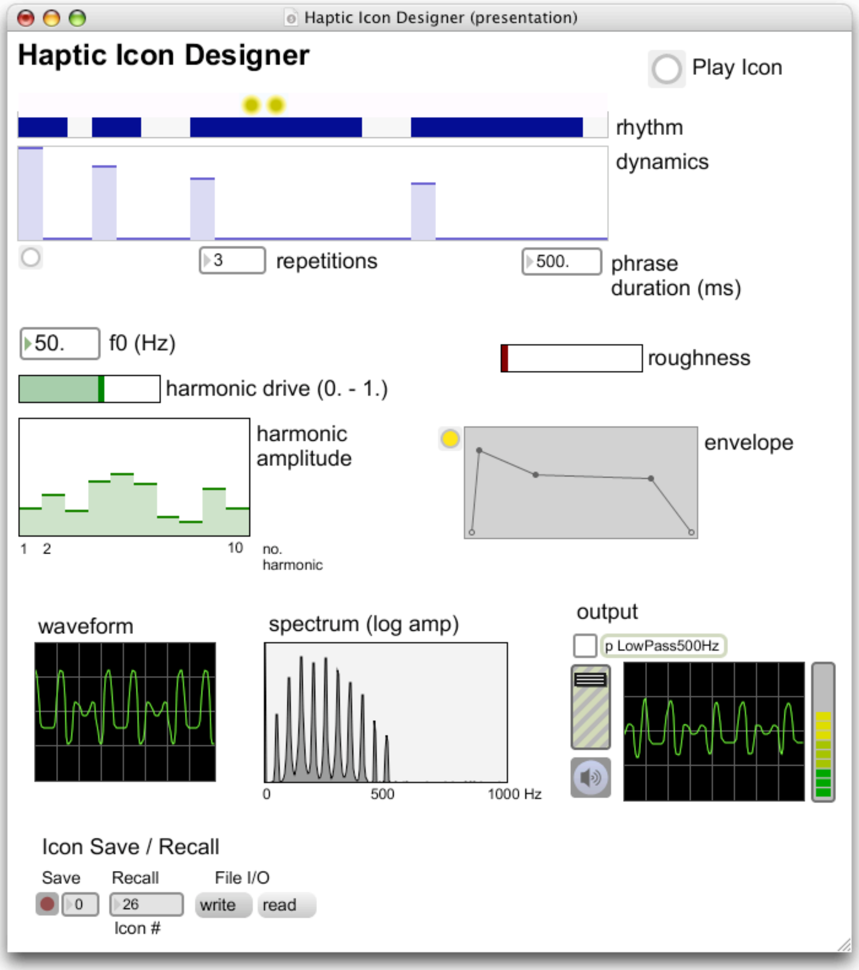

Figure 3: Screenshot of the haptic icon design software interface, during playback of an icon. The yellow dots above the note sequence (notes are represented by blue bars) denote the current time index along the musical phrase. User interface elements allow to control parameters defining the vibrotactile stimulus.

other areas of vibrotactile information display. The second was that greater confusion would be seen for shorter duration icons, due to information limitations, and for icons with more information near the onset of icon playback, perhaps due to the surprising nature of the stimulation method.

5.1 Methodology

Eight people between the ages of 20 and 39 years old took part in the experiment. Four of them were male and four were female. Five were university students. All participants were presented with the same task and stimulus sets. Each was given hard-soled men's dress shoes in his or her size to wear for the experiment. Apart from size differences, all the shoes were identical. The amplitude of vibration of the tile was adjusted for each participant, using a reference vibrotactile noise signal. At the beginning of the session, participants received instructions, together with an explanation and demonstration of the display function. At all subsequent stages (except during breaks), participants were required to wear headphones playing pink noise at a volume sufficient to mask the (generally low-level) sounds produced by the apparatus. The application used during the experiment ran on a personal computer, and was based on the vibrotactile icon design software described in section 4. In addition to the floor tile, the interface consisted of a graphical user interface with numbered buttons, one for each icon (figure 3).

The experiment was based on absolute identification, incorporating a set of 8 icons and a unique correct response for each, consisting of the numerical ID of the icon, ranging from 1 to 8. The same icons were used for all participants and all sessions of the experiment.

After an introduction to the device and interaction method, participants were given four minutes to interact with the icons used in the study, by standing on the floor tile, selecting a numerical ID, and receiving the stimulus corresponding to their selection.

The rest of the experiment was divided into six sessions. During each session, all stimuli were presented twice, in a different randomized order during each session. Thus, overall, each participant was asked to identify every vibrotactile icon a total of twelve times. Each session took an average of about four minutes to be completed. Participants were presented with stimuli sequentially during each session. At each presentation, they could press a button to play the stimulus up to four times before supplying a response. Feedback, in the form of the correct stimulus ID, was provided after each response was given. As in previous studies [8], the reason for providing feedback was to facilitate the assessment of recognition after learning and rate of learning throughout the experiment.

5.2 Results and Discussion

A log of the stimuli and responses was recorded by the application throughout the experiments. Participants were also interviewed following the experiment.

Although the icon set used in this preliminary experiment was small, the task was difficult, because it required participants to both distinguish the icons from each other, and to learn a symbolic association to the index of the icon, and to do so with very little training (a total of approximately 28 minutes, on average), after only 20 reinforced presentations of each stimulus.

The correct identification rate after six sessions of testing with enforced learning (feedback), averaged between all participants, was 55%, with a between-participant standard deviation of 25%. Chance performance would correspond to 12%. Improvements during the course of enforced learning varied considerably between individuals. One individual showed consistent improvement between sessions, attaining a 94% average correct identification rate in session 6, while others showed nearly no improvement. Average correct identification rates during each session are shown in table 1. The performance for each individual during session 6 is summarized in figure 5.2. Several participants reported feeling mental fatigue by the end of the study, which is one possible explanation for the increased average variation and reduced improvement during the last two sessions.

The results obtained are roughly comparable to published results on absolute identification of vibrotactile stimuli via manual interfaces after short periods of learning. For example, Enriquez et al. report average identification performance of 73% (relative to an expected chance performance rate of 33%) after an average of 20 minutes of training [4]. As noted below, a more direct comparison with performance using a manual vibrotactile display would be interesting.

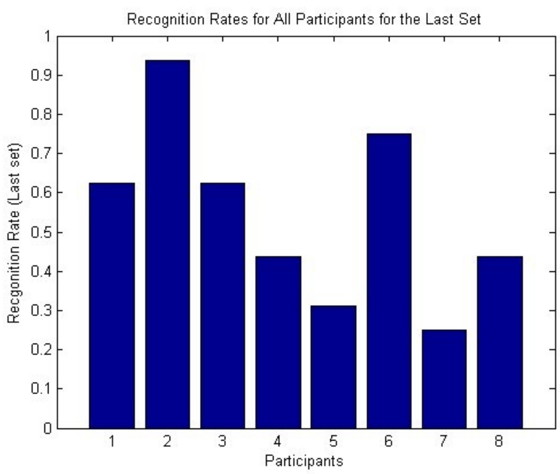

Figure 4: Identification rate (percent correct) for each participant, after 6 sessions of assessment with enforced learning.

The confusion matrix for the stimuli in the experiment is shown in figure 5.2, averaged between all sessions and participants. The least confused stimulus was identified at an average rate of 61%, while the most confused stimulus was identified at an average rate of only 25%. Comparing these confusions with the icon set did not reveal any easily discernable property of the least confused stimulus that might have caused it to be confused, nor was there any clear difference in identifiability of shorter and longer stimuli, or of stimuli with different numbers of notes. Due to the limited data available, it was not possible to infer more precise design guidelines, but we anticipate presenting further data in a final version of

Table 1: Average Performance During Each Session

Session	Average Correct	Standard Dev.
1	37%	15%
2	41%	13%
3	44%	16%
4	55%	13%
5	51%	24%
6	55%	23%

this paper.

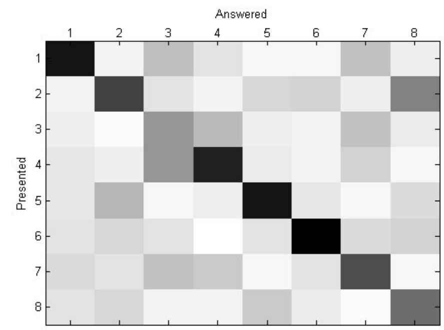

Figure 5: Confusion pattern for the 8 stimuli in the experiment, averaged between all sessions and participants.

Some participants felt that they were limited by the difficulty of the association part of the experiment – that is, the task of associating the stimuli to numbers from a list. Three of them suggested that the task would have been facilitated by a non-numerical semantic or mnemonic symbol, such as an animal name. Such an approach could hold potential for further improving the identification performance seen here (albeit in a way that does not speak to the design of the stimuli themselves). In adhering to a simple numerical labeling, we aimed to avoid introducing unknown effects linked to the relative fitness of the mnemonic(s) chosen. An earlier study by Enriquez et al. found no difference in learning and 2-week recall of arbitrarily assigned (abstract) vs. user-chosen (semantic) labels for 10 perceptually optimized vibrotactile icons [2]. The implication is that icon set selection may be more important than labeling, and that, given amenable conditions, an arbitrary association may be learned. Assuming this to be true does not, of course, rule out the possibility that the preliminary results presented here are degraded by the association task. However, it would be difficult to argue that these results are optimistic, which is arguably more important for a feasibility study such as ours.

Participants reported adopting diverse cognitive strategies for memorizing the signals, attending to frequency, perceived amplitude, pattern characteristics, or other features.

This study also aimed to assess the acceptability of the stimulation method to potential users. Participants were asked to rate the vibrotactile stimuli on a five point scale from 5 (comfortable) to 1 (uncomfortable). The average rating was 3.44 with a standard deviation of 1.1. No participants rated the stimuli as uncomfortable (although some reported growing tired of standing in place during each session.)

6 Conclusion

In this paper, we have described our continuing research on the display of vibrotactile information via floor interfaces. The low cost and robust nature of the components involved suggest that devices based on this principle could become a meaningful addition to everyday contexts that might profit from the additional information channel. Other advantages include the ubiquitous nature of contact with the potential display surface, and the fact that users of such a system do not require any special equipment.

In order for this model of information display and interaction to achieve relevance and acceptance, design guidelines appropriate to it would need to be formulated. In turn, this would require a better understanding of the distinctive properties of the display relative to tactile perception via the feet.

6.1 Future work

As noted above, one can readily identify distinguishing features of the floor display that should be investigated further, not least effects that may be related to the unusually forceful coupling between the body and the actuated surface. This coupling allows, when desired, to transmit vibrations that propagate beyond the soles of the feet.

Two participants suggested the display might be improved if the note-level stimuli were less similar to oscillatory patterns, and more like transient knock or impact events. This is something we intend to explore through the development of a second, *Ecological* Haptic Icon Design application. In that approach, oscillatory note-level events are to be replaced by impact transients, which are synthesized in real time, and controlled through physical parameters such as hardness and contact shape. We intend to evaluate the relative fitness of such cues in a future study.

It would also be interesting to compare the floor display with a previously studied vibrotactile display (for example, one grasped in the hand) using stimuli that are as similar as possible between the two interfaces, and this is something we plan to address in future work.

Finally, the suitability of these cues to situations in which a person addressed by the display is either preoccupied with some form of workload, or is physically moving, remains to be determined.

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