Touch Is Everywhere: Floor Surfaces as Ambient Haptic Interfaces

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Abstract—Floor surfaces are notable for the diverse roles that they play in our negotiation of everyday environments. Haptic communication via floor surfaces could enhance or enable many computer-supported activities that involve movement on foot. In this paper, we discuss potential applications of such interfaces in everyday environments and present a haptically augmented floor component through which several interaction methods are being evaluated. We describe two approaches to the design of structured vibrotactile signals for this device. The first is centered on a musical phrase metaphor, as employed in prior work on tactile display. The second is based upon the synthesis of rhythmic patterns of virtual physical impact transients. We report on an experiment in which participants were able to identify communication units that were constructed from these signals and displayed via a floor interface at well above chance levels. The results support the feasibility of tactile information display via such interfaces and provide further indications as to how to effectively design vibrotactile signals for them.

Index Terms—Vibrotactile interfaces, ubiquitous computing, haptic communication design, floor surfaces.

✦

1 INTRODUCTION

Tactile feedback has received growing attention as a means of enhancing or enabling information display in diverse computing applications. As human-computer interaction has extended beyond the desktop computing paradigm, and into every other domain of human activity, tactile display has grown in importance. This is attributable, in part, to its ability to overcome the sensory overload and attentional demands that arise in complex, multitasking environments.

Two new paradigms that have emerged within this context are those of mobile or wearable information appliances, and of ambient computing. While significant attention has been devoted to the opportunities for tactile display to enhance mobile applications, less has been given to haptic interaction with computationally augmented environments. Nonetheless, the fundamental role that floor surfaces play in our haptic negotiation of everyday environments suggests that they hold significant potential for active tactile information display.

The design of haptic information for ground surfaces has a long history, as is evidenced in urban environments. Haptic markers are commonly used to indicate locations or paths of interest to visually impaired people. Similarly, they are employed to emphasize low-lying features, such as subway stairs, that need to be highlighted even to sighted individuals. Many everyday ground surfaces could also be profitably augmented with active tactile information displays. Such displays might find roles that are complementary to those that have been explored in the mobile computing domain. Some simple end-user scenarios may be helpful to guide the discussion.

- A visually impaired pedestrian is traveling to an appointment on foot and by public transportation. Reaching a noisy urban crosswalk, she is able to infer, via a vibrotactile cue received near the curb, that the crossing signal is red. Later, she receives a cue indicating that it is safe to cross (Fig. 1). She enters the subway and is able to feel, via haptic feedback supplied near the platform edge, that the train has not arrived. Once it arrives, similar cues indicate the locations of the train doors. She reaches the building of an office, 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.
- An elderly person taking a shower in his home receives subtle vibrotactile feedback to his feet, unconsciously aiding him in maintaining his balance in response to sensed shifts in his center of mass and pressure.
- A rescue team is engaged in an augmented reality training simulation that aids them in learning to evaluate and respond to the changing conditions of a structure during an emergency. They receive realistic cues through the response of a haptically actuated floor delivering signals appropriate to the material and local stability of the ground surface in the simulation.

1.1 Potential Advantages

Floor-based haptic communication interfaces may share many positive features that are characteristic of other kinds of haptic communication.

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Fig. 1. A possible end-user scenario: pedestrians receive vibrotactile cues via the ground surface (shown as shading around the feet), indicating the location of the crossing and state of its signal.

- *Complementarity to other modalities:* Such displays can function well even when visual attention is occupied, or when the environment is noisy.
- *Attentional salience:* Tactile displays can be an effective means of directing attention to a significant event or location, in the presence of task load or sensory distraction.
- *Discreetness:* Information received through such a display need only be apparent to its user.

Haptic communication via floor interfaces may, in addition, offer some specific advantages, such as those of:

- *Ubiquity and unintrusiveness:* Reflecting the near universal presence of foot-floor contact in human environments.
- *Acceptability:* While people may be averse to touching certain objects in public spaces such as restrooms, floor surfaces are broadly acceptable to touch, via the shoes.
- *Ready accessibility:* Floor-based interfaces need not require users to possess or wear any special technology, making them accessible to a wider range of users.
- *Lack of specific demands on visual or manual search:* An interface might be positioned at a location (such as a pedestrian crossing) in such a way that little visual or manual search is required to locate it. This can be an advantage for users with visual impairments.
- *Location, navigation, and event salience:* Such interfaces may be well suited for applications that involve pedestrian navigation, wayfinding, or location-based information display.
- *Locomotion-specific effects:* As noted below, a floor might be readily designed to actively enhance specific sensorimotor aspects of walking.

2 BACKGROUND

While the literature on haptic interaction design for the feet is quite limited, much of what is known about haptic communication via other areas of the body may be readily extended to the case of interest. In addition, in large part through research conducted over the last two decades, more is now known about tactile sensation in the feet. This background knowledge can, by extension, inform the design of floor-based interfaces, and it also raises issues that are uniquely applicable to haptic communication design for floor surfaces.

2.1 Tactile Sensation and Psychophysics of the Foot

The tactile sensory physiology and psychophysics of the foot have been the subject of considerable research, if to a lesser extent than in the case of the hand. The foot has, since the mid-20th century, been acknowledged as one of the most sensitive parts of the body to vibrotactile stimulation [42], [40]. The sensory physiology of the sole of the foot is similar to that of the glabrous skin of the hand, including the same types of tactile mechanoreceptors as are present in the latter [34], namely, fast-adapting type I and II receptors (FA I, FA II) and slow-adapting type I and II receptors (SA I, SA II). Their nervous responses largely mirror those of receptors in the hand [17], although some differences in peripheral vibrotactile information coding have been identified (see, e.g., Ribot-Ciscar et al. [26]). With regard to the receptor spatial distribution, Kennedy and Inglis found those in glabrous skin of the foot sole to be relatively widely distributed, with (in contrast to the hand) little preferential accumulation in the toe areas [17]. Receptive fields were found to be larger than in the hand by a factor of about three. Physiological activation thresholds were determined to be higher, on average—by a factor of approximately eight, in the case of FA II receptors [17]. This latter finding agrees with earlier observations of higher psychophysical thresholds to vibrotactile stimulation of the foot compared to the hand [40]. It has been suggested that this is due, in part, to biomechanical differences between the skin of the hands and of the feet, and possibly to mechanoreceptor properties [41]. The ball and arch of the foot have been found to be the areas most sensitive to vibrotactile stimulation [14].

Sensitivity has also been assessed for populations of different ages, with elderly people demonstrating elevated thresholds for vibrotactile stimulation at FA II mediated frequencies [14] (i.e., those most often targeted by vibrotactile displays [37]). Thus, age is a significant factor in haptic interaction design for floor interfaces. As in other areas of haptic communication, such differences may be compensated by learning on the part of users, or by plasticity effects, whereby repeated exposure over time has been found to improve vibrotactile discrimination [7].

Distinctive functional characteristics of the foot relative to the hand include the reduced prehensile dexterity of the former (which is reflected in the kinds of activities in which it is involved), and the fact that static and dynamic forces on the feet during stance are higher and more sustained than those in the hand (i.e., on the order of 100-1,000 Newtons in the former case). Thus, while the thresholds measured in the studies cited above were assessed as subjects were lying down or otherwise off their feet, when individuals are walking, those thresholds may be higher, due to adaptation effects resulting from the large forces involved [8]. As in the case of the hand, most of the receptor types of the foot are simultaneously active during normal motor activities, unlike the more segregated responses that are observed to accompany simpler cutaneous stimulation by static probes, vibrators, or electrodes [17], [34]. Ribot-Ciscar et al. observed that vibrotactile stimulation of the foot can lead to a transformation of physiological messages potentially leading to the overestimation of static forces through coactivation of SA I afferents [26]. As a result, the application of extrinsic vibrotactile stimulation can result in unintended behavioral modifications affecting posture and gait. Ribot-Ciscar et al., among others, have previously identified similar, manual sensorimotor impairments affecting workers exposed to high-amplitude vibrations [25]. Roll and Gilhodes have investigated various proprioceptive illusions that can be induced by vibrotactile stimulation [28].

Humans on foot are implicitly engaged in a sensorimotor task (e.g., quiet stance or normal walking). The cutaneous tactile channels addressed by the types of interface we describe here are active in the peripheral regulation of balance and locomotion through reflexes coordinating stimuli felt through the feet to muscles in the leg and foot (see, e.g., Tax et al. [32], Zehr et al. [43]). During locomotion, the coupling of motor reflexes to cutaneous stimulation has been found to depend on both stimulus properties and on the instantaneous gait phase at the time of stimulation. Thus, if a display is meant to be accessed during locomotion, careful consideration is warranted of stimulus design and the timing of presentation. Such entanglements of tactile sensation in the feet and motor behavior suggest that constraints on the design of actuated floor displays are needed in order to avoid adverse effects on gait and stance. At the same time, certain applications might exploit such effects. For example, a person entering a dangerous area might stop more quickly if cued by a suitable vibrotactile warning signal from the floor.

Finally, there has been much recent interest in the observation that it is possible to enhance sensation in the feet, and thereby postural and gait control, by providing subthreshold noise to the foot soles [23]. This effect is seen as significant for elderly populations, and for others with peripheral neuropathies. Sensory aids of this type could be implemented through the kinds of display described in this paper, either as a central or complementary feature.

2.2 Prior Research on Interfaces for the Feet

While there has been little research on the design of haptically actuated floor surfaces, much may be learned from past work in areas such as the passive haptic design of ground surfaces, tactile feedback in foot-based human-computer interaction, and locomotion interfaces for virtual environments.

2.2.1 Haptic Design of Ground Surfaces

Public transit areas, such as urban sidewalks, pose special risks to pedestrians with visual impairments. This is partly due to the fact that they cannot make use of visual cues or signs that are the most common means of marking hazards (e.g., at intersections). Tactile ground surface indicators consist of regularly textured areas of ground, in the form of patterns of raised domes, bars, or other bumps, arranged on the sidewalk to mark significant paths or points of safety concern [29]. While international specifications for such markers remain to be established, they must be clearly identifiable, without being obtrusive. When higher than about 5 mm, they have been found to pose risks for stumbling or falling [19]. Alternative means of demarcating floor areas have been proposed to remedy this. Kobayashi et al. investigated the discrimination of floor areas by elasticity, in order to determine the feasibility of using this type of material variation as a substitute for ground surface indicators [18]. An active vibrotactile cue supplied through the ground could provide another approach.

2.2.2 Haptic Locomotion Interfaces

One area of recent research has concerned the engineering of locomotion interfaces for virtual environments, as recently reviewed by Iwata [15] and Hollerbach [12]. However, this research has predominantly focused on the challenging problems of high-fidelity force-reflecting haptic interaction for omnidirectional virtual walking experiences. The display of vibrotactile information underfoot for the purpose of increasing immersion during locomotion in virtual environments has only recently begun to be addressed [20].

2.2.3 Tactile Communication with the Feet

Vibrotactile displays for presenting information-bearing stimuli to the soles of the feet have been little explored to date. Shoes for this purpose have, for example, been investigated for information conveyance via nonintrusive or hands-free interfaces [31], [36]. Rovers et al. found that users were able to identify several families of haptic icons, consisting of moving patterns on the foot sole presented through an array of small vibration motors in the sole of a shoe-like apparatus [31].

Despite the limited research that has addressed the feet, there is ample evidence that information can be transmitted via diverse body surfaces, devices, encodings, and under many different conditions; extensive reviews of related considerations from the literature in these areas are provided in [7], [37], [21]. Beginning in the 1960s, Geldard and others systematically studied the use of tactile displays for communicating symbolic information via different parts of the body. Later, research on sensory substitution aimed at conveying information about shape, spatial configuration, or environmental conditions near a user of a distributed tactile display; such displays were designed for body parts such as the tongue, forehead, thigh, or back [37]. Basic guidelines for stimulation by vibrotactile feedback are now being formulated [16]. Trends in recent research aim at uncovering central capacities for, and limitations on, tactile information processing [7], and at establishing a foundation for the design of large sets of structured vibrotactile messages, based on perceptual and usability criteria [21]. Although such guidelines necessarily depend on the display device, application, and user community addressed, basic strategies have been successfully applied to many different interfaces and sensory modalities. We profit from prior research on musically inspired tactile communication design discussed in Section 3.7.

2.2.4 Human-Machine and Human-Computer Interfaces

There are many control interfaces for machine operation by foot (car accelerator pedals, dental equipment, and sewing machines), and somewhat fewer for human-computer interaction (foot-controlled computer mice, sensing floors, and shoes). Few of these have profited from active haptic feedback. Systems providing haptic warning cues via an automobile's accelerator pedal have been researched for many years as a means of improving driving safety [22], and implementations have now reached the market (e.g., Infiniti's Distance Control Assist). Ferber et al. studied haptic communication during a human control task conducted on a haptically augmented stair climbing machine. They found some simple haptic cues supplied to the feet via an exercise machine to be effective at aiding participants in maintaining a target exercise level. The cues consisted of regularly spaced tapping sequences encouraging the person exercising to exert more effort when he or she slowed down [6]. Rovan and Hayward developed vibrotactile interfaces for furnishing additional feedback during computer music performance, including augmented floor tiles and in-shoe stimulators [30]. While they reported the feedback to be subjectively effective at conveying spatial and temporal information, no systematic evaluation was performed. We are not aware of any prior work on the design of vibrotactile information displays for pedestrians via the actuation of floor surfaces.

3 AMBIENT HAPTIC FLOORS: DISPLAY DESIGN

Since ambient haptic floor displays have only recently been developed, the potential design space has been little explored to date. In this section, we highlight roles that such interfaces might profitably take on in future applications and discuss design issues, including prototyping methods. We present a prototype floor platform and describe several design strategies that we have implemented for it.

3.1 Roles for Haptic Communication

Although application requirements depend on factors that are difficult to anticipate outside of a case-based discussion, a number of possible roles for a haptic floor interface can be identified.

Location-based information display. Due, in part, to the commonality of foot-ground contact, such a device may be suited for providing notifications about a current or future event associated with a location (e.g., the arrival of a bus at its stop), or of informing about an ongoing process.

Display of navigation-salient information. Such a device could be highly suited for demarcating a location or region of interest to pedestrians (e.g., a crosswalk location, or an in-store promotion), a direction or directions of interest, or for indicating a pedestrian path or passage (e.g., the route to a nearby emergency exit).

Functional augmentation of features or devices. In interactive settings, floors as interfaces may prove useful for supplementing the functionality of existing architectural features (e.g., steps, entrances, stairs, and tactile ground surface indicators) or interfaces (e.g., foot switches, haptic locomotion interfaces, and exercise machines [6]).

Creative, entertainment, or emotional communication. They may also be used for diversion, comfort, entertainment, or in the context of artistic creation, for example, by silently providing a common tempo to musical performers, or by communicating information to a computer music performer [30].

Sensorimotor aids. Cutaneous tactile stimulation via the soles of the feet can be designed to improve locomotion during rehabilitation or normal activities [24], [10]. It could also be used to provoke reflexes meant to avert a pedestrian from stepping in the path of danger.

Virtual reality display. Augmented floor surfaces can be used for simulating natural ground surface features (e.g., earth, sand, and stone) for virtual reality or augmented reality simulations that involve movement on foot (see [38] and Section 3.5).

3.2 Physical Interaction Design Considerations

Good design demands consideration of the device's physical configuration and other factors affecting the interaction. Some relevant considerations include: Whether the interface is to be integrated with an existing feature or device (e.g., an area of tactile ground surface indicators), or if it is to constitute a new artifact, such as a custom-built floor platform; Whether the interaction is to be afforded to a single person or to a group; The required spatial resolution; The level of interactivity that is needed; The level of independence of stimulation to each foot. Such considerations can only be addressed in detail through a particular design.

3.3 Prototyping Technologies and Methods

Many of the technologies needed for prototyping vibrotactile floor displays are readily available and require comparatively little engineering to deploy. The necessary electronic components consist of vibrotactile transducers, amplifiers, and signal generation circuitry (typically some form of computer with associated digital to analog converter).

Among the distinguishing technical requirements are the relatively higher power demands, owing to both the elevated vibrotactile sensory thresholds in the feet relative to those in the hand, and to the requirement of actuating a floor surface bearing a large mass.

Among other commercially available actuation technologies, one suitable choice is the linear voice coil motor. It consists of a metallic mass suspended on an elastic structure between the coils of an electromagnet, which, when driven, exerts a force directly against a structure to which it is attached (see the recent review article [9] for a discussion). An advantage of these actuators is that they provide independent control over amplitude and frequency, which is not the case for simpler devices, such as the eccentric mass motors commonly used in mobile phones. A second advantage is that the entire actuator may be concealed within the device. Several commercially available voice coil actuators exist that may be suitable for prototyping floor surface applications such as those described here.[1] The main technical requirements are that they possess a usable frequency bandwidth overlapping the domain of sensitivity

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[1] Examples include the IBEAM VT200 (Sonic Immersion LLC, Hürth, Germany) and the TST239 (Clark Synthesis, Inc., Littleton, Colorado).

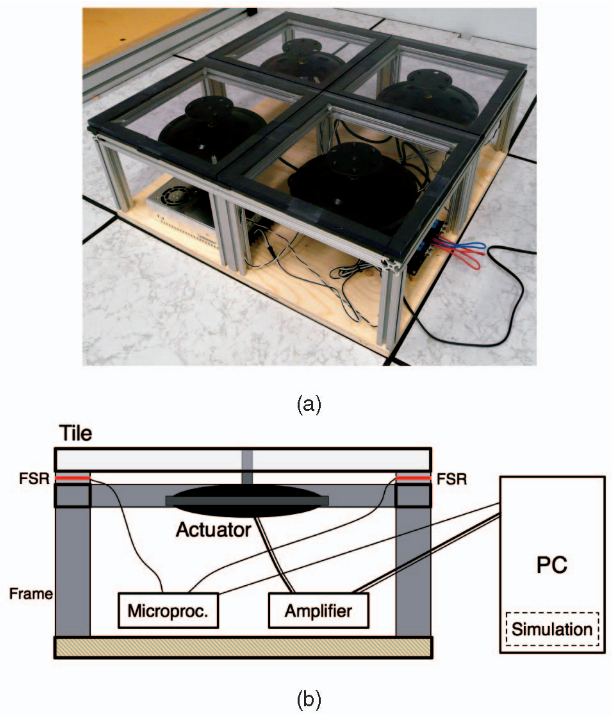

Fig. 2. (a) Interactive, four-tile prototype described in the text. (b) Diagram of same, with PC and rendering software.

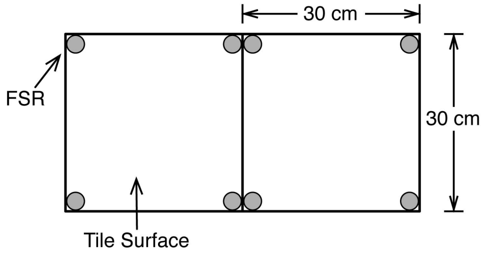

Fig. 3. A 2×2 tile prototype seen from above. Force sensing resistors are positioned as shown.

of FA II receptors in the feet and are capable of supplying sufficient power to actuate the surface. Such actuators can readily be driven with normal audio amplifiers.

Some technical simplifications are made possible by presenting vibrotactile stimuli via a rigid, actuated floor surface. First, this approach facilitates the protection of all electronic components beneath the surface of the floor (see Section 3.4). Second, the size of the surface being actuated means that if it is driven at frequencies extending into the audible band, usable auditory feedback can be supplied through the same interface, allowing for cross-modal information display. Since vibrations above about 1,000 Hz are not felt, higher frequency signal components may, in part, be shaped so as to improve the accompanying auditory feedback. While we have found this feedback usable in practice, there are significant limitations arising from structural resonances and emission characteristics of the foot-floor system.

In some cases, a stimulus may be supplied through the floor in a way that is conditional upon, or computed as a function of, forces supplied by a pedestrian stepping onto that area of the floor. For example, a floor surface may be configured to provide a response resembling a (virtual) foot switch, controlled by foot pressure. Interactivity may be enabled via an array of force sensors embedded in the floor. A detailed discussion is omitted here. One example is described below.

We would like to address a few concerns that may arise in the mind of the reader regarding such interactions. First, despite the coupling between actuator and sensor, the forces supplied by the former are often negligible, because the magnitudes involved (on the order of a few Newtons or less) are much smaller than the low-frequency forces exerted by pedestrians against the ground (i.e., as large as 1,000 Newtons). Second, although actuator size or other constraints may dictate a coarse spatial arrangement of actuators (distributed with a spacing of one or several feet in distance) this need not necessarily be apparent to a user. A stimulus is generally felt through each area of the foot in proportion to the force it exerts on the vibrating surface. Thus, even though the spatial density of actuators may be very coarse, the resulting experience is that the stimulus originates at the locus of foot-floor contact. The effect is similar to that used to present virtual tactile buttons on touchscreen displays. For similar reasons, boundaries between individual tiles are less noticeable than might be expected, provided similar responses are supplied by adjacent tiles.

3.4 Prototype Vibrotactile Device

The device used in our work has evolved through a series of earlier prototypes [38] to pedestrians standing or walking upon it. It is assumed that they are wearing their accustomed footwear, and no special equipment is required to be worn. In addition to the actuators, force sensing capabilities have been integrated to enable interactivity, along the lines described above. We have previously used this interface to interactively synthesize vibrotactile signatures similar to those that would normally be generated by walking on natural materials, such as snow or gravel [38].

The device is simple and robust in construction. A prototype is shown in Fig. 2. The four tiles are rigid polycarbonate, of dimensions $30.5\ \mathrm{cm} \times 30.5\ \mathrm{cm} \times 1.25$ cm. They rest on an aluminum substructure. A 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 (Fig. 3).

A vibrotactile actuator is rigidly attached to the underside of each tile via a steel mounting bracket. In applications that are interactive, data from the force sensors are digitized and transmitted via a serial USB link to a personal computer that interactively generates the vibrotactile signals. The actuators are inertial voice coil motors (Clark Synthesis model TST-239). They are capable of driving the floor surface with a greater power (by a factor of about four) than is required for the tiles used here. However, they are also used to prototype applications in which much larger tile surfaces are driven.

3.5 Temporal Interaction Design Considerations

A floor-based haptic communication display, such as that described above, can also be characterized in terms of temporal properties of the stimuli involved, and the user interactions, if any, that generate them. Conceptually, one can group these qualities into those describing short-time properties of the vibrotactile signals being displayed, the manner in which they are patterned on longer time scales, and the type of interactivity afforded by the display and application.

For the purpose of this paper, *short-time* features are those related to time scales (smaller than about 200 ms) over which the stimulus may be thought to be relatively stationary or unitary. Such signals can be thought of as building blocks from which more complex stimuli can be built. They may be characterized by properties related to their frequency content, temporal extent, temporal amplitude envelope, or modulation that is applied to any of these. Alternatively, they might, as discussed below, be designed by analogy to a physical event, such as an impact transient (IT), with properties resembling hardness or resonance.

Low-level signals can be profitably organized into structured *temporal patterns*. A motivation for doing so is to improve identifiability or to increase perceptual information content in a set of stimuli. The frequency bandwidth and temporal resolution of the tactile channel limit the amount of information that can be encoded via short-time features. In recent research on vibrotactile communication, musically inspired structures (motifs or rhythms) have been profitably used to design larger sets of vibrotactile icons that are perceptually well distinguished from each other [3], [35], [33], [21]. An alternative approach, discussed further below, is to arrange low-level signals to resemble the temporal pattern of a physical process, such as bouncing or breaking (for an example from an auditory perspective, see [39]).

Finally, properties related to the *interaction* itself refer to the manner in which vibrotactile signals are generated in response to user actions, as captured through sensors of the device. Here, one can also allow for the possibility that the device is noninteractive. Properties of the interaction are determined by the sensing method used, and the way in which the resulting data are used to control the synthesis of the vibrotactile signal. According to the nature of this control mapping, the interaction may be characterized as *discrete* or *continuous*. A continuous interaction gesture can be described as *effective* (in the gestural typology suggested by Cadoz [4]) if the vibrotactile signal is generated in a way that energetically increases with the energy of users' actions. A related notion is that stimuli may be synthesized as if generated by a virtual physical system, such as a bed of gravel, which is meant to be stepped upon.

3.6 Three Interaction Cases

To illustrate these design considerations, we present three different interaction case examples (Fig. 4) developed for the interface described in Section 3.4.

1. A floor surface displays structured vibrotactile signals composed of abstract elements (such as a sum of sinusoids with a certain temporal envelope) resembling musical notes and arranged in a rhythmic pattern (i.e., a *tacton*).

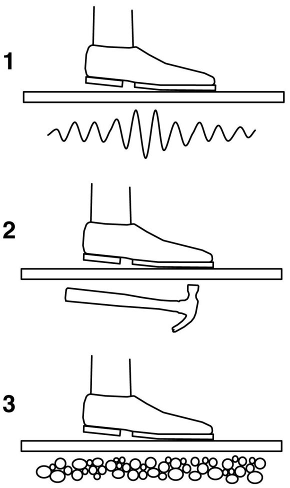

Fig. 4. Representations of three interaction paradigms. **1.** A vibrotactile message designed using waveform-level properties (i.e., a *tacton*). **2.** One derived from a model of a physical process, such as an object tapping on the tile. **3.** A virtual physical material interaction, such as a step onto a bed of gravel.

2. Such a surface presents stimuli that resemble the vibrational signature resulting from a physical object, such as a hammer, tapping with a rhythmic pattern on the underside of the tile. These representationally coded signals may be thought of as *tactile icons*.
3. A tile surface responds to the applied force exerted by a footstep with a signature approximating that of a natural ground material, such as gravel or snow. A computer simulation is responsible for rendering this feedback in a way that is highly dependent upon the measured force profile with which the step is executed in time [38].

Case 3 has been explored in an earlier publication by the authors [38]. Methods for the design of stimuli for cases 1 and 2 are described in detail in Section 3.7. They are evaluated in the experiments described in Section 4.

3.7 Vibrotactile Stimulus Design

Methods for the presentation of structured vibrotactile stimuli corresponding to case examples 2 and 3 of Section 3.6 were prototyped. The approach is based, in part, on a musical phrase metaphor that has been evaluated positively in recent literature on vibrotactile display [33], [3], [35]. In it, a stimulus is encoded in a rhythmic phrase, characterized by a set of notes each having a certain onset time, duration, and amplitude. A phrase is constrained to consist of two or more repetitions of a musical bar. The time domain of a single bar is quantized into 24 unit steps. A tempo is set, determining the total duration of a bar (in seconds). Notes can begin at any step and possess durations given by integer numbers of steps. Only a single note is allowed to play at any time. The amplitude of each is specified at its onset. Notes within the pattern of a given vibrotactile signal differ only in their amplitudes and durations, so that all possess the same short-time parameters (e.g., frequency and roughness). This limits the number of parameters that must be specified for each

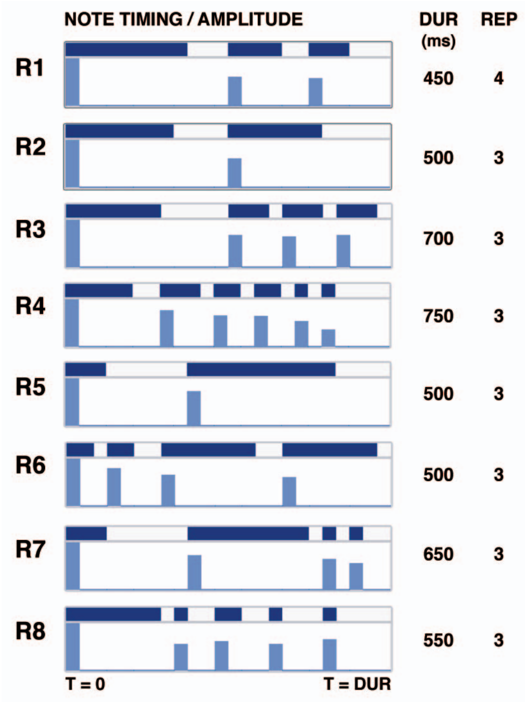

Fig. 5. The eight rhythms (R1-R8) from which both sets of stimuli were built. Time runs left to right. The bold horizontal lines show the temporal extent of notes. The vertical bars coincident with the onsets indicate amplitude. Bar duration and number of repetitions are shown.

stimulus. The algorithms used to synthesize the note-level signals are described in the sections that follow.

The vibrotactile signals used in the experiment described in Section 4 were built from a set of eight rhythmic patterns generated using this method. The corresponding bars are shown in Fig. 5. The duration of each bar is between 450 and 750 ms, and each is repeated a fixed number of times (either three or four). As shown in the figure, an accented note marks the beginning of each bar, serving as an "anchor" for the pattern [33]. The waveform of a stimulus from the experimental set, corresponding to rhythm R1 from Fig. 5, is shown in Fig. 7.

3.7.1 Waveshaping Synthesis

The first approach we adopted to the design of short-time stimuli is based on the specification of basic signal properties affecting the frequency content, duration, amplitude modulation, and amplitude temporal envelope of the signal, as prescribed in case example 1 of Section 3.6.

A basic harmonic signal $s(t)$ is composed of a sum of a fundamental sinusoidal component $s_0(t) = \sin(\omega_0 t)$ at angular frequency ω_0, and N harmonic components at frequencies $\omega_k = k\omega_0$. The desired waveform can be efficiently generated by a standard technique from audio synthesis, known as Chebychev waveshaping [1]. In it, $s_0(t)$ is passed through a static nonlinear transfer function $w(x) = \sum_k a_k T_k(x)$, where a_k are the desired harmonic amplitudes and $T_k(x)$ is the kth Chebychev polynomial. The result gives the desired harmonic signal $s(t)$ as

$$s(t) = w(s_0(t)) = \sum_k a_k T_k(s_0(t)) \tag{1}$$

$$= \sum_{k=0}^{N-1} a_k \sin(\omega_k t). \tag{2}$$

Using this method, it is simple to design a waveform whose energy lies within the target frequency band, centered on approximately 250 Hz.

The complete short-time waveform $y(t)$ is obtained by multiplying the harmonic waveform $s(t)$ by an amplitude envelope function $e(t)$ with desired starting time t_s, duration T, amplitude A, and attack and decay times t_a and t_d. Finally, it is subjected to form of roughening, via amplitude modulation with a signal $r(t) = 1 + m_r \sin(2\pi f_r t)$ of frequency f_r and modulation depth m_r. That is, $y(t) = s(t)\, e(t)\, r(t)$.

o generate the stimuli used in the experiment (Section 4), $N = 10$ harmonics were used, with fundamental frequency f_0 between 30 and 70 Hz, and a modulation frequency of $f_r = 25$ Hz. The harmonic amplitudes a_k and the roughness m_r, were set heuristically by the designer, as was the base frequency f_0. Waveforms used in the experiments are shown in Fig. 6a.

3.7.2 Synthesis of Virtual Impact Transients

The second method used to synthesize short-time stimulus components is based on virtual impact events, consisting of transient forces generated by the collision of two virtual elements: an exciting, but nonresonant object, termed the

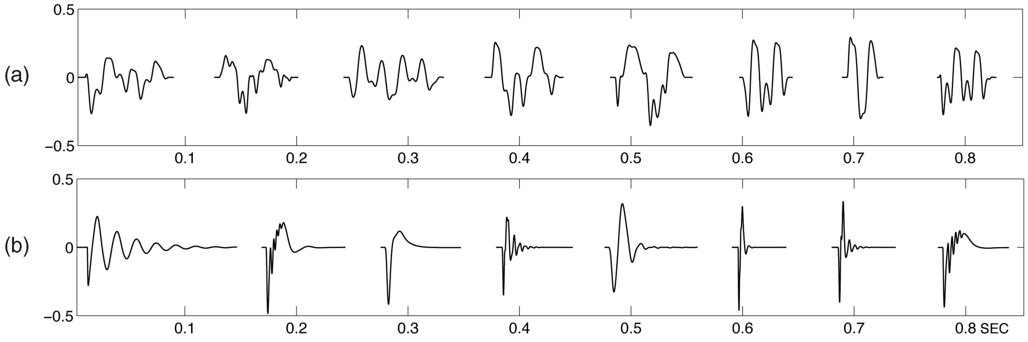

Fig. 6. Waveforms used to generate stimuli used in the evaluation, ordered as reported on in the experiment. (a) Those generated using waveshaping synthesis. (b) Those generated using virtual impact transient model. The final stimulus sets result upon superimposing the rhythmic patterns described in Section 3.7.

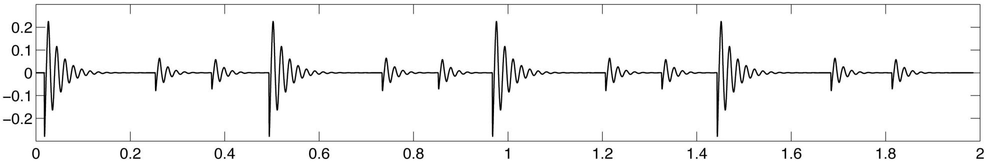

Fig. 7. Example of a stimulus used in the experiment, resulting from the model settings that produced the first "impact" waveform of Fig. 6 in combination with the first rhythmic pattern of Fig. 5.

hammer, and a resonant object, termed the sounding object [27]. The impact force $F(t)$ is generated by an efficient, physically based synthesis model obtained from a simplified version of Hertz' law, known as the Hunt-Crossley model [13]. It is obtained by numerically integrating the differential equation

$$F(t) = kx(t)^{\alpha} - \lambda x(t)^{\alpha}\dot{x}(t). \quad (3)$$

Here, $x(t)$ is the compression displacement and $\dot{x}(t)$ is the compression velocity. The impact force has parameters governing stiffness k, dissipation λ, and contact shape α. This force is provided as an input to the resonant sounding object. The latter is modeled as a set of N resonant filters operating in parallel, with a combined impulse response given by

$$y(t) = \sum_{i=1}^{N} a_i e^{-b_i t} \sin(\omega_i t), \quad (4)$$

and determined by a set of parameters governing the modal amplitudes a_i, decay rates b_i, and resonant angular frequencies ω_i. An impact event is synthesized by initializing (3) with the desired velocity v_I of impact, and subsequently, integrating the composite system in time. See [27] for a more detailed discussion, including an overview of the numerical implementation we have used, which is based on the open source Sound Design Toolkit from the University of Verona.

The impact event transients used in the evaluation part of this paper were synthesized with two resonant modes ($N = 2$). The transients themselves exhibit more complex frequency spectra than this might suggest, due to dynamic coupling of the nonlinear impact model with the modal resonant object [27]. Exemplary waveforms synthesized for the evaluation using this method are shown in the bottom of Fig. 6.

4 EVALUATION

An evaluation of the methods for vibrotactile information display via floor surfaces that were described above has been conducted. The aim was to determine whether vibrotactile signals designed in the two ways described could be distinguished when presented via a floor surface. Two sets of eight signals were designed, one based on the waveshaping method and the other based on the virtual impact transient method. (We refer to these as sets WS and IT, respectively.) Both sets were designed using the same eight underlying rhythmic patterns (shown in Fig. 5) as noted in Section 3.7.

The vibrotactile stimulus sets differed, therefore, only in the note-level signals from which they were composed. Each tacton from the waveshaping synthesis (WS) set was assigned distinct values of the fundamental frequency f_0, ten harmonic amplitudes a_k, and amplitude modulation depth m_r. Stimuli from the impact transient set were each designed with different values of the hardness k, contact shape α, and of the frequencies ω_i and decay factors b_i of the two modes. The latter were chosen so that the frequency spectrum of the stimulus had most of its energy near 250 Hz.

Another significant difference between the two sets of stimuli is that the notes from the waveshaping synthesis set differ in duration according to the length of the note in the bar, while in the impact transient set, the amplitude envelope of each note decays exponentially as determined by the modal decay factors b_i. However, because the relevant decay times were generally short, as can be seen in row 2 of Fig. 6, the durations were shorter, in nearly all cases, than in the WS set, and they were independent of the note duration specified in the rhythmic pattern.

The experiment assessed both the rate of correct identification and learning for the two sets. In descriptive comments received during pretesting, we observed a tendency for people to describe the IT stimulus set in terms of familiar impact events. As a result, we hypothesized that these stimuli might prove more recognizable, despite the smaller number of parameters that were used to distinguish them, and the relative lack of note duration information in the patterns.

4.1 Methodology

A total of 24 people aged between 20 and 39 years took part in the experiment. All gave their informed consent in agreement with university ethics guidelines. Twelve of them were male and 12 were female. Fourteen of them were university students. The experiment was designed with a single independent factor, resulting in each group of 12 participants being presented with the task of identifying stimuli from one set. A between-groups design was used because the rhythmic content in the two stimulus sets is identical, so participants exposed to one set would be expected to perform better than otherwise expected with the second set.

Each participant was given a pair of hard soled men's dress shoes in his or her size to wear during the experiment. Apart from size differences, all the shoes were identical. The amplitude of vibration of the tile was adjusted as needed for each participant, depending on his or her ability to detect a reference vibrotactile noise signal. At the beginning of the session, participants received instructions, together with an explanation and demonstration of the experimental interface and the operation of the display. At all subsequent stages (except during pauses), participants were required to stand on the actuated floor surface, and to wear closed-ear headphones playing pink noise at a loudness sufficient to mask the (generally low-level) sounds produced by the apparatus. The software application used during the experiment ran on a personal computer, implementing the respective design method from Section 3.7. In addition to the floor tile, the interface consisted of a graphical user interface with numbered buttons, one for each icon, presented on a computer monitor. Participants selected items in the graphical user interface using a mouse.

The experiment was based on absolute identification of the eight stimuli from the respective set, with a unique correct response required for each (the numerical identifier of the icon, ranging from 1 to 8). The same stimuli were used for all participants within a given group, but they were presented in random order in each session of the experiment, with a different ordering presented to each participant.

After an introduction to the device and interaction method, participants were given five minutes of self-guided learning. During this time, they could select a numerical identifier and be presented with the stimulus corresponding to their selection. The rest of the experiment was divided into six sessions. During each session, all stimuli were presented twice. Thus, overall, each participant was asked to identify every vibrotactile stimulus from their set a total of 12 times. Each session took less than about four minutes to be completed. Participants were allowed a short break between sessions, but in most cases, preferred to continue so as to avoid forgetting the learned associations. Participants were presented with stimuli sequentially. 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 [11], the reason for providing feedback was to facilitate the assessment of recognition after learning and rate of learning throughout the experiment.

4.2 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.

The stimulus sets each included eight items, near the limit of what participants might be expected to retain in working memory. Training was limited, consisting of a maximum of, on average, 20 reinforced presentations of each stimulus at the end of the final session. The stimuli were not assigned any mnemonic, other than an arbitrary numerical index, that could be used to remember them. Although introducing a semantic association to each stimulus (for example, the name of a meaningful event) can be used to improve recall, good design of display and stimuli is a prerequisite to good performance [33]. Since our intention was to assess the suitability of the display methods behind these two stimulus sets, we wished to avoid introducing any external effects that might be associated to the choice of semantic labels.

The mean rate of correct identification after six sessions of enforced learning, averaged between all participants (including both stimulus sets) was 61 percent, with a standard deviation of 21 percent. Chance performance would correspond to 12.5 percent. Postlearning identification rates for participants in the impact transient group and for those in the waveshaping synthesis group are shown in Fig. 8. Four of the 12 participants in the IT group were able to achieve 80 percent or better correct identification after less than 20 minutes of enforced learning. One of the 12 participants in the WS group was able to reach this level of performance.

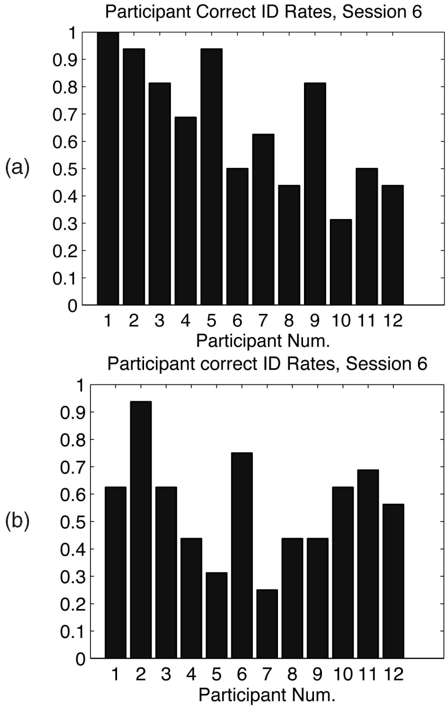

Fig. 8. (a) Correct identification rate for each of the 12 participants in group assigned to stimulus set IT, after six sessions of assessment with enforced learning. (b) Similar rates for the WS set group.

The results obtained appear to be comparable to published results on absolute identification of vibrotactile stimuli via manual interfaces after short periods of learning. For example, Enriquez et al. reported average identification performance of 73 percent (versus the expected chance performance rate of 33 percent) after an average of 20 minutes of learning [5].

The confusion patterns for the stimuli in each group of the experiment are shown in Fig. 9, averaged between all sessions and participants. The least confused stimulus was identified at an average rate of 80 percent, while the most confused stimulus was identified at an average rate of only 25 percent. A close comparison of the confusions within each stimulus set with the stimulus properties themselves did not reveal any easily discernible feature of the rhythms or the short-time waveforms that caused them to be confused. Nonetheless, the confusion patterns for the two sets appear to be relatively distinguished from one another, which suggests that the short-time features were perceived differently. Performance varied considerably between participants as the experiment proceeded, with a few showing consistently high improvement between sessions, while

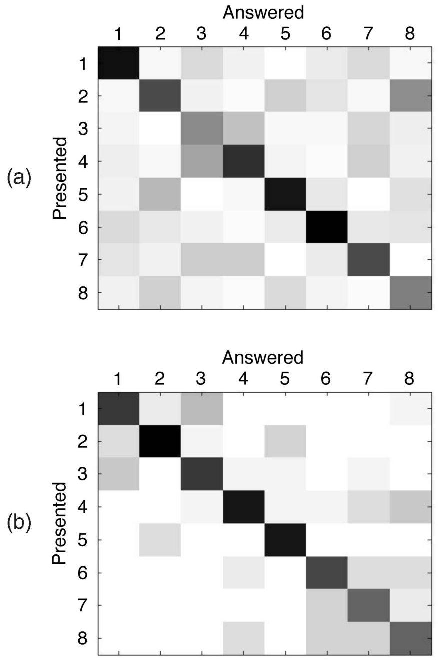

Fig. 9. (a) Confusion pattern within the set of eight WS stimuli in session 6, averaged between participants. (b) The same data for the set of eight IT stimuli.

others showed nearly none. A summary of the mean correct identification rate using each icon set, averaged between all sessions, is provided in Fig. 11. Mean performance on the impact transient set was higher than on the waveshaping synthesis set, but the level of significance is marginal (ANOVA 1-way $p = 0.06$). Mean correct identification rates in each enforced learning session are shown in Fig. 10. The mean correct identification rate after each of the first two training sessions was significantly higher for the IT set ($p = 0.01$ and 0.02, respectively), but thereafter, the results lacked significance ($p > 0.1$ in all cases).

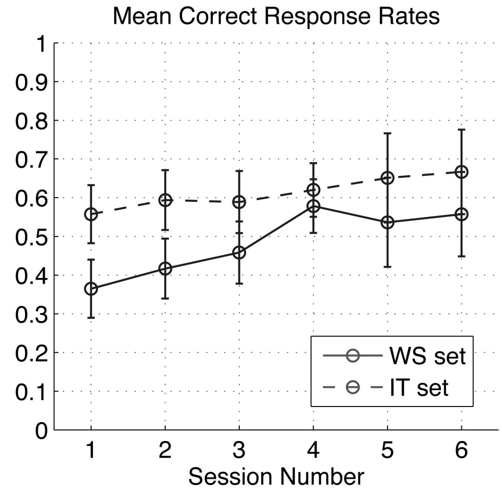

Fig. 10. Mean correct identification rates in each session. The error bars show 95 percent confidence intervals.

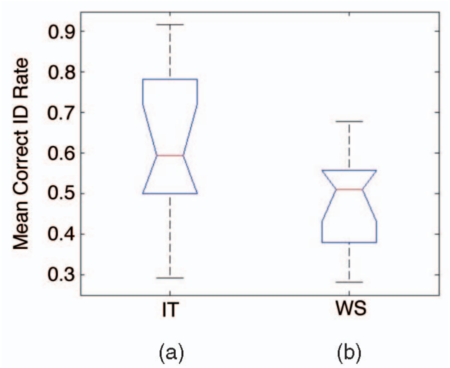

Fig. 11. Box plot summary of the mean correct identification rate for the (a) IT and (b) WS stimulus sets.

The IT group approached its peak performance with far fewer presentations of the stimuli than was the case for the WS group. Concretely, after session 1, the IT group achieved more than 80 percent of the performance it reached in session 6, a rate that the WS group would not achieve until session 3. This suggests that stimuli similar to the IT set might be advantageous for applications in which little training would be expected, although further investigation of this is needed. Examples of such applications could include displays in public spaces, such as crosswalk indicators.

4.2.1 Subjective Ratings and Comments

Participants completed questionnaires after the experiment, rating the task difficulty, subjective properties of the stimuli, providing descriptive feedback regarding the strategies they adopted. Participants were asked to rate the difficulty of the first task session and the last session on a scale from 1 (very easy) to 5 (very hard). As expected, the first task session was rated as significantly harder than the last session (mean 3.96 versus 3.04, with $p = 0.04$).

An analysis of the rated difficulty of the first session (Anova one-way), with the stimulus set type as the independent factor, revealed the WS set was perceived as initially harder than the IT set (mean 4.4 versus 3.5, with $p = 0.02$). However, there were no statistically significant differences between the rated difficulties of the stimulus sets during the last session. This echoes what was seen in the performance data: the IT stimulus set was more identifiable than the WS set at the beginning of the experiment, but the difference faded before the end of the experiment. Based on participant comments, cognitive fatigue may have been a factor here.

The study also aimed to assess the level of comfort to users of a vibrotactile display employing these stimuli. Participants were asked to rate the vibrotactile stimuli on a five-point scale from 5 (comfortable) to 1 (uncomfortable). The average rating among all participants was 3.5 with a standard deviation of 1.1. No participant rated the stimuli as uncomfortable, and no significant differences in comfort ratings were found between the two groups. Some of them noted becoming uncomfortable with standing in the same place and posture during each session.

During subsequent interviews, several participants reported that the association part of the task, which required them to learn the numerical indices of the stimuli, was the hardest part of the experiment, and that they experienced cognitive fatigue as the experiment wore on. Some participants suggested the task may have been facilitated by the addition of semantic information or a nonnumerical mnemonic symbol (e.g., an animal name). As discussed above, this observation may hold potential for aiding the association part of the task, and, while it would certainly make sense for an application designer to consider, it does not necessarily speak of the design of the stimuli themselves.

4.2.2 Description of the Cause of the Stimulus

In a separate study, 10 people who did not participate in the forgoing experiment were presented with the 16 stimuli from the sets used above, in random sequential order, and were asked to provide, using their own words, a short label describing what caused the vibration. Sensory conditions were the same as in the first experiment. The most common response was "unknown" (about 18 percent of IT set labels and 40 percent of WS set labels). One hundred and thirteen other responses were obtained, 72 of which were unique, if often very similar (e.g., "door knock" and "angry door knock"). Among these labels, most were related to familiar impact events, including: "door knock," "horse gallop," "hammer," "drum," "foot falls overhead," and "tapping." To give one example, the second IT stimulus was described by seven of 10 participants as caused by a "knock" or "knocking," and by another two as originating from a "hammer." There appeared to be a greater tendency for IT set stimuli to be attributed to such events than was the case for WS set stimuli (mean 58 percent versus 18 percent, with $p = 0.0002$). Here, however, we used our own judgement in deciding whether a label referred to an impact. Several labels were associated only to the WS set, including: "bass guitar," "cellphone," "machinery," and "car start."

While it seems likely that there are differences in causal interpretation between the two groups of stimuli, more research is clearly needed. It is tempting to suggest that such differences, if established, might be linked to the effectiveness of the stimuli at communicating information. However, analogous research in the auditory display domain, comparing the effectiveness of melodically designed "earcons" with representational "auditory icons," has shown that this issue is far from simple or straightforward [2].

5 CONCLUSION

Floor surfaces already play roles that intimately link tactile sensation in the feet to our everyday activities. The use of such surfaces as displays for active haptic communication appears to be a valuable idea, and one that naturally extends accepted areas of practice in the design of haptic information for ground surfaces. We have highlighted the range of roles that such an interface might play in future applications, and have pointed to a few potential end user applications that illustrate these roles.

Distinguishing advantages of these displays include their applicability to a wide range of settings and environments, their ready accessibility to anyone on foot, and their potential for seamlessly presenting dynamic information linked to a specific location, navigational, or locomotor task.

We have outlined design considerations for haptic communication through floor surfaces and detailed a device and set of interaction studies that have been developed to embody these. The technological feasibility of such devices is high and the cost of prototyping them is low.

A characterization in terms of temporal interaction properties was used to organize different possible interaction designs presented through the floor interface, and three demonstrations that we have developed were described and situated within it. Stimulus design methods based on signal-level specifications were highlighted, by close analogy to prior work on vibrotactile information display. Design methods based on physical metaphors, such as virtual impact events or structured materials, were also presented.

The experimental results support the identifiability of vibrotactile messages conveyed through floor surfaces and point toward the adaptation of design guidelines developed for other modes of haptic display to this setting. They also suggest that physical metaphors may hold promise for improving the design of stimuli for such an information display, although further research is needed on this subject.

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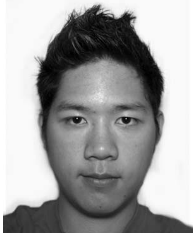

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