HaptWrap: Augmenting Non-Visual Travel via Visual-to-Tactile Mapping of Objects in Motion

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ABSTRACT

Access to real-time situational information at a distance, including the relative position and motion of surrounding objects, is essential for an individual to travel safely and independently. For blind and low vision travelers, access to critical environmental information is unattainable if it is positioned beyond the reach of their preferred mobility aid or outside their path of travel. Due to its cost and versatility, and the dynamic information which can be aggregated through its use, the long white cane remains the most widely used mobility aid for non-visual travelers. Physical characteristics such as texture, slope, and position can be identified with the long white cane, but only when the traveler is within close proximity to an object. In this work, we introduce a wearable technology to augment non-visual travel methods by communicating spatial information at a distance. We propose a vibrotactile device, the HaptWrap, equipped with vibration motors capable of communicating an object's position relative to the user's orientation, as well as its relative variations in position as the object moves about the user. An experiment supports the use of haptics to represent objects in motion around an individual as a substitute modality for vision.

CCS CONCEPTS

• CCS → Human-centered computing → Accessibility → Accessibility technologies

KEYWORDS

Nonvisual travel; Haptics; Vibrotactile display; Assistive device

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1 Introduction

Non-visual travel is primarily achieved using a long white cane, guide dog, or human guide. According to the World Health Organization, "188.5 million people have mild vision impairment, 217 million have moderate to severe vision impairment, and 36 million people are blind" [1]. Although the exact number of white cane users is unknown, it is estimated that only two percent of individuals who identify as blind or low vision use a guide dog as their primary means of non-visual travel. Of the estimated two percent who use a guide dog, they must also be capable of independent travel via another method which suggests they are also white cane users. However, due to the limited capability of these non-technical mobility methods to detect objects above the waist, objects approaching from the rear, or objects at a distance, mobility aids utilizing technology are being explored to augment non-visual travel.

There are three subcategories of assistive technology designed to enhance non-visual travel. Electronic Travel Aids or ETAs are used to gather real-time information about the environment, such as objects which pose as obstacles, before presenting it to the user through another modality such as speech, audio, and/or haptics. Electronic Orientation Aids or EOAs are used to provide orientation information to the user prior to or during travel to augment non-technical methods of travel. Position Locator Aids or PLAs utilize Global Positioning Systems (GPS) to assist in way-finding or step-by-step directions, primarily conveyed through speech, to assist the user with locating a specified destination.

At the present time, current technologies are inefficient as a substitute for non-technical orientation and mobility skills, methods, or aids, but can be effective in augmenting the amount of accessible information for non-visual travelers. For example, a cane user interrogates his or her immediate surroundings to obtain identifiable information about objects such as texture, size, slope, and position. Consequently, the white cane has a limited reach for detecting these objects from a distance, and requires individuals to collide with objects, which poses safety concerns. In contrast to the white cane, a guide dog assists with obstacle avoidance; however, by avoiding obstacles, the user is unable to obtain useful information regarding their surroundings, limiting their access to critical landmarks used for way-finding. To effectively augment non-visual travel, a discreet and nonintrusive solution should provide details about the environment at a distance greater than the user already has access to through current non-technical methods.

Little work has been done to understand the techniques, methods, and tools involved in non-visual travel. To gain an in-depth perspective, we surveyed 90 individuals who identified as blind or low vision. Additionally, we conducted interviews with 15 orientation and mobility professionals who all hold a certification from an accredited university in the strategies and technologies involved in non-visual travel. Need-finding results guided the development of the proposed technology by carefully ensuring our design decisions appropriately addressed the wants and concerns of the target population.

We propose a wearable technology capable of enabling 360 degrees of spatial awareness through the use of vibration motors worn around the torso of the user in a form factor we refer to as the HaptWrap. The design leverages our egocentric frame of reference to intuitively communicate the relative positions of objects in a user's surrounding space. We provide support for the use of haptics to communicate the state of static (stationary) or dynamic (moving) objects in a user's environment using a multidimensional vibrotactile mapping of an object's relative elevation, distance, and direction. Experimental results demonstrate the ease and naturalness of recognizing dynamic patterns (i.e., patterns describing movement) compared to static patterns (i.e., patterns describing a stationary object) given the rich complementary and redundant information in an object's motion as its position and orientation vary relative to the user. This work focuses on exploring how spatial information may be delivered to the sense of touch. Future work will explore 360-degree vision-based systems for detecting objects and classifying obstacles to drive the HaptWrap in real-time and in real-world environments.

2 Related Work

Technology for augmenting non-visual indoor and outdoor travel through sensory substitution (i.e., replacing one modality, such as vision, with another modality, such as touch) has explored presenting visual information through three alternative methods: audio, speech, and haptics. The primary objective of indoor navigation is obstacle avoidance in a confined environment. Drishti [2] was proposed for both indoor and outdoor navigation using voice commands and speech output to independently guide users who are blind through familiar and unfamiliar settings. Jain [3] deployed a mobile application at a New Delhi national museum to provide step-by-step navigation through the displayed artifacts using audio and speech guidance. Safe navigational assistance indoors comes with challenges: Existing infrastructure is needed for indoor positioning, and a system capable of providing the precision and accuracy necessary to ensure safety is expensive and difficult to scale or modify. Moreover, the speech output of previous approaches for describing objects and obstacles in this setting deprives users of their sense of hearing.

Outdoor navigation utilizes GPS, but not without introducing complexities not present in indoor travel. For example, when traveling on busy streets or residential walkways, an assistive device must take into account low-hanging obstacles, such as trees, and path barriers such as signs, benches, or other pedestrians as well as vehicles. The University of Santa Cruz surveyed 300 individuals who identified as blind or low vision, and found "86 percent of the head-level accidents happened outdoors, with 8 percent of the respondents reporting accidents both indoors and outdoors, and 6 percent only indoors" [4]. The survey results also revealed that tree branches were the majority of outdoor accidents, but vehicles, construction equipment, poles and signs commonly caused accidents as well. Some work has explored solutions for real-time detection of head-level obstacles using haptic feedback [5-8].

Our sense of touch offers a promising alternative modality for discreetly communicating spatial and situational information. Our skin has impressive temporal and spatial acuity [9], and is our largest sensory organ [10], providing an expansive surface area for mapping visual information to tactile stimulation. In this work, we introduce a novel vibrotactile device called the HaptWrap: A wearable two-dimensional array of vibration motors that is worn around the user's torso. We investigate how to map objects in three-dimensional space to multidimensional vibrotactile stimulation patterns to assist individuals who are blind with building better cognitive mappings of their environment. Enhancing spatial perception will support obstacle avoidance, identification of points of interest, and information discovery in familiar and new real-world environments.

3 Proposed Approach

3.1 Hardware and Software Design

The HaptWrap, depicted in Fig. 1, consists of a waist-trainer outfitted with a two-dimensional array of vibration motors, attached directly to its inner lining. Custom-designed printed circuit boards drive twenty-four (three rows and eight columns) 8 mm eccentric rotating mass (ERM) vibrating motors. The eight columns of motors are equidistantly spaced horizontally to cover a user's waist 360 degrees. While horizontal spacing varies based on a user's waist size, vertical spacing of motors remains constant at 2 inches center-to-center. Both horizontal and vertical spacing are well within the limits of vibrotactile spatial acuity for the torso [9].

The motors are driven by an 8-bit pulse width modulation (PWM) signal provided by an LED driving integrated circuit (IC) implementing the WS2811 protocol. The PWM signal is connected to the gate of a transistor to increase the amount of current to 80 mA as well as to protect the IC from the back EMF voltages of up to 40 v from the motors. The WS2811 ICs operate on a one-wire repeater protocol, where updates are sent in packets and each IC takes in the first 24 bits through the data-in pin and forwards the remaining through the data-out pin. This allows a large number of motors to be strung together and controlled from a single pin on a microcontroller.

For control, we use a Raspberry Pi 3 b+ with a quad core arm processor clocked at 1.4 Ghz and 1 GB of SRAM. The HaptWrap software was developed using the Python programming language, and interfaces with vibration motors via the NeoPixel library built for the Raspbery PI, distributed by Adafruit.

Figure 1: A model demonstrating how to wear the HaptWrap. Typically, the HaptWrap is worn underneath clothing for discreet use. The HaptWrap is in the form a waist trainer worn just below the rib cage, and at or above the waist. Based on waist size, the positions of motors are easily adjustable using Velcro.

3.2 Visual-to-Tactile Mapping

Duarte et al. previously explored how dimensions of elevation, distance, and direction of objects in front of the user could be displayed on their back using a two-dimensional array of fourty-eight vibration motors (six rows and eight columns) [11]. While this previous work was limited to static patterns and 180 degrees in front of the user, these pilot results reveal the potential of mapping visual information of surrounding objects to multidimensional vibrotactile patterns for augmenting non-visual travel. Here, we improve upon their proposed mapping by expanding the display area to the torso (just below the rib cage, and at or above the waist) to enable perception of objects 360 degrees around the wearer.

An object's elevation is mapped vertically, i.e., to one of the three rows of the HaptWrap; angle (direction) is mapped horizontally, i.e., to one of the eight columns of the HaptWrap; and distance is mapped to a tactile rhythm analogous to a heartbeat that varies in tempo. The design of our proposed tactile rhythms is inspired by the work of McDaniel et al. [12] where similar patterns were successfully used for conveying interpersonal distance within a vision-based social assistive aid for individuals who are blind. In the work of McDaniel et al., the analogy of a heartbeat was used to enhance the perception of someone coming closer to you by increasing the tempo of a vibrotactile rhythm, i.e., the interaction is becoming more intimate as someone nears you. This analogy carries over well to objects in a user's environment. Three tempos were selected to convey three distances: a slow heartbeat indicates an object is far at 20 feet; a fast heartbeat indicates an object is close at 10 feet (at 5 to 7 feet, the object will come into contact with the user's white cane); and a heartbeat at a tempo between these slow and fast speeds indicates an object at 15 feet.

3.2.1 Static Representation. Objects in the environment can be stationary (static) or moving. For a stationary object's relative position, its static representation for display on the HaptWrap consists of the following. Each row of the HaptWrap, from top to bottom, represents a different elevation: head-height (e.g., a person), chest-height (e.g., a vehicle), and waist-height (e.g., a chair). Each column of the HaptWrap represents a different direction: 0 degrees (user's midline), 45 degrees, 90 degrees (user's right side), 135 degrees, 180 degrees (user's spine), 225 degree, 270 degrees (user's left side), and 315 degrees. Each of the three tactile rhythms represents a different distance as previously described. For example, if an object has an elevation of head-height (e.g., a low-hanging tree branch), direction of 0 degrees (directly in front of the user), and a distance of approximately 10 feet, the vibration motor at the top row directly in line with the belly-button would execute a heartbeat rhythm with a fast tempo. Fig. 2 depicts the mapping of elevation and direction to body sites around the waist. Fig. 3 depicts the mapping of distance to vibrotactile rhythm.

3.2.2 Dynamic Representation. Objects are considered to be in motion when moving and/or when the user is moving through his or her environment. Dynamic representations consist of consecutive presentations of an object's varying relative position, each represented by a static pattern. The HaptWrap employs an attention-grabbing vibrotactile pulse, triggered immediately before the presentation of any dynamic pattern. This pointer beat (0.99 s pulse width) serves two purposes: First, the pulse alerts the user of the presence of an object at a specific direction, thereby quickly communicating the "where," followed by information that allows the user to ascertain the "what." Second, the pulse provides a comparative baseline for easing recognition of the different elevations. The pointer beat is always triggered at chest-height. Objects at head-height or waist-height are perceived as shifts upward or downward in elevation, respectively, or no shift when the object's height is waist-height. Fig. 5 depicts two examples of dynamic patterns.

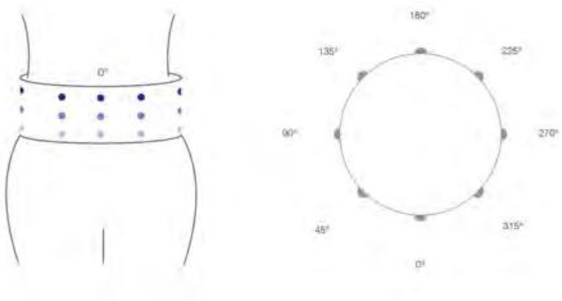

Figure 2: An artist's rendition of the HaptWrap. The drawing on the left depicts a frontal view; elevation is mapped to vertical body sites. The drawing on the right depicts a top-view of the layout of actuators around the waist; direction is mapped to equidistantly spaced body sites around the waist in 45-degree increments.

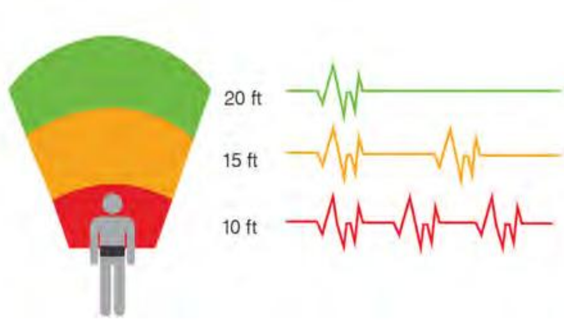

Figure 3: Artist's rendition of tactile rhythms. Rhythm design was inspired by the work of [12]. A single "heartbeat" consists of two beats, each of pulse width 0.55 s, and separated by a gap of 0.06 s. The rhythm for 10 feet separates each heartbeat by a gap of 0.25 s. The rhythm for 15 feet separates each heartbeat by a gap of 0.5 s. The rhythm for 20 feet separates each heartbeat by a gap of 1 s.

4 Experiment

4.1 Aim

This aim of this study is to investigate the ease of recognition and naturalness of the proposed visual-to-tactile mapping of elevation, distance, and direction, both statically and dynamically. In particular, we are interested in any perceptual differences between static and dynamic representations given that most objects in the environment will be encountered under non-stationary scenarios, i.e., the object and/or the user is moving.

4.2 Subjects

Eight individuals who self-identified as blind or visually impaired were enrolled in and completed this IRB-approved research study. One of these subjects could not complete the last 10 minutes of the study due to mental and physical fatigue, but the data that had been collected was still usable and therefore included in the analysis. The eight participants consisted of three males and five females, ages ranging from 23 to 74 years old (*M*: 45, *SD*: 17). Two participants were born blind, and the remaining acquired blindness later in life.

4.3 Apparatus

The HaptWrap, as described under Section 3, was used without modification. Additionally, a Graphical User Interface (GUI) was designed to ease the experimental procedure. To conduct a controlled study, static and dynamic patterns were manually created rather than relying on computer vision to extract situational cues from the environment; although this is the intended future use of the technology, and will therefore be the subject of subsequent work. Each static pattern consisted of a list containing three values representing indices identifying an object's elevation, distance, and direction. Dynamic patterns were hand-designed to describe real-life situations where objects are encountered by an individual traveling in society. Some examples include a pedestrian walking up behind the traveler and passing to the right around him or her and continuing on; a vehicle passing left to right in front of the user; or approaching a chair in a large room. A total of seventeen dynamic patterns were created and stored as a dictionary containing a list of lists. The construction of a single dynamic pattern was designed by defining individual static patterns that intuitively describe an object in motion. Both static and dynamic patterns were stored in a json formatted flat file. The GUI easily allowed the experimenter to send static or dynamic patterns to the HaptWrap, and record participants' guesses.

4.4 Procedure

The experimental procedure consisted of two phases: a static phase followed by a dynamic phase. During the static phase, participants start with a familiarization stage where they are introduced to each dimension (elevation, distance, and direction) individually. Participants were then evaluated on their recognition accuracy of twenty-nine static patterns representing objects in three-dimensional space. For each participant, these patterns are randomly selected from a total of seventy-two possible patterns representing all combinations of values for the three dimensions. Participants were asked to identify each dimensional value making up the full multidimensional pattern. Participants were allowed to request any number of pattern repeats, which were tracked by our software to assess performance. Guesses were also recorded by the experimenter and entered into the GUI to assess recognition accuracy. Incorrect guesses were corrected and correct guesses were confirmed to support learning during the static phase in preparation for the dynamic phase.

To assess the naturalness and ease of recognizing dynamic patterns, the dynamic phase skipped familiarization. Participants were randomly presented, and asked to describe in detail, seventeen dynamic patterns representing an object in motion around them, or alternatively, their movement toward a stationary object. As described previously, each dynamic pattern conveys a real-life scenario using a series of static patterns. Rather than identify each individual dimension, participants were asked to explain, in their own words, what they interpreted. Participants were allowed to request any number of pattern repeats, which were recorded. Accurate descriptions were confirmed, and any inaccuracies were corrected to support learning during the dynamic phase.

Finally, a post-experiment survey was completed by each participant to record subjective feedback regarding the ease of recognizing the stimuli as well as the naturalness of the proposed mapping.

4.5 Results

We define recognition accuracy as the percentage of correct guesses out of the total number of pattern presentations. During the static phase, the mean recognition accuracy of the complete, multidimensional vibrotactile pattern (averaged across participants) was *M*: 62.4%, *SD*: 14.6%. For the complete pattern, a guess is counted as correct if the participant guesses all individual dimensions (elevation, distance, and direction) correctly. Investigating the recognition accuracy of the individual dimensions alone, we find a mean recognition accuracy (again, averaged across participants) of *M*: 95.7%, *SD*: 6.4% for elevation; *M*: 66.3%, *SD*: 11.8% for distance; and *M*: 98%, *SD*: 2.4% for direction. Each participant requested, on average, 11.6 repeats (*SD*: 11) for the whole experiment (static condition).

During the dynamic phase, the mean recognition accuracy of the complete, multidimensional vibrotactile pattern (averaged across participants) was *M*: 95.3%, *SD*: 6.1%. Guesses for complete patterns are counted as correct when the participant accurately describes all dimensions, i.e., elevation is described correctly (e.g., person, vehicle, etc.), distance is described correctly (e.g., the person is far away, now walking closer to me, passes me, and is now walking farther away again), and direction is described correctly (e.g., the person is at my right side, now moves around me to my front, and now moves around me to my left side). Recognition accuracy for individual dimensions are *M*: 99%, *SD*: 2.7% for elevation; *M*: 99.2%, *SD*: 2% for distance; and *M*: 97%, *SD*: 6.2% for direction. Each participant requested, on average, 1 repeat (*SD*: 1.5) for the whole experiment (dynamic condition). Fig. 4 depicts a bar plot of static versus dynamic mean recognition performance for comparison. Table 1 presents the post-survey questionnaire assessing subjective ease of recognition and naturalness of the proposed patterns.

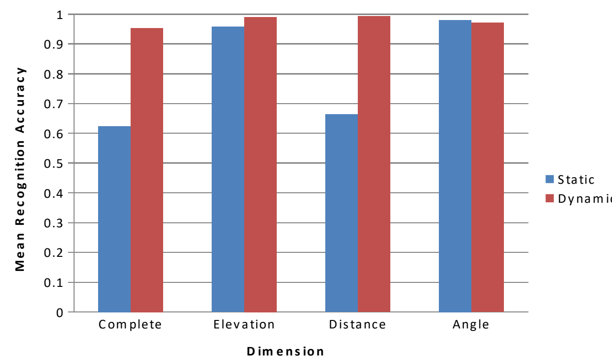

Figure 4: Static and dynamic mean recognition accuracy of the proposed multidimensional patterns and each individual dimension including elevation, distance, and angle (direction).

Table 1: Survey responses. (*A*) Ease of recognizing individual dimensions. (*B*) Naturalness of mapping for individual dimensions. Likert scale: 1 (very hard) to 5 (very easy).

Questions	*M (A)*	*SD (A)*	*M (B)*	*SD (B)*
Waist-Height	4.5	0.7	4.0	1.2
Chest-Height	4.7	0.4	4.2	1.2
Head-Height	4.8	0.3	4.1	1.2
0° (center)	5.0	0.0	4.8	0.3
45° (right, front)	4.7	0.4	4.7	0.4
90° (right side)	5.0	0.0	4.8	0.3
135° (back right)	4.8	0.3	4.7	0.4
180° (back center)	4.8	0.3	4.8	0.3
225° (back left)	4.8	0.3	4.7	0.4
270° (left side)	5.0	0.0	4.8	0.3
315° (front left)	4.7	0.4	4.7	0.4
20 feet	3.4	0.9	3.2	1.2
15 feet	2.5	0.9	2.8	1.5
10 feet	3.0	0.5	3.2	1.2

4.6 Discussion

A paired samples *t*-test was conducted to compare static and dynamic mean recognition performance. An alpha value of 0.01 was used for all tests. A significant difference was found between static and dynamic recognition accuracy for complete, multidimensional patterns, $t\ (7) = -6.717$, $p < 0.001$, two-tailed. This result shows that the relative information inherently embedded in dynamic patterns eases recognition following training on static patterns. While a direct comparison is difficult (static patterns require participants to recognize exact values of dimensions, e.g., 20 feet, 180 degrees, etc., whereas dynamic patterns require only relative descriptions, e.g., it is farther away, now moving closer, it is to my right side, etc.), this result is still very impressive considering participants had no prior familiarization with dynamic patterns. While participants are not directly trained to interpret dynamic patterns before testing, they are trained to recognize individual (static) patterns since static patterns are the building blocks of dynamic patterns; in other words, all participants completed the static condition before the dynamic condition (i.e., conditions were not counterbalanced). This design was intentional as we envision users undergoing similar training on a small set of static patterns for preparation for general use for perceiving an infinite set of dynamic patterns. Therefore, while learning is taking place between the static and dynamic conditions, and even during the dynamic condition itself due to experimenter feedback between patterns, participants achieved impressive recognition accuracy in the dynamic condition on complex patterns they had not felt before, demonstrating good generalization.

No significant differences were found between static and dynamic recognition accuracies for dimensions of elevation and angle, t (7) = -2.008, p = 0.085, two-tailed, and t (7) = 0.418, p = 0.689, two-tailed, respectively. These results demonstrate the ease at which participants could recognize dimensions of elevation and angle either in isolation or relatively. A significant difference was found between static and dynamic recognition accuracy for the dimension of distance, t (7) = -7.372, p < 0.001, two-tailed. Participants had difficulty recognizing tactile rhythms in isolation; rather, recognizing variations in tactile rhythms was a much easier task. This result corroborates with the subjective feedback collected from participants via the post-experiment questionnaire (see Table 1). Overall, the ease of recognition and intuitiveness of patterns for elevation and angle were rated higher compared to patterns for distance. This confirms that participants felt distance was more difficult to recognize compared to the other dimensions, and that they did not find the design as natural.

5. Conclusion

This paper introduced a novel vibrotactile device called the HaptWrap aimed at augmenting non-visual travel for individuals who are blind by providing access to spatial information about objects around them. We proposed a mapping between visual information (elevation, distance, and direction) and vibrotactile stimulation represented as a multidimensional pattern that varies both spatially and temporally as an object (and/or user) moves through space. We conducted an experiment to investigate how well participants could recognize a static (stationary) object, and how their performance changed when complementary and redundant information was presented during object motion, i.e., absolute versus relative identification. The performance differences between static and dynamic phases are impressive. With only a short static phase to learn the mapping, participants were able to perform very well on, and generalize to, a variety of dynamic patterns without any familiarization. This result shows the intuitiveness of the dynamic representation, and participants' ease at generalizing to new scenarios. The static and dynamic phases were not counterbalanced since we assume that the static patterns are required training to interpret the proposed dynamic patterns; and in a real-world setting, we envision users undergoing static training first. However, as part of future work, we will test this assumption by exploring direct training and performance on dynamic patterns, and whether participants can still generalize to unfamiliar dynamic patterns including static cases.

Possible directions for future work include: (1) The current version of the HaptWrap does not fit all waist sizes, and so improvements to the form factor are needed. We've redesigned the form factor to fit any waist size using durable, stretchable fabric and detachable bands outfitted with vibrating motors, depicted in Fig. 6. The revised form factor will allow more people to participant to acquire a larger number of participants for future user studies. Also, the new design has simplified donning and doffing. (2) Participants had the greatest difficulty recognizing the tactile rhythms. The rhythms will be redesigned. We will also investigate how fast movements can be reliably perceived. Currently, the rhythms take time to perceive, and therefore, may not work well for fast moving objects. (3) Finally, the proposed HaptWrap will be coupled with a 360-degree vision-based system for test trials in the wild to assess how well the HaptWrap augments non-visual travel.

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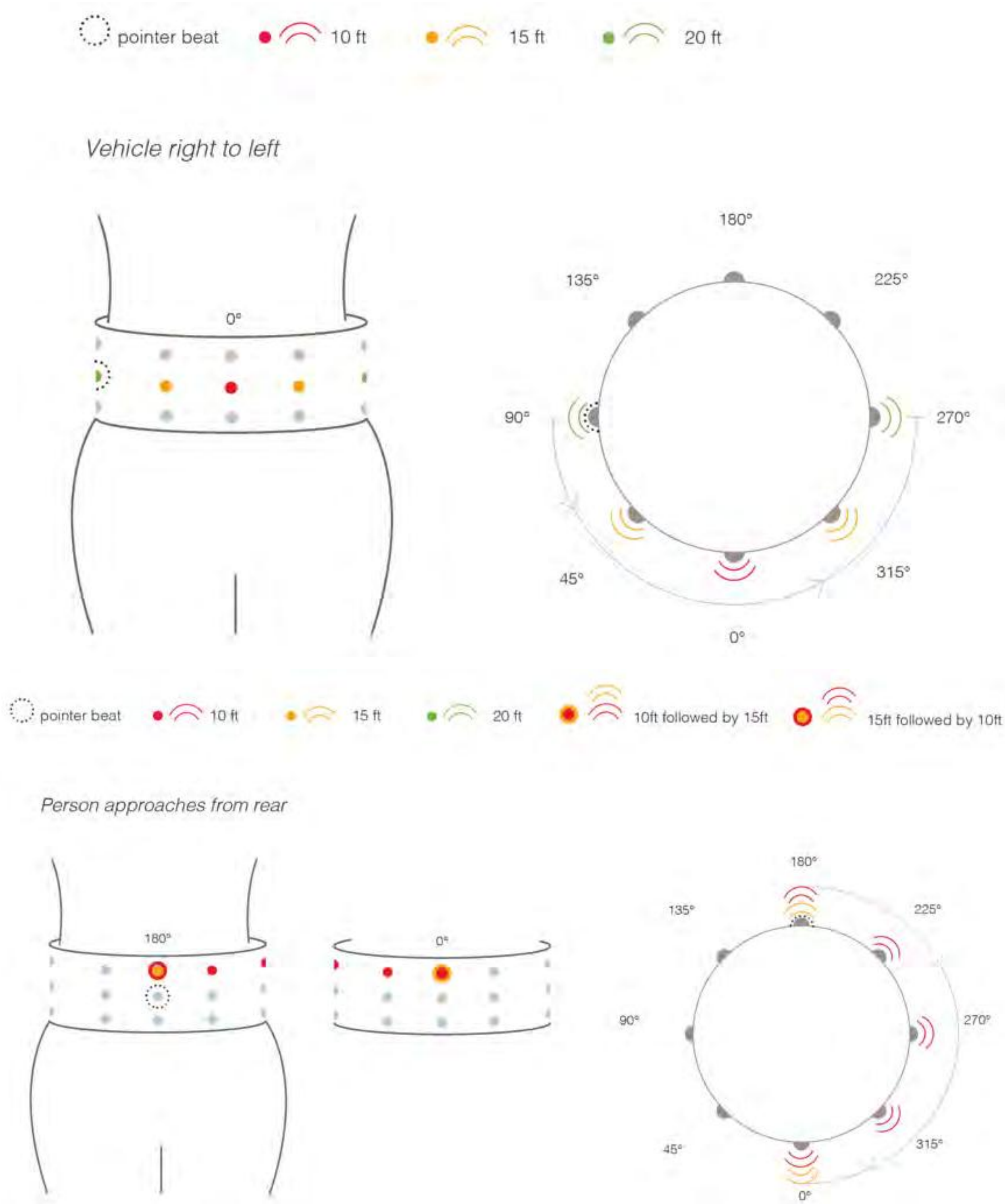

Figure 5: Top drawing depicts the dynamic pattern for a vehicle moving from right to left with respect to the user. Bottom drawing depicts the dynamic pattern for a person approaching the user from his or her rear, passing on his or her left side, and continuing forward, away from the user. Both are examples of dynamic patterns.

Figure 6: HaptWrap Version 2.0 consists of the following improvements: (1) Vibration motors are affixed to fabric bands, moveable along a stretchable belt to fit any waist size; (2) Vibration motors are inserted into a 3D printed structure such that the ERM's off-center mass spins orthogonal , rather than parallel, to the skin to ensure vibrations are hard to miss during ambulation; (3) Wireless communication capabilities.