The HapBack: Evaluation of Absolute and Relative Distance Encoding to Enhance Spatial Awareness in a Wearable Tactile Device

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Abstract. For the significant global population of individuals who are blind or visually impaired, spatial awareness during navigation remains a challenge. Tactile Electronic Travel Aids have been designed to assist with the provision of spatiotemporal information, but an intuitive method for mapping this information to patterns on a vibrotactile display remains to be determined. This paper explores the encoding of distance from a navigator to an object using two strategies: absolute and relative. A wearable prototype, the HapBack, is presented with two straps of vertically aligned vibrotactile motors mapped to five distances, with each distance mapped to a row on the display. Absolute patterns emit a single vibration at the row corresponding to a distance, while relative patterns emit a sequence of vibrations starting from the bottom row and ending at the row mapped to that distance. These two encoding strategies are comparatively evaluated for identification accuracy and perceived intuitiveness of mapping among ten adult participants who are blind or visually impaired. No significant difference was found between the intuitiveness of the two encodings based on these metrics, with each showing promising results for application during navigation tasks.

Keywords: Wearable tactile display · Nonvisual navigation · Spatial awareness

1 Introduction

Navigation in the absence or impairment of visual information is a fairly common task. For the estimated one third of the global population who are blind or visually impaired [27,41], nonvisual navigation is a daily challenge. Even for sighted individuals, characteristics of the environment may obscure vision, making information about obstacles, landmarks, other objects and people very difficult to access through this sensory modality. This spatiotemporal information plays a crucial role in the formation of spatial awareness, a necessity for safe

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and efficient navigation especially through dynamic environments [12]. For individuals who live or work in nonvisual conditions, mobility and an independent lifestyle therefore require the use of sensory substitution using audio, touch or other senses for building spatial awareness during navigation.

Traditional methods for navigation include the cane, guide dog, and human guide. However, these methods each have significant limitations: a cane while walking can only alert the navigator to objects of interest (OI) up to roughly 4–5 ft in front, and only up to waist level; a guide dog and human guide both direct the navigator, signaling him or her on which actions to take, rather than providing the navigator with information to allow him/her to maintain autonomy and control over path planning and movement decisions while navigating. These challenges have resulted in the development of technological solutions designed to assist travel, called Electronic Travel Aids (ETAs). Yet, despite decades of research and development in this field, the adoption rate of ETAs remain quite low relative to traditional approaches.

To determine the reasons for these shortcomings, we conducted a survey of 80 individuals who are blind or visually impaired on the topic of nonvisual travel. This preliminary survey had revealed that, indeed, the cane (63%), guide dog (30%), and sighted human aid (5%) were overwhelmingly popular as the three primary forms of assistance used during travel. Where technological solutions were used, often they were abandoned within five or fewer uses due to the several limitations, which we represent as requirements for an effective ETA:

- *Intuitive*: Information was difficult to understand or took too long to interpret.
- *Non-Audio*: The ETA used audio which served as a distraction or overload to the navigator's sense of hearing, the primary modality used to sense and interact with the environment in the absence of vision.
- *Hands-Free*: The ETA (primarly a smartphone app) required constant usage of the hand, which was non-ideal as the hands were needed to hold a cane or open doors.
- *Discreet*: The device or its interaction violated the navigator's sense of privacy in public spaces.

The latter three requirements relate to the design of the interface, while the former relates to the language of communication. To address these limitations in existing ETAs and the limitations of traditional tools for navigation, this study explores the design of an intuitive tactile language and hands-free, wearable and discreet tactile display (the HapBack) for the delivery of spatiotemporal data to enhance spatial awareness. As a first step in achieving this complex task, we focus this study on evaluating the intuitiveness of a novel tactile language communicating the location of an OI during navigation. In previous work [9], we explored the representation of this information in three dimensions: direction, height, and distance of an OI. While our previous language design delivered highly intuitive direction and height encodings, the intuitive encoding of distance remains a challenge. In the current work, two strategies for encoding an OI's distance from the navigator are explored: absolute patterns, which represent an immediate pulse of the object's distance, and relative patterns, which utilize a series of pulses from a consistent baseline in an attempt to better represent relative distances.

In Sect.. 2, several categories of ETAs and the limitations of current work in each on achieving the above requirements are discussed. In Sect. 3, we detail the design of the HapBack prototype and absolute/relative tactile patterns with examples of each. Section 4 describes the evaluation performed in this study on 10 subjects who are blind or visually impaired, wherein the absolute and relative mappings were evaluated using objective (response accuracy for absolute identification tasks) and subjective (self-reported naturalness of mapping) metrics of intuitiveness. We conclude in Sect. 5 with directions for future development.

2 Related Work

2.1 Nonvisual Navigation

Two frames for the representation of object locations exist: allocentric, wherein an object's location is described relative to that of another object in the environment, or egocentric, wherein an object's location is described relative to the subject [21]. It has been shown in studies of spatial representation that while individuals with vision utilize both for spatial awareness, those who do not have access to vision generally rely on the latter (egocentric) representation for spatial awareness [25,33]. A growing body of evidence supports that access to spatial information is a modal, in that it does not necessarily require the use of a specific modality such as vision and can be abstracted from this sensory mechanism, allowing for sensory substitution strategies to be employed [37]. In fact, with proper sensory substitution, it has been shown that individuals who are congenitally blind can reach equivalent spatial representation to their sighted peers [5].

2.2 Electronic Travel Aids

Cane Augmentation. Perhaps the first and one of the most commonly used sensory substitution device for nonvisual acquisition of spatial awareness is the cane, which demonstrated the effect of neuroplasticity on spatial learning [23]. Many ETA research approaches thus attempt to augment the cane with additional spatiotemporal information in order to overcome its limited range and height of detection. These approaches generally augment the white cane with technology such as sonar, cameras or other sensors and additional real-time feedback [1,6,18,34,43]. For example, one recent approach by Rahman et al. [30] utilizes a laser and camera mounted on the cane for the purpose of detection of obstacles, holes, stairs and other OIs while the individual navigates. Once an OI is detected such as an obstacle, a vibrotactile signal is emitted from the cane and felt by the individual. The closer an individual moves to that obstacle, the greater the frequency of vibration. In this case, the laser and camera mechanism improve the sensing range while a simple tactile signal is used to augment spacial awareness.

Generally, however, smart canes do not provide significantly higher performance at the detection of most obstacles over traditional canes [35]. Several factors may contribute to this observation. One is that when using the cane to send tactile feedback, the interface is limited to the contact between the hand and cane, which is a rather small surface area with relatively low resolution for a tactile display. Hence, sensitivity to distinct signals may be reduced, and many smart cane approaches instead turn to audio for feedback, the limitations of which are discussed below. Another is that the design and usage of a cane make it difficult to implement technology directly within or on the cane for this purpose as the weight of the cane must be kept to a minimum [2] and the cane is constantly being moved left and right while walking, making it difficult to use a camera or other sensing mechanism on the device.

Audio Devices. Alternative solutions have utilized audio or audio-haptic cues for the delivery of real-time feedback on spatiotemporal data [14,22,29]. The advantage of audio as a target modality is that it is highly attuned to distance recognition. Echolocation, for example, is the act of bouncing audio signals off of objects in the environment and using the acoustic properties of the sound's echo to determine size, distance and other attributes of these objects. Echolocation is a commonly used mechanism for audio-based distance detection [39]. Some recent approaches [38,42] have even chosen to leverage echolocation with audio feedback as an ETA, in an attempt to build upon an existing skillset for navigators.

Unfortunately, all interfaces which use audio as a modality for feedback and cueing in the context of nonvisual and navigation share one massive drawback: individuals who are blind or visually impaired utilize hearing as the main sensory channel by which to interact in their environment in the absence of vision, making audio a less ideal modality for guidance [3]. For example, while navigating outdoors, an individual may listen for audio cues at pedestrian crossings or be engaged in a telephone conversation. In each of these cases, audio cues from the ETA may conflict with the interactions already present in this channel or induce unnecessarily high cognitive load [19].

Tactile Devices. As a more effective alternative, tactile ETAs outside of cane augmentation have emerged to assist with the task of nonvisual navigation [11,17,26,36,40]. These interfaces, often implemented as wearables, are designed to leverage the spatial acuity of the body's surface at various sites toward touch stimuli [7] to deliver information discreetly. A majority of these implementations either implement static spatial representations such as room layouts as tactile maps on a display (for example, the refreshable top-down display style of [26]) or calculate the optimal path for the navigator to take and then utilize tactile signals to direct the navigator past obstacles (for example, the *turn left*, *turn right*, and *go straight* metaphors in approaches such as [40]).

However, many of these methods each have significant challenges for adoption. Tactile map views utilize survey-style (allocentric) reference frames which contradict the egocentric preference of spatial mapping [28], such that when used in conjunction with the traditionally egocentric cane, guide dog or human aid, these devices require simultaneous use of both reference frames for navigation. Furthermore, they require that a reliable and sufficiently informed sensing infrastructure is in place for retrieving the entire spatial layout of the environment prior to and during navigation [31], which may be impractical when used to navigate outdoors in dynamic environments including traffic, people and other moving parts. Tactile interfaces which provide directions for navigation focus on directing, rather than informing the navigator. In this case, the locus of navigational decision making is on the device rather than the user. These interfaces may be undesirable in that they reduce the autonomy of the navigator [4,24,32], reducing the ability to independently form a cognitive map.

Perhaps the most promising method, based on the requirements for ETA use outlined in the nonvisual navigation survey feedback above, is that of van Erp et al. [11], who focused on the provision of spatiotemporal information exhibiting the location of OIs in multiple dimensions: horizontal direction (simply referred to here as direction), distance from the navigator (simply referred to as distance), height (a reference of the height of the OI relative to the navigator) and ID (classification of the OI among several commonly encountered objects during navigation such as stairs). A two-dimensional wearable vibrotactile display on a belt was implemented and utilized to evaluate a tactile language wherein rows, columns, temporal patterns and frequencies were utilized to encode each dimension of this information. It was found that an intuitive depiction of this information requires the design of dimensional encodings that are not only intuitive on their own, but also maintain distinctiveness when combined into multidimensional representations. The implementation had satisfied three of the four requirements above for ETA design (*non-audio*, *hands-free*, *discreet*), with the last requirement (*intuitive*) left for further exploration.

To address these findings, we had previously explored the interplay between body surface, tactor locations, display resolution and spatiotemporal encoding in the design of a vibrotactile display on a wearable belt, the HaptWrap [9], for spatial awareness during nonvisual navigation. In this study, the dimensions of ID and height from above were found to be useful when combined to leverage their redundancies (objects could be classified in major categories based on height when considered as obstacles) which resulted in three dimensions of information: direction, height, and distance. These dimensions were mapped to the columns, rows and rhythmic frequency of vibrotactile cues, respectively. During evaluation it was found that while the encodings of direction and height were highly intuitive in multidimensional patterns, distances were more difficult to distinguish when different rhythmic frequencies were assigned to each. This is consistent with the findings in [11].

Based on the above, the current study focuses on the design and evaluation of intuitiveness of two different implementations of spatial mappings to encode the dimension of distance.

3 Methodology

3.1 HapBack Device Design

As an initial note, the full design of an ETA consists of several components, including a sensing mechanism by which raw visual information is gathered (such as a mounted camera), a processing mechanism by which this information is processed and converted to a multidimensional spatiotemporal representation (such as an image processing mechanism which identifies an OI and estimates the direction, distance and height of the OI based on features of the image/video), and finally, communication (the processed spatiotemporal data is communicated to the navigator). In this work, we are primarily concerned with the communication component. Therefore, for the sake of simplicity, we assume, for now, that at any point, a single OI has been sensed and identified, and its egocentric distance from the navigator is known and readily available; the addition of sensing and processing components to our design will be the focus of future work.

Fig. 1. Prototype of the HapBack device shown from the front (left) and back (right).

In accordance with the aforementioned requirements for ETA design, a wearable tactile interface was chosen as the design for the current prototype. Named the Hapback, this prototype consists of two back-worn vertical straps each embedded with a single column of five vertically distributed vibrotactile motors as shown in Fig. 1. Whereas in the previous HaptWrap implementation, the waist was chosen as the contact site for the haptic display, the back was chosen in this iteration due to the relatively high spatial resolution and stability during motion of the back compared to the waist, forearms and other areas in use while walking [8,15,16].

The motors are connected in pairs by elastic bands along the spine, and the vertical straps are connected at the top and bottom through horizontal straps secured around the top of the chest and the torso to ensure that the device maintains contact with the back of the user. An ESP-WROOM-32 microcontroller allows for real-time automated control of the motors and the delivery of vibrotactile cues in real-time through a partner app installed on a laptop. The entire system is powered by a portable USB rechargeable battery and can be worn above or underneath clothing to use on-the-go, ensuring discreetness and hands-free portable use of tactile feedback.

3.2 Distance Encoding Strategy

Distance in this study refers to egocentric distance, measured in feet, from the navigator to an OI. As a continuous measure, this would require an infinite amount of distinct vibrotactile patterns to represent all possible distances. Fortunately, the context of navigation, the length of the cane, and the intuitions of proxemics [13], a study of the regions of interpersonal distance, together form a set of parameters by which this continuous range can be subdivided into discrete categories. Given that the cane can detect at a range of roughly 4–5 ft, the first distance category represented in this language is 5 ft from the navigator. From there, intervals of 5 ft are used, each representing one full cane length, to reach ranges of the personal, social, public, and beyond public spaces, respectively, as adjustments to the interaction regions defined in American cultural context through proxemics. Therefore, five total distance categories are represented in this approach: 5, 10, 15, 20, and 25 ft. An object's precise location is approximated to the nearest of these five categories. For example, an object at 17.6 ft would be assigned to the 20 ft distance category. Objects outside of the 5–25 foot range are considered not of interest within the walking context, as anything below 5 ft would be detected by a cane and anything above 25 ft would require less immediate attention (with the exception of fast-moving objects, which would be moving too quickly for most detection mechanisms to sufficiently warn the navigator). Note that the value of these categories is not itself significant; when applied to a different context, they can be rescaled as necessary.

Each of these five distance categories corresponds to row of motors on the HapBack device. 5 ft is assigned to the top row, followed by 10 ft in the second row, 15 ft in the third, 20 ft in the fourth, and finally, 25 ft in the bottom row. As the two straps on the hapback are aligned by connecting the motors pairwise on each row, each distance category is therefore mapped to the pair of motors in the corresponding row of the HapBack prototype. When a signal is sent to a particular row, the pair of vibrotactile motors on that row vibrate at the same frequency and amplitude and for the same duration in this implementation. Therefore, the two straps forming the display can effectively be treated as a single column for the sake of mapping.

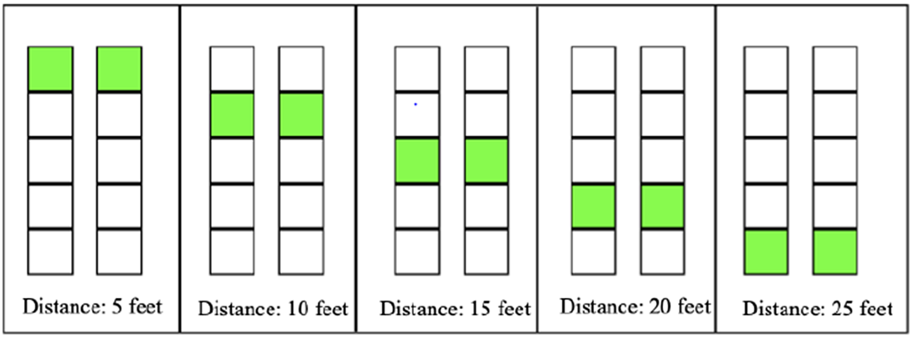

Fig. 2. Illustration of five absolute feedback patterns.

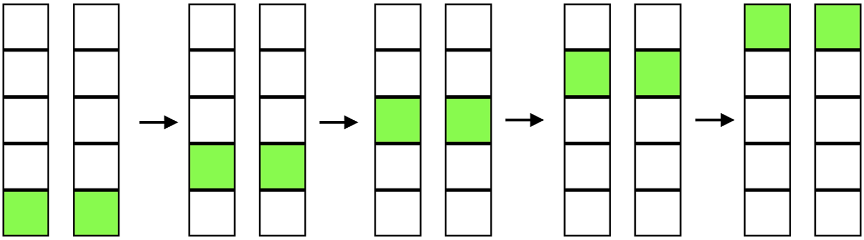

Fig. 3. Illustration of pattern sequence for 5 ft relative feedback pattern.

Two representations are presented in this work to encode a distance in one of the five assigned distance categories: absolute and relative. In the absolute encoding strategy, to communicate a particular distance, the HapBack display pulses its corresponding row once for a preset length of time (roughly 100 ms). For example, to communicate that an object is currently roughly 10 ft away, the second from the top row of the HapBack vibrates a single time. This mapping is shown in Fig. 2. This representation has the advantage of being rapid as only a single vibration is used in every case, allowing for quick capture of an object's location. However, as the only element distinguishing the five patterns in this case is their vertical location along the spine, it is hypothesized that distinguishing between these patterns, particularly those adjacent to one another, may not be as easy as an implementation in which they were also distinct temporally.

To address this hypothesis, a relative representation was developed as an alternative. The relative representation uses the same mapping of rows to distances, but instead of vibrating only the row corresponding to the communicated distance once, the rows of the HapBack are vibrated in a sequence starting from the bottom row and stopping at the row corresponding to that distance. For example, as shown in Fig. 3, to communicate that an object is currently roughly 5 ft away, the fifth row is vibrated, followed by the fourth, the third, the second, and finally the top row which is mapped to 5 ft. These vibrations are spaced evenly apart with 0 ms time delay between them (one vibration starts as soon as the previous one stops). In the case of 25 ft, only the bottom row is vibrated, making it equivalent in its absolute and relative representations. The relative encoding therefore allows us to comparatively evaluate the addition of a temporal sequencing element on an individual's ability to distinguish between one distance and another. It should be noted, however, that with the addition of the temporal element in the relative encoding comes a major drawback: patterns take longer to present, particularly for 5 ft which is a sequence of five vibrations. This makes the communication of distance significantly slower and may even be impractical when the navigator or OI is in motion. Therefore, a tradeoff of time consumption for distinctive clarity is hypothesized.

4 Evaluation

For this study, the goal of evaluation is to comparatively determine how intuitively the relative and absolute modes encode the five categories of distance in the proposed tactile mapping. This is measured objectively through absolute identification accuracy over the range of distances in the language, and subjectively through questionnaire results, as has been shown in previous work [10,11,20].

4.1 Procedure

The evaluation was conducted at the Center for Cognitive Ubiquitous Computing laboratory (CUbiC) at Arizona State University along with a private room at SAAVI Services for the Blind in Phoenix. Ten adults (18 years of age or older) who are blind or visually impaired (19 recruited, with 9 dropped due to issues in the experimental setup) participated in the study. All participation was voluntary and each subject signed a consent form prior to participation. The study was approved by Arizona State University Institutional Review Board prior to initiation.

After giving consent, each subject was asked to wear the HapBack device while seated. The experimenter could then transmit tactile patterns directly to the subject through a laptop interface visible only to the experimenter. Each subject was then evaluated on his or her response to two conditions: absolute (in which the absolute pattern mechanism described above was used) and relative (using the relative patterns described above). The ordering of these two conditions were counterbalanced between the subjects to control for ordering effects.

Each condition consisted of a familiarization phase followed by a testing phase. In the familiarization phase, the experimenter presented each of the five patterns in the current condition (corresponding to the five distances) to the subject in an ordered fashion (smallest to largest or largest to smallest). For each pattern, the experimenter first stated the distance that the pattern corresponded to, and then activated the pattern on the subject's HapBack. Once the subject had felt the pattern, he or she could ask for any number of repetitions. For each repetition, the experimenter would once again state the distance of the pattern and then activate it for the subject to feel. No data was recorded during the familiarization phase.

Once all the distances were presented in the familiarization phase, the testing phase would begin. In this phase, a randomized sequence of 15 patterns in the current condition would be presented to the subject, in which each of the five patterns was included exactly three times. Each time a pattern was presented, the subject was asked to identify the distance to which that pattern corresponded. The correct response and subject's response were both recorded. No feedback was given to the subject in this phase, including whether or not the subject's response was correct. A response was scored correct if it matched the intended distance in the mapping, and incorrect if it did not.

Once each subject had completed all four of these phases (a familiarization and testing phase with relative patterns, followed by a familiarization and testing phase with absolute patterns, or vice versa), he or she was then asked to complete a post-experiment questionnaire with four questions, two for each of the testing conditions (absolute and relative). For each condition, the first question asked the subject to rate, on a Likert scale from 1 to 5, with 1 being *Very Hard* and 5 being *Very Easy*, how natural (intuitive) the mapping was between the vibration patterns for that condition. This was followed by a second question for each condition that asked the subject to explain the ranking he or she chose. This gave each subject a chance to elaborate on why he or she felt a particular mapping was more or less intuitive.

4.2 Results and Discussion

The identification accuracy for each subject in each of the two distance encodings, represented as the number of correct distances identified out of fifteen patterns given in each encoding, is shown in Fig. 4. The average accuracy over all subjects was then collected for each condition and used to determine the intuitiveness of that encoding. Results indicated that both absolute and relative encodings were quite intuitive, with 73% response accuracy (st. dev. 0.182) for absolute patterns and 87% accuracy (st. dev. 0.122) for relative patterns. These are impressive response accuracies given that the subjects did not receive any prior training other than the brief familiarization phase to learn the mappings.

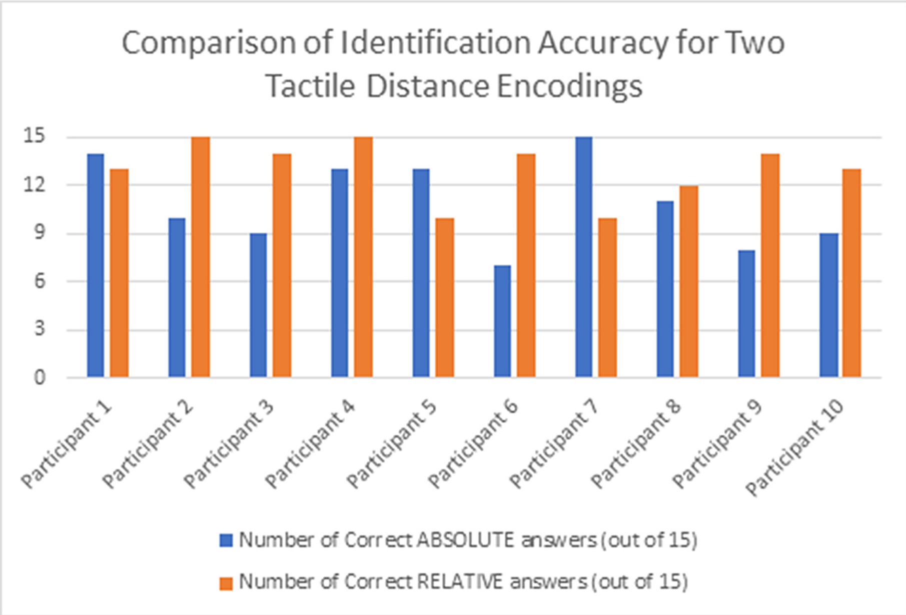

Fig. 4. Identification accuracy for 10 subjects in absolute and relative distance encoding.

Table 1. Post-experiment questionnaire responses on perceived intuitiveness of mapping

Subject	Absolute	Relative
1	4	5
2	3	5
3	2	5
4	5	5
5	3	5
6	4	5
7	4	3
8	4	1
9	4	4
10	4	4

No statistically significant difference was found in response accuracy between the two modes based on a paired two-sample t-test ($P = 0.135$ two-tail, $\alpha = 0.01$), suggesting that both approaches were equally viable for the subject sample.

Post-experiment questionnaire responses (out of 5) for perceived intuitiveness of mapping are shown in Table 1. Subjects reported an average intuitiveness score of 3.7 (st. dev. 0.823) for absolute patterns and 4.2 (st. dev. 1.317) for relative patterns. No statistically significant difference was found in perceived intuitiveness of mapping between the two modes based on a paired two-sample t-test ($P = 0.380$ two-tail, $\alpha = 0.01$), supporting the findings from the experimental phases. However, subject explanations for their questionnaire scores in the open-ended questions provided some further insight into the differences between how the two were felt. Some subjects reported some difficulty in discerning between adjacent patterns/distances in the absolute condition, but found it easier in the relative condition because they could count the number of vibrations and use that as a backup strategy to identify the distance in that condition. Many reported that this difficulty was alleviated over the course of the experiment as they found it easier to identify the patterns that were presented later in each phase.

5 Conclusions and Future Work

Based on the results shown during evaluation, the HapBack prototype and tactile language presented serve as an intuitive method by which distance can be communicated in real-time as a part of a novel ETA for spatial awareness. Furthermore, the wearable, discreet, hands-free and non-audio nature of the HapBack prototype, as well as the provision of spatiotemporal information rather than predetermined path directions, afford the navigator a greater sense of control, privacy and usability. Given that no significant difference could be found between absolute and relative encodings, and both were considered highly intuitive on first use by subjects, it is proposed that the absolute encoding be utilized in most cases as it has the advantage of utilizing only a single tactile pulse for each distance, ensuring speed of delivery and allowing for more practical use in dynamic environments.

The evaluation performed here serves a preliminary purpose in the intuitive encoding of a single dimension of spatiotemporal information. However, to achieve spatial awareness, this dimension of tactile patterns must be integrated with other dimensions of information (direction, height) to form complete, multidimensional representations of OI location. Integration of this mapping with the effective components of the previous mapping used in the HaptWrap require careful consideration of the role of rows in the tactile display, as both distance in the HapBack and height in the HaptWrap are mapped to rows in their corresponding tactile language. Future work will evaluate how it might be possible to combine these elements while maintaining intuitiveness without the use of a temporal element on a two-dimensional display. The integration of multiple wearables (the HapBack in combination with the HaptWrap) is also under consideration, with careful attention toward the effect of multiple displays on cognitive load during a navigation task.

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