Developing a head-mounted tactile prototype to support situational awareness

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A R T I C L E   I N F O

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- Situational awareness
- Tactile interfaces
- Tactile perception

A B S T R A C T

In this paper, we describe the design and evaluation of a head-mounted tactile prototype and multi-parameter coding scheme to support situational awareness among users. The head has been selected as the location for the interaction because it has been relatively under-researched compared to the torso or hands, and offers potential for hands-free attention direction and integration with new head and eyewear technology. Two studies have been conducted. The first examined the user’s ability to discern three-parameter tactile signals presented at sites on the head. Findings highlighted that while multi-parameter cues could be interpreted with low error, challenges were faced when interpreting specific combinations of waveform and interval type, and when performing identification of interval pattern and stimulation location while visually-distracted. A second study investigated how use of the three-parameter tactile coding scheme impacted participants’ situational awareness under several exertion conditions. Significant interaction was found between the exertion conditions and subjective cognitive workload. The relationship between situational awareness phases of participant SAGAT assessment scores were consistent between conditions, with perception and prediction phases outpacing comprehension. This suggests, pending further study of the suitability of situational awareness evaluation methods for tactile perception, that quickly trained participants may struggle to understand multi-parameter coding intended to convey changing events. Interpretations of coding schemes were found to vary, highlighting the importance of carefully selecting and mapping signals for presentation. Insights from our study can support interface designers aiming to heighten levels of spatial and situational awareness among their users through use of the tactile channel.

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1. Introduction

Research into tactile stimulation suggests potential for this sensory channel to play a valuable role in supplementing overloaded visual and auditory channels in interfaces to aid spatial and situational awareness. Development of real-world applications in work domains, such as aviation and pedestrian navigation, also indicate potential for practical tactile aids to support effective attention direction in a wide array of vexing scenarios where users are often distracted by multitasking and sensory overload (Wickens, 2008). Additionally, tactile cues (also referred to as ‘tactile signals’ or ‘tactons’ in this paper) offer a “private channel” to provide feedback more inconspicuously and unobtrusively in loud or threatening situations than visual or auditory options (Jones and Sarter, 2008). Research involving wearable tactile devices, in forms such as belts and bracelets offering vibrational feedback, demonstrates considerable potential for improving spatial and situational cognizance. This potential may apply to performing everyday pedestrian navigation tasks, as well to cognitively and perceptually demanding industrial and military situations, where vision may be restricted or unavailable (Raj and Braithwaite, 1999). Situational awareness in the context of this research generally refers to a graduated model, including perception of what is happening in the vicinity, comprehension of that information, and prediction of its impact on one’s goals and objectives (Wickens, 2008). Decisions or judgments can be made, once an understanding of the situation has been gained. However, measurement of decision making is notably difficult to perform, as valid reproducible conclusions depend on both process and outcome measures, and assessment of process often depends on the user’s limited ability to consistently define and report their own cognition.

While the role of situational awareness has been examined within challenging work domains such as air traffic control, military navigation, and aviation, research has yet to focus intensively on ways to support the user in developing and maintaining awareness when performing day-to-day attention-demanding tasks, where the visual channel may not be fully available to monitor the wider environment. Research has also been generally limited regarding tactile interaction through head-mounted devices (HMD) compared to other wearable forms. This avenue of inquiry has generally been concerned with assistive applications for

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distracted or visually impaired pedestrians, or for users in loud or stressful environments. Despite these research trends, the head holds promise as a location for tactile interaction research, given the large cutaneous surface area and potential for intuitive integration with hands-free eye and headwear. These types of devices, including networking and augmented vision capabilities which could integrate with tactile alerting, are entering the consumer and professional market.

This paper describes two experiments conducted with the intent of measuring how effectively a tactile coding scheme might be understood by users of a wearable, head-mounted device under realistic conditions. The first study was a perceptual experiment, conducted using the head-mounted device, to explore three aspects of user interaction with 3-parameter tactile cues. Firstly, we assessed user precision in interpreting 3-parameter tactile cues (hypothesis H1.1: Identification error rates will be no higher than 15% for a three-parameter tactile stimulus identification task, similar to rates identified in other studies (e.g. Qian et al., 2014) where three-parameter tactons were presented). Secondly, we examined the effect of a realistic distraction condition on accuracy of parameter identification (hypothesis H1.2: When the user is engaged in a visually demanding task, performance accuracy of a tactile signal identification task will decline, compared to a visually unencumbered condition), and upon subjective cognitive workload measures (hypothesis H1.3: When a user is engaged with a visually demanding task, perceived cognitive workload levels will be higher, compared to a visually unencumbered condition). These hypotheses are described in Section 5.1. The parameters of location, waveform, and interval (essentially, the rhythmic pattern of pulses in a signal) were manipulated, with the aim of identifying combinations which are easier to discern. The second study investigated two aspects of users’ ability to maintain understanding of a realistic pedestrian scenario (“tactile storyline”) portrayed through multi-parameter tactile icons, presented through an HMD. Firstly, we measured whether levels of realistic exertion (sitting stationary, walking slowly, and walking quickly) increased self-reported cognitive workload when identifying tactons (hypothesis 2.1), and secondly, whether those exertion conditions reduced 3-level situational awareness measures in a SAGAT method assessment (Hypothesis H2.2). These hypotheses are described in Section 4.1. In our first study, we conclude that: (a) users can identify 3-parameter signals with relatively low error despite difficult combination effects (conclusion C1.1, Section 3.5), and (b) visual and cognitive distraction impacts pattern and location parameter identification (conclusion C1.2). In our second study, we conclude that: (a) exertion does impact CW and should be carefully accounted for (conclusion C2.1, Section 4.5), and that (b) users’ improvised interpretations of coding should also be carefully accounted for in tactile applications (conclusion C2.2), and that (to support user situational awareness) parameters for dynamic tactile signals should be chosen to map intuitively to realistic conditions (conclusion C2.3).

2. Related work

This research attempts to join and build upon existing studies on design of tactile cues, and their suitability to wearable applications under real world conditions. Additionally, we discuss how this type of tactile design has been combined with performance measurement from the domain of situational awareness. Specifically, we survey several methods utilized to attempt to quantify situational awareness conditions (i.e. perception, comprehension, prediction).

2.1. Wearable tactile interfaces

Tactile wearable displays, given their practical potential to augment other sensory channels and assist in maintaining spatial orientation and situational awareness, have been studied in many forms, such as belts, vests, bracelets and gloves. Many of these wearable devices have been torso-based, to take advantage of natural circumferential mapping and hands free configuration. Examples include research by Chiasson et al. (2003) on the Tactical Situation Awareness System – Special Forces (TSAS-SF), and van Veen and van Erp’s (2003) research on a tactile vest for pilots. The TSAS-SF is a belt-based spatial orientation and navigation system fielded by the U.S. military in different configurations for pilots, scuba divers, and land navigation. Chiasson et al. assessed efficacy in improving situational awareness by scattering small test objects across a navigation course. A TSAS-enabled group outscored a control group equipped with handheld GPS units, 9.25 versus 5.25 out of 20, in spotting and tallying the objects while crossing the course. van Veen & van Erp researched spatial cues to trainee helicopter pilots in simulated hover and low level flight tasks, using a vest with 128 embedded tactors. Across several modes of spatial cues, the tactile display improved pilot performance. Performance with a parallel auditory memorization task was also found to be more resilient with the tactile aid (van Veen and van Erp, 2003).

While most tactile feedback solutions examined have been torso-based, other innovative locations have been studied. These forms included wrist-mounted displays to guide users’ physical articulation (Weber et al., 2011; Sergi et al., 2008), or convey robot interaction (Scheggi et al., 2012). In a review by Lindeman et al. (2005), the researchers describe the studies by Yano et al. (1998), which involved presenting tactile information at the thighs and palms, and Kume et al. (1998), where stimuli were presented at the soles of the feet. In the latter study, users wore a slipper-like interface embedded with tactile actuators.

2.1.1. Head-mounted displays

Head-mounted tactile displays are a focus of this study. Research suggests that the head offers considerable potential as a location for presenting tactile cues to spatial and situational hazards. For example, Gilliland and Schlegel (1994) found that participants’ accuracy at localizing directional cues presented on the head increased as the number of localization sites decreased (93% accuracy for 6 sites, to 47% accuracy for 12 sites, across the parietal meridian of the head). Sand et al. (2015) also studied tactile augmentation of Oculus Rift virtual reality headwear, as a location for entry and interpretation of gestural input. Similarly, Cassinelli et al. (2006) found additional qualitative support for this type of interaction. 87% of their participants, equipped with a head-mounted “haptic radar” device, could easily adopt tactile signaling to avoid unseen hazards.

Participants in the study by Dobrzynski et al. (2012) were presented with tactile cues via a head-mounted array. Findings revealed that participants were able to accurately localize the position of multiple tactors concurrently. Identification accuracy differed significantly for different locations on the head, and declined as the number of tactors increased, suggesting that displays with simultaneous signals may be difficult to interpret. Myles and Kalb (2010) also identified that certain regions of the head (parietal, occipital and temple regions) were found to be the most sensitive to vibration stimuli, and consequently more accurate in perceiving cues from HMDs. The researchers suggested optimal frequency ranges for the head, and found recommended auditory and tactile signal frequencies for scenarios masking auditory effects (e.g. noisy industrial or military conditions). Further research undertaken by Myles and Kalb (2010) regarding perceptual thresholds for the scalp confirmed glabrous skin was generally more sensitive than the scalp, and identified effective frequency ranges for those thresholds.

2.2. Situational awareness

There has been a relatively limited amount of research into the interaction of situational awareness constructs with tactile coding through wearable tactile devices. This is despite the relatively unobtrusive form of most tactile displays, and their access to a generally underutilized sensory mode. Prasad et al. (2014) examined the use of a 3×3 grid of tactile actuators attached to a handheld device to examine interpretation of haptic icons, to support soldiers’ situational awareness through
group communications. Kerdegari et al. (2016) studied the effects of time-based parameters in a lexicon of tactile navigation alerts presented through a HMD, finding continuous and repeating cues to be effective in guiding users. Pielot et al. (2010) used a tactile belt as the basis for study of comprehension of spatial cues, and team-based situational awareness. The researchers found that rhythm, duration, and intensity signal parameters all performed adequately for conveying spatial proximity. Additionally, users of their tactile belt performed better as a team in a multiplayer video game exercise, and maintained higher ratings on SART-3 and SPAM situational awareness assessments (methods related to the SAGAT approach taken in our second study).

Sklar and Sarter (1999) also studied the use of tactile feedback in maintaining situational awareness in operating an aircraft, but with a focus on encoding important situational changes, such as modal shifts in flight avionics. Pilots with inner and outer wrist-mounted tactors performed better at detecting important modal shifts, scoring 100% accuracy in the task. However, pilots also demonstrated a subtle kinesthetic interference effect when the same arm wearing the tactile bracelet simultaneously exerted against other flight controls. This exertion in the arm was suspected of having caused the intermittent identification errors. The authors suggested that this observation highlighted the need for carefully informed design of wearable assistive devices for situational awareness in demanding environments. Pacchierotti et al. (2014) also studied the use of tactile feedback applied through control surfaces in a tele-operated robotic surgical device, finding positive user subjective rating of the tactile reproduction of important haptic and tactile feedback from medical procedures.

In a simpler decision making domain, Hincapie-Ramos and Irani (2013) found similar conclusions by prototyping an assistive mobile phone-based display for distracted “heads down” pedestrians. Concise visual alerts, enabled by a wearable Kinect-based vision system, were displayed on the margins of a mobile phone screen. These alerts allowed pedestrians to avoid moving and stationary obstacles in their path, while engaged in a distraction gameplay task. Participants demonstrated no significant degradation in their game scores while using the system. Raj et al. (2000) also studied cues for spatial awareness, by measuring the impact of tactile cues on helicopter pilots’ ability to sustain a stable hover in a simulator, while performing a concurrent secondary arithmetic task. Tactors mounted circumferentially in a pilot vest provided cues. Situational awareness was assessed after each trial through the five-point China Lake Situation Awareness Scale (CLSA), finding improved pilot hover performance in the tactile-enabled condition.

2.3. Tactile design

To expand the range of perceivable stimuli available for presentation via a tactile interface, researchers have examined ways in which parameters of touch can be manipulated and combined to form distinctive tactile icons (often referred to as tactons). This includes research by Kareui et al. (2011) regarding the location and intensity of signals. Brewster and Constantin (2010) also examined the perception of tactons presented through a mobile interface. While participants could recognize 88% of the tactons, accuracy increased when the rate at which events occurred was reduced. Azadi and Jones (2013) varied frequency, amplitude, and pulse duration to tactons presented at the forearm and index finger. The average tacton identification score was low (57%), but varied widely from 30% to 83% for specific designs. Brown et al. (2006) presented tactons at different locations on the body, showing that the identification rate for tactons encoded with three parameters (rhythm, roughness, and spatial location) was just 48%. However, the identification rate increased to 81% when the number of values in one of the parameters was reduced, highlighting limitations of human tactile resolution abilities.

van Erp (2002) also described guidelines for the design of devices and tactile signals for navigation. While the physical location of tactors on the body may support azimuth differentiation as small as ten degrees, the authors suggested that frequency and amplitude were generally not well suited to coding. The authors also noted that temporal issues develop in the comprehension of complicated signals over four seconds in length. Self et al. (2008) summarized tactile display guidelines for military environments. The authors found the torso to be well suited to direction cues. They described mid-sagittal bias, which distorts perception of direction cues towards cardinal directions. Like van Erp et al. (2005), the researchers suggested varying frequency to allow for accurate perception of consecutive signals, and, citing van Erp’s term, cautioned against creating “tactile clutter” through overcomplicated design (Self et al., 2008).

In the context of tactile signal design for the head, existing research is invaluable, but there is a general paucity in the understanding of potential interactions between user perception of tactile signal parameters, situational awareness constructs, and realistic cognitive loading conditions. In this paper, we describe a structured set of studies examining tactile design to support situational awareness. In the first study, we have manipulated parameters of touch to determine the range of cues presented at the head which can be effectively discerned. The second study examines how effectively tactile interactions from Study 1 may be integrated into a person’s mental model of the world around them, under simulated real-world conditions. The aim is to contribute to understanding of tactile design for head-mounted interactions for spatial and situational awareness. The long term goal is to develop cues which can support judgments and decision making by users when on-the-move.

3. Study 1: determining the ability to discern multi-parameter icons presented on sites at the head

3.1. Objectives

This study was undertaken to better understand the range of multi-parameter cues which could be perceived and identified, when presented at locations on the head. Additionally, this study inquired about the potential impact on participants’ performance and perceived cognitive workload, while engaged in a realistic multitasking scenario.

Firstly, we asked whether combinations of tactile signal parameters, such as spatial location, waveform, and interval pattern (rhythm), could be assessed accurately by a user (Hypothesis H1.1). Three-parameter cues were selected for presentation. By manipulating each parameter, a wide range of resulting tactons could be developed, which if discerned appropriately could be mapped to events in the environment to aid the user’s situational awareness. Secondly, given that participants in a previous participatory design study described in 3.2 (Wolf and Kuber, 2014) gave consistent qualitative input describing adverse impacts on their spatial and situational awareness from routine visual and cognitive distraction, we asked whether a distraction condition (induced by gameplay on a handheld device) would impact performance measures while these tactile cues were used (Hypothesis H1.2). Thirdly, we assessed the user’s perceived cognitive workload when asked to identify tactile signal parameters while concurrently performing the distraction task (Hypothesis H1.3).

Hypothesis H1.1. Error rates will be no higher than 15% for a three-parameter tactile stimuli identification task, similar to rates identified in other studies where three-parameter tactons were presented (e.g. Qian et al., 2014).

Hypothesis H1.2. When the user is engaged in a visually demanding task, performance accuracy of a tactile signal identification task will decline, compared to a visually unencumbered condition.

Hypothesis H1.3. When a user is engaged with a visually demanding task, perceived cognitive workload levels will be higher, compared to a visually unencumbered condition.
3.2. Design & methodology

This experiment utilized a $4 \times 2 \times 2$ design, to research the effect of vibration interval pattern (increasing, decreasing, static interval, and single pulse), waveform type (sine, and square wave), and scalp location of the tactile actuator (left and right sides of the head) upon users' ability to accurately discern location and coding of tactile signals. A within-subjects design was selected for this study to maximize potential statistical power of any observed effects, while minimizing any potential variance effects amongst participants.

3.2.1. Rationales for tactile signal parameter selection

As stated in Section 3.1, a prior participatory design-based study provided insight into vibration patterns potential suited to use in realistic cognitive loading conditions with a head-mounted tactile system for situational awareness (Wolf and Kuber, 2014). Concepts for an intuitive coding tactile scheme were iterated upon, and surveys performed regarding participants’ experiences with situational distraction and tactile interaction with mobile phones. These experiences were the basis for use case scenarios, which were used to contextualize the experiment to participants. Additionally, focus groups in this prior participatory design study proposed changing interval times in a vibration pattern to convey a changing hazard in real-time (i.e. an accelerating rhythm to convey an approaching threat) as a potentially valuable approach to tactile coding for situational awareness. These signal parameters were therefore selected as variables to ascertain if those changing intervals could be accurately assessed, as well as any interaction with waveform type and scalp location.

The two waveform types, sine and square wave, were also used based upon the feedback of participants to sample signals in the participatory design study. Participants generally described sine wave signals as more pleasant and less salient than square wave signals. In the participants’ responses salience and appeal were generally deemed important to real-world use. However, these qualities could potentially be contradictory. For example, a mild signal might be more comfortable against the skin, but therefore be less noticeable and useful as a situational alert. Similarly, signals using a more salient waveform, while valuable for noticing a cue against the skin above real-world distractions and mechanical interference, might become obtrusive or even uncomfortable.

3.2.2. Participants

28 participants, aged between 18 and 49 (mean 25.2, SD: 5.5), 11 females, were recruited from a university student population. All participants reported normal levels of auditory and tactile perception.

3.2.3. Apparatus and materials

A head-mounted tactile interface prototype was developed as part of this research (Fig. 1). The interface consists of a set of tactile actuators, controlled by an audio adapter (Vantec USB External 7.1 Channel Adapter) and a laptop, described in Wolf et al. (2014). C2 tactors, commonly used in HCI research, were integrated with the apparatus (Fig. 2). For the perceptual study, these tactors were encased within a lightweight skullcap, providing a tight fit for the tactors against the user’s scalp, while minimizing constriction of the head which might have become uncomfortable over the duration of the study. This arrangement was also intended to enable delivery of tactile information consistently across the broadest possible range of potential head sizes and hair arrangements.

3.2.4. Tactile signal design

Sixteen signal configurations were used, providing an instance of each selected parameter, including each of four interval patterns (a continuous no-interval pattern, a regularly-spaced interval pattern, an increasing interval pattern, and a decreasing interval pattern), in each of two directions (left and right), based upon each of the two waveform types (sine and square wave). The audio signal parameters chosen to drive the tactors for the experiment were based upon two sources. Firstly, existing research and design guidelines for tactile display at the head were referenced. For example, based on the research of Kalb et al. (2008), tactors were located at two scalp locations, based upon standard 10–20 EEG position naming methodology (F7 and F8), on opposite sides of the head. Based on the same research guidelines, all cues utilized a frequency of 45 Hz, falling within the 32–64 Hz range recommended for effective, comfortable tactile-only communication. Myles and Kalb (2010) specified this range, based on their research upon tactile presentation to the head, to avoid higher frequencies that can produce discomfort and incidental auditory effects. Based upon tactile design guidelines described by van Erp (2002), intervals within the tactile signal were no less than 100 milliseconds, to allow for actuation of the tactor devices and provide an effective minimum duty cycle. The coding for the scalp position was accomplished through basic stereo panning the 2-channel WAV signal file, actuated by the two tactors driven through a single digital stereo amplifier.

3.2.5. Training

Participants were first introduced to the tactile parameter terms and concepts related to the experiment. This was facilitated with a simple illustration (Fig. 3) depicting a user walking outside, with a visual sensor and head-mounted tactile device providing cues to events and physical obstacles. The three parameters of the tactile signals utilized as independent variables (direction, waveform, and interval) were then defined and presented comparatively through the C2 tactors several times. A basic chart (Fig. 4) showing the audio waveforms was used to introduce the four interval types. A series of these training signals was then played through the C2 tactors, and participants were asked to identify the three signal parameters for each. This exercise was repeated until

Fig. 1. Researcher wearing lightweight skullcap tactile device with visible C2 tactor points of attachment, and audio amplifiers.

Fig. 2. A C2 tactor, produced by Engineering Acoustics, Inc., which uses a moving magnet linear actuator. The device is 1.17 “in diameter, and 0.30” thick.
participants indicated and demonstrated satisfaction with their ability to reliably identify the signal parameters.

3.2.6. Task conditions

A randomized, within-subjects approach was utilized with three task conditions (intended to address hypothesis H1.2), termed Identification Only task, Identification and Distraction task, and Distraction Only task. The three conditions were based on the addition of a distraction condition (playing a visually-focused interactive “whack-a-mole” style game) on a HTC Nexus One Android mobile phone (Fig. 5). The handheld game was chosen as a task to assess interaction between tactile signal identification and a constant visual and cognitive distraction. This distraction task was chosen because it closely relates to prospective applications of this research (i.e. wearable technology assisting pedestrians and other users to better maintain spatial awareness), and because engaged gameplay very closely resembles behaviors contributing to the distraction and situational impairment experiences participants described in the earlier participatory design research dealing with tactile alerts (Wolf and Kuber, 2014). Participants were allowed to select any hand and grip they wanted for holding the phone and playing the game. Ninety-six total signal trials were administered through the HMD (not including training), with forty-eight presented in each of the two signal-related task conditions (Identification Only, and Identification and Distraction). This total number of signals presented was chosen to balance quantity, as a driver for statistical power, with the potential for user fatigue.

After each signal was presented, participants were first asked to verbally identify each of its three variable parameters (spatial location, waveform, and interval pattern). Participants were not given feedback regarding the accuracy of their identifications. Secondly, participants were asked to rate on a seven-point Likert scale (1 being very easy effort, 7 being very hard effort), for each signal, their cognitive workload when identifying the parameters. Per training instructions supplied in advance, participants could skip or repeat signals as they deemed necessary. Performance time was recorded for each task condition, but participants were advised not to worry about their completion time. For the Distraction Only condition, performance time was simply limited to sixty seconds, in order to provide a comparative baseline for undistracted gameplay scoring rate. For the two task conditions that included the game task, a final score was also recorded.

After each of the three task conditions, participants were asked to fill out an unweighted (Raw TLX) NASA Task Load Index questionnaire, using the procedures standard dimension definitions for training.2 This tool gathered the user’s subjective 7-point rating of workload in six standard dimensions (mental, physical, temporal, performance, effort, and frustration). Each participant was also asked afterwards for any impressions of the system or device, including ease or difficulty in identifying the variable parameters of the signals, any impact the game playing task may have had on their performance, and any opinions on the potential efficacy of the system concept to their real-world situational awareness needs.

3.3. Results

All participants attempted all tasks, achieving, on average, 94.66% accuracy (SD: 2.62%), across both identification-based task conditions. An ANOVA was run to determine the effect of location, waveform and interval pattern. A Friedman’s Chi-Square test was used to examine the effects on subjective cognitive workload, as the test detects differences between groups when the outcome is ordinal.

Impact of stimuli design

A repeated measures analysis was conducted examining the number of errors made (Fig. 6). Effects were detected for spatial location (F(1,32) = 7.188, p = 0.012), waveform (F(1,32) = 257.125, p = 0.001) and interval pattern (F(1,32) = 16.091, p = 0.001). Pairwise analysis revealed that fewer errors were made when stimuli were presented at the left side of the head (8), compared with the right side (35) (p = 0.012). Fewer errors were made identifying the waveform of tactile stimuli when encoded with sine waves (7) compared with square waves (12) (p = 0.001). Pairwise comparisons showed significant effects between the following levels: no interval vs. decreasing interval (54 vs 105, p = 0.001), no interval vs. increasing interval (54 vs 132, p = 0.001), and static interval vs. increasing interval (78 vs 132, p = 0.001), highlighting the challenge to identification posed to users when identifying ‘changing’ intervals (i.e. those with increasing or decreasing intervals).

Table 1 shows the number of identification errors made with all sixteen of the tacton designs (composed of the three signal parameters). The four interval types are illustrated in Fig. 4. Manipulations in the design of one parameter can lead to difficulties. For example, in tacton set #4 (spatial location: left, waveform: square, interval: increasing interval) 15 errors were made. By simply modifying the tacton (signal design) to present a sine wave (set #8), the number of errors was observed to be more than triple. An effect was confirmed through a paired t-test (t(5) = -8.624, p < 0.001).

Impact of task condition

Findings indicated that 15.5% more errors were made when the user’s visual channel was occupied (Identification + Distraction condition average total error rate: 5.73%, SD: 0.087, 231 errors) compared to when the channel was free to concentrate on the task (Identification Only task condition average total error rate: 4.96%, SD: 0.59, 200 errors). Paired t-tests were run, and the results show that while there was a significant difference between the Identification + Distraction task condition and the Identification Only task condition specifically for interval pattern identification error (t(47)=−3.362, p = 0.002) and location identification error (t(47)=2.729, p = 0.009), there was no significant difference for waveform or total errors (p > 0.05).

In terms of performance in the distraction task, participants scored 1.14 (SD: 0.27) hits per second in the game in the Distraction Only condition, and 0.89 (SD: 0.17) in the Identification + Distraction condition. No significant effect could be detected between conditions.

Cognitive workload

Levels of perceived cognitive workload are shown in Table 2, Fig. 7 and A1. Although findings indicated that slightly higher levels of cognitive workload were experienced under the Identification + Distraction condition (2.84, SD: 1.15) compared to the Distraction Only condition (2.72, SD: 1.21), findings from a Friedman’s Chi Square Test revealed that there was not a statistically significant difference (χ²(1) = 1.333, p = 0.248). Interestingly, results for cognitive workload did appear to follow a similar relationship with signal param-

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2 http://humansystems.arc.nasa.gov/groups/TLX/.
3.3.1. Rate of error in tactile parameter identification

Our first hypothesis (H1.1) related to whether three parameter tactile stimuli could be discerned at sites on the head with an identification error rate below 15%, a percentage drawn from existing studies examining three parameter tacton perception at other sites on the body (Qian et al., 2014). The total identification error rate in the Identification and Identification + Distraction conditions was 5.43% (SD: 2.62). Having achieved accuracy below that identified 15% threshold supports failure to reject H1.1. Pairwise analysis, described in Section 3.3, has suggested that stimuli presented at the left side of the head compared with the right (p = 0.012), and sine waves rather than square waves may be recognized with lower levels of error when encoded within multi-parametered tactons (p = 0.001). Similarly, specific interval types may also impact identification (Section 3.3).

3.3.2. Rate of error, by task condition

Our second hypothesis (H1.2) examined effects on error rate by task condition. Although results suggested more errors were made in the Identification + Distraction condition compared to the Identification Only task condition, significant effect for total error was not found (p > 0.05). As a result, we reject H1.2. However, significant effects were identified by parameter type (e.g. pattern identification error (p = 0.002) and location identification error (p = 0.009)). The interaction between task condition and these secondary identification error types is worthy of further study.

3.3.3. Cognitive workload, by task condition

Our third hypothesis (H1.3) examined how cognitive workload (CW) differs by task condition. Although findings suggested slightly higher levels of cognitive workload were experienced under the Identification + Distraction condition, a statistically significant difference could not be identified (χ²(1) = 1.333, p = 0.248). Given this, and the only

Table 1

<table>
<thead>
<tr>
<th>Sets</th>
<th>Location</th>
<th>Waveform</th>
<th>Interval</th>
<th>Errors (rate)</th>
<th>Avg. cognitive workload (CW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left</td>
<td>Square</td>
<td>No interval</td>
<td>2 (0.4%)</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>Left</td>
<td>Square</td>
<td>Static interval</td>
<td>5 (0.99%)</td>
<td>1.5</td>
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<tr>
<td>3</td>
<td>Left</td>
<td>Square</td>
<td>Decreasing int.</td>
<td>13 (2.58%)</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>Left</td>
<td>Square</td>
<td>Increasing int.</td>
<td>15 (2.76%)</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>Left</td>
<td>Sine</td>
<td>No interval</td>
<td>16 (3.17%)</td>
<td>3.2</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>Sine</td>
<td>Static interval</td>
<td>39 (7.74%)</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>Sine</td>
<td>Decreasing int.</td>
<td>44 (8.73%)</td>
<td>4.1</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>Sine</td>
<td>Increasing int.</td>
<td>55 (10.91%)</td>
<td>4.4</td>
</tr>
<tr>
<td>9</td>
<td>Right</td>
<td>Square</td>
<td>No interval</td>
<td>6 (1.19%)</td>
<td>1.3</td>
</tr>
<tr>
<td>10</td>
<td>Right</td>
<td>Square</td>
<td>Static interval</td>
<td>10 (1.98%)</td>
<td>1.4</td>
</tr>
<tr>
<td>11</td>
<td>Right</td>
<td>Square</td>
<td>Decreasing int.</td>
<td>18 (3.57%)</td>
<td>2.0</td>
</tr>
<tr>
<td>12</td>
<td>Right</td>
<td>Square</td>
<td>Increasing int.</td>
<td>23 (4.56%)</td>
<td>2.1</td>
</tr>
<tr>
<td>13</td>
<td>Right</td>
<td>Sine</td>
<td>No interval</td>
<td>43 (8.52%)</td>
<td>3.7</td>
</tr>
<tr>
<td>14</td>
<td>Right</td>
<td>Sine</td>
<td>Static interval</td>
<td>40 (7.94%)</td>
<td>3.8</td>
</tr>
<tr>
<td>15</td>
<td>Right</td>
<td>Sine</td>
<td>Decreasing int.</td>
<td>41 (8.13%)</td>
<td>4.1</td>
</tr>
<tr>
<td>16</td>
<td>Right</td>
<td>Sine</td>
<td>Increasing int.</td>
<td>61 (12.1%)</td>
<td>4.2</td>
</tr>
</tbody>
</table>
slight difference in average CW between conditions, this hypothesis was rejected.

3.4. Discussion

Several interesting interactions were found in participants’ data, with potential significance to design of tactile user interfaces. Notably, participants consistently described square wave signals as much more salient than sine wave in post hoc interviews, and demonstrated significantly different identification error rates with the two waveform types ($p = 0.001$). This is likely also reflected in the notably higher average cognitive workload rating given to sine wave signals compared to square waves (1.65, SD: 0.4 to 3.88, SD:.45, $p < 0.001$, noted already in our findings), related to participants’ struggle to accurately perceive the sine wave signals they deemed less salient (Fig. 7). This difficulty was described by participants as especially true for signals that com-

![Fig. 6. Total number of identification errors, by tactile design feature.](image)

**Table 2**

<table>
<thead>
<tr>
<th>Sets</th>
<th>Location</th>
<th>Waveform</th>
<th>Interval</th>
<th>ID Only Avg. CW</th>
<th>ID + D Avg. CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Left</td>
<td>Square</td>
<td>No int.</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>Left</td>
<td>Square</td>
<td>Static int.</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>Left</td>
<td>Square</td>
<td>Decreasing int.</td>
<td>1.8</td>
<td>2.1</td>
</tr>
<tr>
<td>4</td>
<td>Left</td>
<td>Square</td>
<td>Increasing int.</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>Left</td>
<td>Sine</td>
<td>No int.</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>Sine</td>
<td>Static int.</td>
<td>3.7</td>
<td>3.5</td>
</tr>
<tr>
<td>7</td>
<td>Left</td>
<td>Sine</td>
<td>Decreasing int.</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>8</td>
<td>Left</td>
<td>Sine</td>
<td>Increasing int.</td>
<td>4.5</td>
<td>4.3</td>
</tr>
<tr>
<td>9</td>
<td>Right</td>
<td>Square</td>
<td>No int.</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>10</td>
<td>Right</td>
<td>Square</td>
<td>Static int.</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>11</td>
<td>Right</td>
<td>Square</td>
<td>Decreasing int.</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>12</td>
<td>Right</td>
<td>Square</td>
<td>Increasing int.</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>13</td>
<td>Right</td>
<td>Sine</td>
<td>No int.</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>14</td>
<td>Right</td>
<td>Sine</td>
<td>Static int.</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>15</td>
<td>Right</td>
<td>Sine</td>
<td>Decreasing int.</td>
<td>3.9</td>
<td>4.3</td>
</tr>
<tr>
<td>16</td>
<td>Right</td>
<td>Sine</td>
<td>Increasing int.</td>
<td>4.0</td>
<td>4.4</td>
</tr>
</tbody>
</table>

![Fig. 7. Average subjective cognitive work, by tactile design feature (1 = low, 7 = high).](image)
bined sine wave and changing interval pattern parameters. While waveform identification errors were more common for square waves compared to sine waves (Fig. 6), for more pattern identification errors were made by participants when perceiving sine versus square wave signals ($p = 0.001$). Also, participants often volunteered in post hoc interviews that sine wave signals seemed “quieter” and required more effort to focus upon and identify signals correctly. While some felt certain that sine waves were less or totally inaudible, there was subjective unanimity that square waves were more perceptually salient than sine waves to both touch and hearing. While the signal parameters were designed based on existing tactile guidelines with the intent of making the tactor motion inaudible, some participants heard audio effects, and some also felt it helped their performance by reinforcing their perception of the signal. This was acknowledged as a limitation of the study. To better address individual perceptual differences, researchers have conducted individualized calibration to establish a minimum perceptual threshold with each participant. The addition of an individualized calibration protocol to future studies will support more representative research on tactile perception, accounting for likely variation in users’ tactile sensitivity and use of related technology.

As stated in our Results section (Section 3.3), participants’ performance ($p = 0.001$) and subjective rating ($p < 0.001$) issues with sine wave encoding was notably exacerbated for those signals with changing interval patterns. Some participants explained that the changing interval seemed more challenging to identify because it required a much longer period of concentration to distinguish the changing pattern, compared to static patterns. All signals were three seconds in duration. Several changing interval patterns (both increasing and decreasing) also had higher levels of identification error than regular or no-interval patterns ($p = 0.001$) (Section 3.3). The additional effort to identify changing interval signals described by participants may also be reflected in the slightly higher cognitive workload ratings ($p < 0.001$) (Fig. 7 and A1).

In post hoc interviews, participants did not describe the task of identifying which side of their head was being stimulated as being challenging. However, there was an unusual deviation in spatial location identification error results towards the right side ($p = 0.012$), shown in Fig. 6. These results are worthy of further study to determine the ways in which location of stimuli can impact interaction.

In terms of cognitive workload, average scores from the NASA TLX test suggested that greater levels of demand were experienced in the Identification + Distraction condition (Fig. 8), although no significant effect was found for subjective cognitive work (3.3 - Cognitive Workload). This may not be surprising, given that in this condition participants were asked to perform at the same time both a tactile identification task and gameplay task that were new to them. It bears consideration whether providing more training might reproduce the sort of familiarity that users of mobile technology develop with their most frequent device interactions. This familiarity might have significant effect on the distribution of perceived cognitive load across the task conditions.

Participants were instructed to prioritize the accuracy of their signal identification work over their task completion time. However, times were recorded for the Identification + Distraction condition, allowing average hits per second to be compared with the Distraction Only condition, as a supplemental consideration for discussion. Lower scores were obtained in the Identification and Distraction condition, potentially supporting the assumption that performance of the distraction task was diminished by the addition of the signal identification task. However, this would need to be confirmed through further statistical analysis.

### 3.5. Conclusions for tactile design

Our findings suggested several points of guidance to be considered by wearable interface designers:

- **Conclusion C1.1:** Care should be taken in the tactile design process when manipulating the parameter of waveform for presentation at the head. Participants can identify three-parameter tactons presented at the head with lower levels of error. While sine waves were found to be detected by participants with fewer waveform identification errors compared with square waves, the user may experience greater levels overall of pattern identification error ($p = 0.001$) and cognitive workload ($p < 0.001$). However, existing tactile guidelines clearly describe counteractive effects (e.g. headaches or numbness) from prolonged use of higher salience coding, such as the square wave coding examined in this experiment. Several participants subjectively described light to moderate fatigue over the course of the three trials, which they attributed to experiencing the stronger square wave signals. Combined, these observations and user feedback suggest moderating the use of waveforms, possibly by reserving higher salience square wave signals for cues to high priority situational awareness events, such as for urgent spatial hazards to navigation. Additionally, our findings suggest that interval should be carefully considered in use with multi-parameter cues. Fewer identification errors were made with static interval cues (regularly spaced or continuous pulses), versus changing interval cues (either increasing or decreasing). Designers may want to consider other parameters and user conditions if wishing to differentiate cues in simple coding schemes.

- **Conclusion C1.2:** Tactile pattern and location identification accuracy reduced when the user was visually distracted. Designers should be aware that the interval pattern ($p = 0.002$) and location ($p = 0.009$) identification process can be impacted negatively.
by common stress conditions, and should therefore design and test salient cues under realistic conditions (i.e. when distracted by a cognitively-demanding task on a mobile interface) to assess the potential impact on users’ cognitive workload.

4. Study 2: investigating the feasibility of presenting tactile cues at the head to heighten levels of situational awareness

4.1. Objectives

Our second study expanded upon the tactile signal design conclusions of the first perceptual study by inquiring how a related coding scheme would assist participants in maintaining their situational awareness over the course of a tactile “storyline,” which would simulate real world pedestrian spatial hazards under realistic conditions. Participants followed a progressive series of events, based upon the same pedestrian use-case scenarios used in our first perceptual study. These events were communicated through a head-mounted device and playback equipment, via a tactile scheme based closely upon the design conclusions of the first study (Section 3.5).

A modified version of the SAGAT situational awareness assessment procedure was used to administer “freeze probes” (questions posed to participants, during a timeout, about their understanding of relevant test events) over the course of three trials, in which participants were asked to sit, walk slowly, or walk briskly. The probes inquired progressively about participants’ perception, comprehension, and ability to predict the storyline events, to reflect Endsley’s standard three-stage model of situational awareness (Wickens, 2008). For example, after a signal indicating a hazard approaching from the left, a Perception question would inquire as to what signals were felt. Comprehension questions would inquire if, based upon any perceived signals, the user felt there was a hazard, and, if so, where it’s proximity, priority and position was in relation to the user. Prediction questions would then inquire if any responses did or did not seem required by the scenario. As with the perceptual study, this experiment also included subjective cognitive workload as a variable. The intent of this was to see if significant interaction might occur between the exertion conditions and cognitive workload (Hypothesis H2.1), and situational awareness stage (Hypothesis H2.2).

Hypothesis H2.1. Increased exertion (walking slowly, quickly, or sitting stationary) will increase self-reported cognitive workload when identifying tactors.

Hypothesis H2.2. Increased exertion (walking slowly, quickly, or sitting stationary) will reduce SAGAT-type situational awareness scores, by level (perception, comprehension, prediction) when identifying tactors.

4.2. Design & methodology

The experiment utilized a 3 x 3 x 3 design, to research the effects of tactile parameters (amplitude, interval, and waveform), and participant exertion condition (sitting stationary, slow walking, and fast walking) on levels of situational awareness (perception, comprehension, prediction) for three trials of the storyline (total numbers of observations for these measures are described in Section 4.3, Results). As with our first study, a within-subjects design was used for this study, to maximize potential statistical power of any observed effects, while minimizing any potential variance effects amongst participants.

Tactile cues were displayed to participants using the same head-mounted device from Study 1. These cues portrayed events from scenarios related to the pedestrian experiences described in the survey data collected in the initial participatory design phase (Wolf and Kuber, 2014), and used in the first study. These scenarios intended to invoke participants’ ability to recognize and interpret tactile signals under realistic and challenging conditions related to multi-tasking. The assessment of tactile signal identification was based upon prior studies concerned with tactile coding, regarding navigation and situational awareness. Performance measures were devised, addressing accuracy of perceiving, comprehending, and extrapolating predictions based upon tactile information parameters. These parameters were in turn based upon the results of our first study, and were intended to effectively convey three types of situational context (Table 3).

Participants

Twenty-seven participants, aged 18–49 (mean 26.4, SD: 7.2), 7 females, were recruited for the task. All participants reported normal levels of auditory and tactile perception.

4.2.1. Tactile signal design

4.2.1.1. Vibration pattern. The vibration pattern conditions were based upon existing tactile design guidelines (Jones and Sarter, 2008; Myles and Kalb, 2010; van Erp, 2002), participant feedback from our earlier participatory design research (Wolf and Kuber, 2014), and conclusions from the first study (Section 3.5, Conclusions for Tactile Design). Focus group observations from the initial participatory design research described the potential usefulness of changing interval times (or rhythm) in a vibration pattern to convey a changing threat condition (i.e. a decreasing interval to signal an approaching threat). The reliability of presenting these parameters to distracted users was explored in the first study. These signal parameters were modified in this second study to convey position, proximity, and urgency of a series of hypothetical spatial threats. For example, expanding upon the conclusions (conclusion C1.1) of the first experiment, lower salience sine wave signals were assigned to cues presented for low-priority events, and higher amplitude square wave signals were mapped to high-priority scenario conditions, such as near-range spatial hazards. Changing the rhythmic interval of the tactile cues was mapped to the proximity of hazards. Spatial hazards were also localized to the azimuth of the threat, through one of four head-mounted tactors.

Based on the research of Myles and Kalb (2010), the frequency utilized for all cues was 45 Hz, falling within the 32–64 Hz range recommended for effective, comfortable tactile-only communication (by avoiding higher frequencies that can produce discomfort and incidental auditory effects). The intervals within any tactile signal were no less than 100 ms, which were intended to provide for an effective minimum duty cycle in the C2 tactor devices. Citing van Erp’s (2002) tactile guidelines, pattern-based signals did not use intervals of less than 10 ms, and users were not expected to discriminate between more than four degrees of amplitude. Temporal intervals (pauses between buzzes), based on the ranges explored in the first study, were constrained from 600 to 100 ms. Similarly, amplitude of the unadjusted base signals was 12 dB, consistent with conclusions from the preceding perceptual study.

4.2.1.2. Update signal to convey relative urgency. In a related participatory design study (Wolf and Kuber, 2014), presentation of concurrent alerts was deemed problematic. An approach to overlapping or com-

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Situational conditions to tactile parameter associations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Situational condition</td>
<td>Tactile signal parameter(s)</td>
</tr>
<tr>
<td>Proximity of spatial hazards to the user</td>
<td>Interval length (longer interval in signal pattern = further distance to hazard), Amplitude also modified (increased with approach of spatial hazard), along with waveform (sine waves for distant hazards, square waves for mid and near-range hazards).</td>
</tr>
<tr>
<td>Priority of concurrent hazards around the user</td>
<td>Rather than simultaneous signaling of multiple hazards, relative urgency was afforded by an “update signal,” played across all four tactors, conveying shift to portraying a new highest-priority hazard, to be followed by cues regarding that threat. Localized to front, back, left, and right tactors on the head-mounted device.</td>
</tr>
<tr>
<td>Spatial position (azimuth) of spatial threats around the user</td>
<td></td>
</tr>
</tbody>
</table>
peting patterns representing multiple hazards was subjectively viewed by participants as especially difficult to resolve. To simplify and focus the tactile coding scheme for this experiment, relative urgency was defined as the realistic need to prioritize the relative urgency of spatial hazards. This was represented by a distinctive “update” status signal, played across all four tactors in the head-mounted device, that participants were trained to recognize as indication that a new hazard has superseded the priority of others.

4.2.2. SAGAT situation awareness assessment method
Participants’ ability to interpret tactile parameters was assessed using a basic form of the SAGAT protocol (Situation Awareness Global Assessment Technique); a method commonly used to measure situational awareness across a use-case scenario. The method assesses perception, comprehension, and prediction of situational context through probe questions at random or scheduled pauses in a scenario, in our case during a tactually presented “storyline.” As stated, this storyline was based directly on seven scenarios derived from user surveys, which were used in our initial participatory design phase. Specifically, the storyline was derived from the compounded conditions described in the scenarios. For example, a scenario described a user who first receives a tactile alert for a slowly approaching spatial hazard directly to their front, in their direction of travel. Then secondly, an additional tactile alert is given for a spatial hazard approaching more rapidly, perpendicular to their direction of travel.

The situational status information driving the tactile signals presented at the head-mounted device was simulated. Signals were prepared as .WAV audio files, and played back in sequence from a laptop via Max/MSP media authoring software. During the initial training portion of this study, participants were presented with an explanation of the system concept (like Fig. 3 from the prior study), and asked to assume the simulated input was presented by a wearable computer vision sensor. The SAGAT situational awareness assessment protocol’s format was chosen to inquire, via freeze probes at three points within each storyline, about the participants’ situational awareness. Per this assessment protocol, probe questions addressed three stages of situational awareness. Questions targeted: (1) accuracy of user perception (including identification of activated tactors’ positions, interval patterns, and relative amplitude), (2) accuracy in user comprehension (i.e. identifying patterns, in terms of stated contextual associations), and (3) accuracy in user ability to describe guesses about progression of events illustrated by a tactile storyline, and provide responses (prediction).

4.2.3. Additional tactor locations
In the first study, the location on the head at which tactile signals were received was generally more accurately identified than other parameters such as interval type (Section 3.3 – Impact of Stimuli Design), and was also more consistently accurate across task conditions. For example, participants on average made slightly more direction-related (left/right) identification errors in the Identification Only task condition (1.107, SD: 1.062) than the Identification + Distraction condition (0.429, SD: 0.484), per 48 signals (p = 0.009, Section 3.3 – Impact of Task Condition). Given the low rates of error in identifying location in Study 1, and the need for more specific directional cues to support a realistic use case, this study utilized four tactors to convey four relative directions. These were positioned in a single row around the head at front, back, left, and right.

4.2.4. Background audio condition
Several focus group participants in our initial participatory design research commented on the importance of a tactile device being inconspicuous on the user, to avoid attracting unwanted attention or danger (Wolf and Kuber, 2014). Subsequently, numerous participants in the first study also responded affirmatively when asked in post-hoc interviews if they perceived sound accompanying each tactile signal. This was particularly true for the square wave signals. Given these observations and results, the interaction of signals and realistic background noise clearly could have impact on the utility of head-mounted tactile signals. To further explore this, a sound condition consistent with constant ambient street noise at 60 dB was added.

4.2.5. Exertion conditions: sitting stationary, slow walking, and fast walking
Based again on survey observations from the initial participatory design phase, realistic exertion conditions were added to identify potential impacts of motion and activity on tactile task performance. These exertion conditions were sitting stationary, slowly walking, and rapidly walking quickly, with the ambulatory conditions performed on a treadmill. Numerous survey respondents in the participatory design phase described scenarios (further applied to use-cases in Study 1) with consequences such as mistakes and accidents attributed to visual and cognitive distraction while walking. Further, research has found masking effects in tactile perceptual performance related to realistic physical and cognitive activity, such as walking and routine mobile phone tasks. Participants were asked to carry out these conditions on and off the treadmill, and at slow and fast walking speeds, to simulate these possible conditions (Oakley and Park, 2007).

4.3. Results
The values used to determine rate of accuracy for situational awareness were based upon accuracy of probe question responses, categorized by situational awareness stage. ‘Average Perception’ for all conditions is established by 729 observations (based upon 3 perception questions, ×3 repeats per trial, ×3 trials per participant, ×27 participants). Similarly, ‘Average Comprehension’ for all exertion conditions is based upon 1134 observations (based upon 14 comprehension questions per trial, ×3 trials, ×27 participants). ‘Average prediction’ for all exertion conditions is established by 486 observations (based upon 2 prediction questions, ×3 repeats per trial, ×3 trials, ×27 participants). These values were averaged. An ANOVA was run to determine the effect of average situational awareness by stage, and stage by walking condition. A Friedman’s Chi-Square test was used to examine the effects on subjective cognitive workload, while a Spearman rank-order correlation coefficient was undertaken to examine the strength and direction of association between situational awareness and cognitive workload for different exertion conditions, as assumptions of the test were satisfied.

The rate of accuracy for situational awareness by stage is shown in Fig. 9. The presence of a significant effect of situational awareness stage was confirmed through repeated measures analysis ($p(2,34) = 4.855$, $p = 0.037$, Greenhouse-Geisser corrected), with post-hoc analysis highlighting that accuracy of responses to perception questions (0.94, SD: 0.07) exceeded comprehension (0.77, SD: 0.31, $p = 0.034$), while prediction (0.91, SD: 0.06) outpaced comprehension (0.77, SD: 0.31, $p = 0.045$). When examining results in more detail, further analysis was undertaken to determine the effect of walking condition on the rate of accuracy by situational awareness stage (data table underneath graph in Fig. 9). A repeated measures ANOVA confirmed the presence of an effect ($F(1,16) = 4.291, p = 0.025$, Greenhouse-Geisser corrected).

A Friedman’s Chi-Square test showed the presence of a significant effect between self-reported levels of cognitive workload and exertion condition ($x^2(2) = 37.872, p < 0.001$). The average cognitive workload reported by participants, for all three sequences of all three trials, showing that greater levels of cognitive workload were reported in the Fast Walk condition (2.84, SD: 1.50), compared to the Sitting Stationary (2.43, SD: 1.54) ($Z = -4.417, p < 0.001$) and Slow Walk (2.48, SD: 1.55) ($Z = -3.906, p < 0.001$) exertion conditions.

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3 https://cycling74.com/.
A Spearman’s rank-order correlation was run to determine the relationship aggregated situational awareness (all three stages) and cognitive workload for different exertion conditions. There was a very weak correlation for the Fast Walk condition, which was statistically significant (\(r_s = 0.136, n = 226, p = 0.040\)). No other significant effects could be determined.

In terms of self-reported values gathered regarding the three tactile signal parameters, participants felt that changes in interval were more noticeable (4.55, SD: 0.66) than amplitude parameter (\(Z = -2.397, p = 0.001\)). The opinions were divided about the efficacy of amplitude and waveform. Participants felt that changes in waveform (4.19, SD: 1.02) were easier to discern than amplitude (3.89, SD: 1.17) (\(Z = -3.366, p = 0.001\)), likely due to the high tactile salience of square waves played through C2 tactors. However, participants reversed their preference between the two parameters regarding which they deemed more useful. Amplitude changes (4.11, SD: 1.03) were rated as more useful to understanding what was happening in the tactile scenarios, than waveform (3.78, SD: 1.26) (\(Z = -2.494, p = 0.013\)).

Further subjective feedback solicited from participants relating to the effect of ambulatory conditions and mapping of signal parameters is discussed in Section 4.4.

4.3.1. Impact of exertion on self reported cognitive workload

Hypothesis H2.1 examined whether increased exertion (walking slowly, quickly, or sitting stationary) would increase self-reported cognitive workload when identifying tactons. A significant effect was identified between self-reported levels of cognitive workload and exertion condition (\(\chi^2(2) = 37.872, p < 0.001\)), with findings suggesting that greater levels of cognitive workload were reported in the Fast Walk condition (2.84, SD: 1.50), compared to the other exertion conditions (\(p < 0.001\)). As a result, H2.1 was not rejected.

4.3.2. Impact of exertion on situational awareness

Results showed that the average accuracy of responses for perception (0.94, SD: 0.07) was higher than comprehension (0.77, SD: 0.31, \(p = 0.034\)), and accuracy of prediction (0.91, SD: 0.06) was higher than comprehension (0.77, SD: 0.31, \(p = 0.045\)). There was very weak support (\(p = 0.040\)) from a Spearman rank-order correlation for situational awareness accuracy and cognitive workload with the Fast Walk exertion condition, but given this limited result our hypothesis (H2.2), that greater exertion would diminish situational awareness scores, was rejected. Further work would be needed to identify the presence of a strong effect.

4.4. Discussion

4.4.1. Effect of ambulatory conditions on increased cognitive workload

As noted in our results (Section 4.3), a significant effect was found between cognitive workload and exertion (\(p < 0.001\)). This likely reflects the added cognitive difficulty imposed by identifying the signals while exercising. Participants also subjectively reported several observations to that effect. For example, a participant explained that the HMD headband holding the tactors against the scalp, while not uncomfortably tight, constrained enough to allow him to mildly feel his pulse. The perception of his pulse was similar enough to the rhythm of the tactile cues to cause confusion, and as his pulse increased in the Fast Walk exertion condition he felt the interference increased.

In a related observation, several participants did describe in their post-hoc subjective commentary that they felt the pace of the Slow Walk condition was slower than their natural walking speed. They related that deliberately maintaining the slower walking speed required a modest amount of mental focus, and may have in turn distracted them slightly from processes related to maintaining situational awareness in the tactile storyline being presented. Clarifying if this effect alone explains the consistently lower Slow Walk condition results would require further study.

4.4.2. Appropriate mapping of tactile signal parameters to environmental conditions

In post-task discussion, several of the participants subjectively related difficulty in distinguishing whether “mid-range” signals fell between those mapped to distant or close spatial hazards. This may be explained by an aspect of the coding scheme devised for this experiment. Based on the results and feedback from the initial participatory design phase and first experiment, only two waveform types were utilized, and thus the parameter only mapped to either distant (sine wave) hazards, or both mid-range and close spatial hazards (square wave). The intent was to produce, through waveform, a distinct “ramp-up” in tactile salience as hazards approached. Amplitude, by comparison, was instead coded to continuously vary for the distance to spatial hazards, from distant to mid-range and near. If perceived accurately, this continuous increase is possibly a more intuitive approach to tactile display for participants to learn. Further, this approach in the tactile coding of the experiment offers a logical explanation of participant preference of amplitude over waveform for utility.

4.4.3. Comparison of situational awareness results to similarly structured research

Our situational awareness results have some similarity to related research on tactile signaling of spatial cues, such as those by...
Pietot et al. (2010) which used the SPAM assessment method. Expressed as a percentage, participants in the study of Pietot et al. scored very closely (0.84) on a similar measure of accuracy to the average of accuracy scores for all three situational awareness stages in our study (0.87, SD: 0.07), while the SPAM method utilized did not include measures that map directly to the SAGAT perception or prediction stages. In research by Kaber et al. (2006), a SAGAT measure closely related to methods of this study was used to assess the impact of manual and automated modes of air traffic control on participants’ situational awareness. The researchers found average comprehension stage scores notably lower than those found in our study, but a similar relationship between stages is apparent in both studies, with mean comprehension scores found by Kaber et al., lagging behind perception (Level 1) and Prediction (Level 2) scores (ranging from approximately 70–80%).

4.4.4. Participants’ deviation from training instructions

4.4.4.1. Low salience hazards. While participants only three times requested repetition of tactile cues across all trials conducted in the study, there were clear issues of interpretation that arose. Primarily, this was demonstrated regarding low-salience tactile signals, which were often perceived and described accurately in response to perceptual stage questions, but then immediately after described inaccurately in response to comprehension stage questions. Participants directly attributed this to the use of the terms “hazard” and “threat” in probe questions. Mild signals were sometimes reinterpreted by participants as not being hazardous or a threat because they did not seem to connote those terms, and participants contradicted their training and the experiment instructions by applying this modified definition to their responses. Several participants described this explicitly in their posthoc comments. Additionally, a significant portion of the cohort for the experiment included participants for whom English was a second language, or who also required translation of instructions into their primary language. In several instances, the definition of these terms required repeated clarification.

4.4.4.2. Added signal interpretations. Additionally, some participants added new interpretations to the parameters presented in the tactile storyline. For example, several participants correctly used their training to relate changes in interval to hazards that were changing in proximity, but then went further and assigned vivid behavioral characteristics to the hazards. Moving hazards depicted by tactile cues were assumed to be cars traveling only in a linear direction, or dogs that might be circling the participant. Another participant described the “visceral” and unexpected reaction of turning in the direction of the tactile signal involuntarily, as if to look at what might be coming. Others described mild anxiety as intervals used to convey proximity accelerated, and felt an instinct to brace or duck as if they might be about to get hit by a car or assailant.

4.5. Implications for design

C2.1: Potential Issues with Modal Shift in Tactile Cues

The results of this study offer some insight for effective tactile design. Exertion impacted participants’ self-reported cognitive workload (p < 0.001), one ambulatory condition introduced more error (p = 0.040), and lower mean accuracy scores were demonstrated for all three situational awareness stages under higher exertion conditions, providing support for hypothesis H2.1. Participants’ subjective comments noted this effect, and attributed it clearly to the expected cognitive and perceptual distraction related to increased physical activity. This observation supports the conclusion that effective tactile design, especially for mobile applications, should account for the probable deleterious impact of higher exertion on concurrent cognitive workload and tactile interaction.

Specifically, one potential approach to this would be to allow preset tactile parameters to be shifted manually or automatically in modes, tailored to types of selected or detected physical or mental activity. For example, amplitude could be increased and rhythmic complexity reduced in tactile modes intended activities with more physical exertion or cognitive distraction. Similar coding was suggested by participatory design participants in our previous research (Wolf and Kuber, 2014), and related tactile research (McGrath et al., 2004). While such modes could offer important adjustments in both the complexity and salience of tactile cues to make them more effective, the results of this study invoke other considerations.

If a potential system intends to convey situational or contextual information, users may depend on their ability to consistently interpret the meaning of tactile cues for safety or awareness. As discussed in related literature on situational awareness and design for decision support, “modal shift” may introduce new problems as it appears to solve old ones (Sklar and Sarter, 1999). Safe, accurate interpretation of modal shift would depend upon users’ ability to continually update their comprehension of tactile cues, in order to maintain their situational awareness. The results of this study suggest that comprehension of complex tactile coding schemes under realistic conditions is not assured, even with recent training, unless parameters are selected and mapped with care to user conditions.

C2.2: Beware Secondary Effect of User Interpretation of Tactile Coding

In subjective comments and probe question responses, several participants accurately described their perception of low-salience signals, but then immediately afterwards inaccurately interpreted those signals in comprehension question responses. Most of these participants later explained that they deliberately contradicted their training because they had re-defined low amplitude and sine wave signals as unimportant “FYI only” events that did not rise to the threshold of “hazards,” as defined in the lexicon of their training and probe questions. Distant threats were disregarded in comprehension questions about the number and position of hazards. While this improvisation was not an intended part of the participants’ role in this study, it is not entirely surprising, or even unhelpful, that users would adjust the definitions of tactile signal thresholds to suit their own goals. This indicates that effective tactile design should anticipate the likely needs of users, and how that context may modify comprehension.

C2.3: Perceived Changes in Tactile Signal Parameters Should Map to Users’ Understanding of the Described Condition

As discussed in Section 4.3, participants reported in post hoc questioning on the usefulness and noticeability of the three signal parameters used for tactile coding, within a 5-point Likert scale. Interval was a clear favorite in mean averages for usefulness (4.46, SD: 0.75, p = 0.001). However, the outcomes for waveform and amplitude were reversed, with waveform (4.19, SD: 1.02) being favored over amplitude (3.89, SD: 1.17) for noticeability (p = 0.001). Amplitude (4.11, SD: 1.03) was instead favored over waveform (3.78, SD: 1.26) for usefulness (p = 0.013). These parameters were used to encode the changing proximity of a hazard. However, while amplitude could change continuously in relationship to proximity, there was a hard shift from less distinct sine wave signals to more distinct square wave signals.

While this obvious shift would explain why participants felt waveform to be the more noticeable parameter, it is curious then that it was not also deemed more useful. One available explanation is that amplitude fits more suitably to participants’ mental model of proximity, because both could change continuously. This raises two considerations for tactile designers. Firstly, a tactile signal parameter intended to vary in relationship to a real world condition should obviously be selected by how well its perceptible degrees of change conform to the number of conditions needed to effectively describe the condition. Secondly, the training scheme for the coding scheme should define this relationship as clearly as possible. For example, in our second study, while a two-mode waveform design for describing proximity may not have fit as well as amplitude, the clear perceptual distinction between sine and square waveforms could have instead been applied more effectively as an added
contextual overlay, if users were prepared to interpret the information display. If that training were part of the prototype, square waves likely could have instead effectively connoted an added danger condition, providing a richer situational display.

5. Conclusion

We first studied the efficacy of a set of multi-parameter tactile cues and a HMD, the design of which was based in participants’ descriptions of real-world distraction and breakdowns in spatial or situational awareness. The suitability of mapping tactile signal parameters (interval, amplitude, frequency and location) to these realistic conditions was the focus of the first perceptual study, and participants demonstrated higher error rates and subjective cognitive workload measures with interpretation of sine wave signals, and with signals in which rhythmic intervals changed, versus those without. Our second study then investigated how use of the three-parameter tactile coding scheme impacted participants’ situational awareness, as measured through the SAGAT assessment procedure, and cognitive workload, across a tactile storyline depicting realistic pedestrian spatial hazards. Significant interaction was found between exertion condition and subjective cognitive workload. Accuracy scores for SAGAT probe questions demonstrated a very weak correlation to higher exertion. Further work would be needed to confirm the presence of a stronger effect. The SAGAT scores also revealed that perception and prediction outpacing comprehension. These findings imply for tactile designers that use of three-parameter tactons for situational awareness requires consideration of their mapping to real world conditions and awareness of user interpretation.

6. Future work

Follow-on studies from this work would endeavor to supply further guidance regarding the effective design of tactile cues for interaction at the head, with specific attention to alerts designed to redirect users’ attention to changing spatial or situational conditions. Additionally, regarding research methodology, we would like to pursue additional applications of situational awareness assessment methods, such as the SAGAT procedure employed in our second study, to address the efficacy of tactile cues. This would intend to find out if more significant interactions between situational awareness stage and variation in tactile design parameters of alerts for pedestrians could be identified by modifying standard aspects of those protocols, such as the language used in freeze probe questions directed to participants.

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Appendix

![Fig. A1. Total errors and cognitive workload, for both signal identification task conditions, by 16 signal types.](image-url)
References


