Addressing the Situational Impairments Encountered by Firefighters through the Design of Alerts

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ABSTRACT

Situationally-induced impairments and disabilities (SIIDs) are experienced by a range of users. Firefighters can be impacted when performing tasks under the inhospitable conditions often present at the scene of a fire (e.g. thick smoke and loud noise). In this paper, we describe the steps of an approach to support situational awareness (SA) among firefighters whose visual and auditory channels may be restricted while performing tasks. A structured multi-step approach was adopted to develop meaningful, perceivable cues that could aid in this process. In order to investigate the efficacy of alerts designed using this approach, cues were evaluated under simulated conditions in a lab. Findings revealed the benefits offered by visual signals when facing SIIDs, in contrast to their tactile and auditory counterparts. However, subjective comments revealed that tactile signals, if designed appropriately, may offer promise to support decision making among firefighters who often encounter SIIDs.

CCS Concepts

• Human-centered computing → Accessibility → Empirical studies in accessibility

Keywords

Alerts; Accessibility; Situational Impairments.

1. INTRODUCTION

Situationally-induced impairments and disabilities (SIIDs) represent an important area of study for accessibility researchers. SIIDs have been described as instances when the situation itself places demands on the user's attention, sensory and motor ability, which may subsequently impact the user attempting to perform a task [13, 25]. This can impact both users with disabilities, and those without. Firefighters represent one group who encounter SIIDs on a frequent basis, as they are often exposed to stressful, dangerous, and rapidly-changing settings. The nature of the conditions experienced can play a role on task performance, the way that situational awareness (SA) is established, and how resulting decisions are made.

At the scene of a fire, the presence of thick smoke can restrict the ability to visually identify other firefighters and gestural cues,

observe critical structural and fire conditions, and may even impact reading equipment gauges. These gauge displays, located on their Self Contained Breathing Apparatus (SCBA) and associated breathing mask, frequently support important safety interactions. When vision is blocked or restricted, it can be difficult to orient position and wayfind. As a result, firefighters rely on the use of tactile cues (e.g. using hand tools to feel for obstacles on the ground or manually following a hose line back to an exit). Furthermore, sounds from either the combustion of the structure, or noise from sirens, ventilation fans, and gas-powered tools (saws) may impact the ability to identify auditory alerts presented via communication devices or via voice. The cognitive and physical demands imposed by the dynamic settings can make planning and performing tasks, along with critical communication and coordination with other firefighters, challenging at best. Fire emergency response requires rapidly processing and communicating information [3, 31]. If communication is restricted due to the conditions faced, and levels of situational awareness are low, it can lead to risk for firefighters.

Our research aims to better match the needs of firefighters when facing SIIDs. In this paper we present a set of methodological findings from our process of inquiry with firefighters, including deriving prototyping scenarios from contextual interviews. We describe a four-step approach to identify and design alerts to assist firefighters with SIIDs they have encountered when performing duties in the field. The method may offer promise to other alert designers intending to work with individuals in dynamically-changing scenarios who encounter SIIDs. We also present results from lab-based assessment of visual, auditory, and tactile alerts tailored to firefighting conditions. The fourth step described, in-process at the time of this writing, aims at further testing the performance of these alerts under realistic field conditions (a fire training simulation facility). By presenting alerts which can be discerned when facing situational, contextual and environmental challenges, we aim to heighten levels of situational awareness and to better inform decision making to remain safe within hazardous environments.

2. RELATED WORK

2.1 Situational Impairments

Researchers examining SIIDs have largely focused on the difficulties mobile device users face when ambulatory [7, 10, 24], or when multi-tasking [36]. The user is required to shift attention from the device to the wider environment to check for obstacles in their path. More recent work has focused on the challenges faced by individuals with disabilities who also encounter SIIDs. Examples include individuals who are blind, whose mobile tasks may be impacted due to their hands being encumbered with a harness or long cane, or by the presence of ambient sounds [1]. Solutions have also been developed to address SIIDs by either manipulating presentation of graphical content, or through the design of alerts which are accessible, even under constrained conditions [15]. The user can then make an informed decision

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regarding whether attention should be diverted to the mobile screen, or whether this can be done at a later point in time. Other work has focused on categorizing SIIDs (e.g., [21]), and differentiating more restrictive SIIDs, termed ‘severely constraining situational impairments’ (SCSIs) from their less constraining counterparts [22]. SCSIs refer to situations where workarounds may be limited due to the complexity of the situation (i.e. multiple channels are unavailable for use).

2.2 Firefighters and SIIDs

HCI researchers have discussed the need for firefighters to make decisions quickly, constantly assess the situation and plan their next set of actions within dangerous environments [6]. However, there has been limited focus on the ways in which cues can be designed to better support firefighters in their tasks when experiencing inhospitable conditions. Tasks performed by firefighters can differ considerably (e.g. fire abatement, control of spread, search and rescue, providing emergency medical care). When the visual or auditory channels are restricted (through the presence of smoke or noise etc.), it may not only impact those tasks but also impact communication and coordination as signals may be masked or occluded.

Figure 1: Firefighters wearing SCBA (airpack), PASS system, and radio entering a burning structure.

Firefighters are known to make little use of computers when at the scene of a fire [6], often relying on a small set of alerts from equipment worn on the body (Figure 1). Alerts presented to firefighters include visual and auditory signals to provide awareness of the volume of air available in their SCBA device (presented both visually and auditorily), and emergency signals emitted from the Personal Alert Safety System (PASS) device highlighting the presence of danger. Other alerts are presented using the same channels. The types of device and resulting alerts (e.g. indicating the presence of gases, toxins etc.) vary from jurisdiction to jurisdiction. Firefighters are known to use a combination of their own knowledge, intuition and support from others, along with existing alerts, to assess relevant threats and perform tasks. However, difficulties may be faced under particularly challenging settings (high cognitive and physical demand), and by those who have not had extensive exposure to different settings.

2.3 Alerts through Alternative Channels

Although less commonly used by firefighters, tactile technologies offer considerable promise under constrained conditions. For example, tactile cues can be accessed when vision and audition are unavailable. Tactile displays developed with firefighters in mind include the glove-mounted two vibrator display described by Walters et al. [35], designed to relay information about 3

temperature ranges to indicate when it is safe to remove their gloves. The researchers used three pulsing frequencies (none, slow and high). Findings revealed that rates of error were relatively high ($> 20\%$), especially if the decision needed was between a safe environment (none, slow) and an unsafe environment. Streefkerk et al. [29] developed a solution with a head mounted visual display and a tactile feedback belt display for providing orientation and situational awareness information for fire rescue tasks. While thought to offer potential, levels of mental effort became significantly higher without a significant improvement in performance. The researchers believed this was likely due to cognitive overload, the slow speed of the displays and poor matching to reality.

2.4 Participatory Design

Participatory Design (PD) approaches enable both designers and users to work together to collaboratively design solutions which better match the needs of the target user. In contrast to User Centered Design approaches, PD is thought to respect users more as partners in the design process and in doing so explicitly give them a more equal and responsible role [23]. PD has been used extensively when designing for individuals with disabilities [2, 9], and for developing alerts for these communities. It is thought to deepen ties with end users, thereby promoting greater buy-in. PD has been used to support emergency service personnel (including firefighters). Examples include using PD to observe the practices of emergency service personnel [8], explore the navigational and search practices of firefighters, and to look for opportunities for the introduction of ubiquitous computing [19] solutions to support these practices.

The limited availability of guidelines for situational impairments, may lead designers to arbitrarily select alerts, without giving due consideration to the preferences of target users, and addressing the situational/environmental constraints that may impact access to these cues (e.g. impact of ambient sounds etc). A structured approach enabling the designers to identify the utility of different types of alert, and how alerts can be designed to be perceivable, meaningful and respected could offer considerable promise. In this paper, we propose a multi-step approach, and focus specifically on designing alerts to convey three types of threat which may be difficult to otherwise detect and monitor. These were identified from contextual interviews with members of the fire service (Section 3.2). A participatory design approach has been adopted, with the aim to develop a solution which better matches needs when SIIDs are encountered. We present findings from a lab-based study of user performance with these alerts, under a selection of simulated conditions (visual occlusion and background noise). The implications of these results are discussed in terms of improving alert design in the three sensory modalities for firefighting tasks. We then outline the in-process fourth step to test these alerts under more rigorous conditions at a fire simulation facility, along with anticipated paths for future work on this topic.

3. METHOD

3.1 Overview

There is a general paucity in the number of design methods used specifically for developing technologies to better meet the needs of users encountering SIIDs. From the few studies that have been completed, empirical techniques such as surveys and/or interviews (e.g., [1, 16, 22, 30]) have been used. Alternatively, methods such as mapping signals to cues have also been performed [17]. A method originally developed to support the design of feedback for

visually impaired users [9], has been adapted to the context of situational impairments, with a view to developing targeted support for interactions. A four-step method proposed is presented in summarized format in Sections 3.2-3.5. The steps include: (1) Contextual interviews, (2) Participatory design, (3) Lab-based testing of alerts, and (4) Evaluation of alerts under situationally impaired conditions. Each step is performed in sequence. Three of the four steps have been completed, while one is currently in progress. After the steps have all been completed, future work would then be performed using these technologies in real world settings. We report on the progress of the three completed steps in this paper, and describe how we aim to conduct the fourth.

3.2 Step 1: Contextual Interviews

3.2.1 Approach

A set of open-ended interviews were conducted with a total of six safety officers and senior fire service personnel from two districts (one urban, one suburban), and a range of firefighters from stations within these locales. The aim was to gain a deeper insight into the practices of firefighters in inhospitable and rapidly changing environments, the types of alerts currently present and their efficacy, along with the description of other situations where further alerts would be beneficial (if appropriate). However, the interviews also allowed us to better understand the experiences of more senior personnel (e.g., safety officers), who may also benefit from alerts, or who may want to provide alerts on-demand (see Table 2 for examples of questions). Interviews lasted between 45-60 minutes. Discussions were transcribed, and research memos generated to record observations. Inductive thematic coding was used to analyze the transcripts and identify key concepts from the discussions, with particular attention to those related to situational impairments, spatial and temporal hazards, and communication practices and challenges experienced by participants.

3.2.2 Outcomes

While alerts from the PASS system and air level were described, findings suggested that *temperature-related alerts were not specifically presented to firefighters when working at the scene of a fire*, meaning that they should instead rely on a combination of their assessment of the environment, and communication with others (e.g. notifications from other firefighters, incident commanders based outside the structure), to identify whether *temperatures have surpassed safe levels*. This could prove even more challenging in highly variable situations within a burning structure where temperature may rapidly rise, causing ‘flashovers’ which were known to lead to fatalities.

Other areas for alerts included presenting more detailed information about *gases, toxins, and carcinogens* present. Although detection mechanisms may be available, greater awareness would enable firefighters to take more timely and appropriate action. The need for *communicating the presence of hazards* was highlighted. This would offer valuable support to other firefighters (i.e. when trying to communicate the presence of holes in the floor which could cause injury to members of their team). It appeared that different teams had varying approaches to communicating the presence of these obstacles, using either verbal warnings that might be missed, gestures that not be seen in thick smoke, or through leaving markers which may also not be visually detected. It was noted that auditory cues, such as low air warnings, were often designed to also be heard by those nearby, not just the individual, so team members could remain aware of emerging problems.

Cues were also suggested for individuals *not responsive* to auditory and visual stimuli, who may be caught up by the cognitive and physical demands of the situation (e.g. evacuation signals). This could be based upon *core body temperature* exceeding a certain level. A final alert was thought to be of benefit to be presented a firefighter, prior to rescue crews going in to the burning building to evacuate the firefighter. Other suggestions were made about providing navigational cues in structures where visibility is highly limited. However, this also brought up discussion of overload of alerts. Participants wanted stressed the value of simplicity in alert design, and cautioned against producing *confusion caused by too many alerts* where mappings would be difficult to remember. Also *multiple alerts* presented via the same sensory domain (e.g. auditory alerts from both home fire detectors, radios, sirens, and body-worn equipment such as the SCBA airpack) might be too similar to quickly discern when distracted by situational, contextual, or environmental factors.

3.2.3 Development of Scenarios

Use of scenario-based prototyping is pervasive in software and usability engineering because it allows motivating narratives about interaction to be both highly detailed were needed and flexible for frequent iteration [20], and has been used in related research [3]. The points raised in the contextual interviews were transformed into sets of five scenarios relating to firefighters using location-independent wearable devices to receive alerts. These were then illustrated for successive participatory design workshops (Figures 1, 2, and 3). In order to determine the validity of the resulting scenarios, checks were made by the original interviewees (domain experts). The scenarios were developed with the intention of encouraging discussion among participants, enabling ideas to be suggested for alerting firefighters. These design ideas would be more targeted to the needs of users. Design generation is described in 3.3.

Figure 2: Example of scenario and illustration indicating

Example of a scenario (abridged): “A physical hazard has been detected by a firefighter in smoke-filled warehouse. They attempt to communicate this to a distracted teammate verbally and visually, but cannot make themselves understood. They are unsure if Incident Commander received the radio warning.”

Example of a scenario (abridged): “A pair of firefighters in a burning structure identify spreading fire, increasingly turbulent colored smoke, and rapidly rising temperatures. They try to communicate via radio, but are impeded by background noise from firefighting tools. The Incident Commander (positioned outside of the structure) acts upon the limited report.”

Other scenarios were also illustrated that related to challenging decision making experiences, such as wayfinding and navigating around hazards in different size burning structures, and dealing

with radio and face-to-face communication confusion. Scenarios also addressed physical and equipment challenges that were described, including the impacts of smoke, overexertion, managing on-site rehabilitation times, and cross-department gear compatibility issues, among others. As demonstrated by the vivid accounts collected in this step, gaining and maintaining situational awareness quickly to make decisions is paramount for all of these scenarios.

Figure 3: Example of scenario and illustration indicating firefighters attempting to report a fire where temperature is rapidly rising.

3.3 Participatory Design

3.3.1 Approach

A set of six design workshops were conducted, with groups comprising of between 4-8 firefighters, staff with incident command experience, and interface designers. The aim was to examine whether each group could work as a team, to design alerts to better meet the needs of firefighters facing inhospitable environments. Participants' firefighting and incident command experience varied considerably (3-35 years of service). Workshops were conducted at fire stations where firefighters were present. These lasted between 60-120 minutes. There was significant overlap in participants between the first contextual interview step and this participatory design step. Reusing the same six participants in both steps was precluded by scheduling availability of the two fire departments. Additional participants in this step had complementary training and experience.

Scenarios developed (described in Section 3.2) were presented in sequence to the teams, along with illustrations of the steps taken by firefighters in each rich story (e.g., Figures 1-3). Participants were asked to consider the conditions faced by the characters (termed "actors") in the scenarios and describe whether alerts would be useful to support SA and decision making, and if so, how these could be designed using visual, auditory and/or tactile feedback. Design suggestions could be made verbally or illustrated. These suggestions would be developed into cues by the researchers for presentation in successive design workshops, presented via a PC (e.g. visual and auditory cues) or tactile motors. Participants were asked to reflect upon each other's ideas. Props such as pen and paper, and auditory/tactile prototyping tools were also presented for teams to represent and evaluate ideas.

The same scenarios were presented to new groups of participants, and prototypes developed by earlier groups were shown to new groups to strengthen designs or to make new suggestions. New suggestions could be discussed in more detail, along with their shortcomings. For example, monitoring of personal exertion was positively reinforced because stress was viewed as a "killer" that should be addressed. By contrast, measuring environmental temperature was deemed by participants to be important but

problematic because of potentially confusing thermal layering effects in confined spaces.

Mock-ups would increase in fidelity in each successive group (i.e., moving from paper to LED strips/output using vibration motors controlled using Arduino). This included refinement of visual and tactile mappings, such as using familiar red and green color coding for hazard conditions and left-to-right capacity gauges that are intuitively "like a gas tank." "Simple is key," one participant stated, because in a chaotic fireground his, "wits might not be there." Another noted the high rate of occupationally related hearing damage in firefighters and the importance of limiting auditory distractions to existing critical radio and alert tones, stating, "I don't need more noises in my life." It was envisaged that after a number of sessions, consensus on design would be reached.

3.3.2 Outcomes

Participants from the workshops conducted were generally able to provide detailed feedback on the scenarios presented, and relate these to their own personal experiences or times when alerts had been missed. Interface designers could offer perspectives on the limitations of technologies and how to design for alerts. Firefighters could offer the benefits of their domain knowledge.

All participants from the first workshop agreed that cues would need to be quick to interpret, as time could not be wasted attempting to discern different forms of feedback. Mappings would need to be simple and intuitive, due to the cognitive demands faced while firefighting. For example, one firefighter noted that she could sometimes feel the tactile buzz from her FitBit underneath her heavy protective clothing (termed "turnout gear") when her daily step count goal was reached, but she doubted more complex encoding could compete with friction and exertion while on a call. If many cues were presented at one time, it could lead to confusion resolving each of these cues, leading to discussion about either improving salience or if presented via multiple devices, temporarily halting cues from one device in order to attend to alerts from another device.

Tactile feedback was found to be of interest in all workshops, as vibrational output is rarely used to support firefighters, thereby gaining the user's attention. However, a wearable device would need to be positioned close to the skin. Otherwise, if affixed to the outside of turnout garments (which are thick in nature) or underneath wide suspenders worn with protective pants, signals would be attenuated. The hand was not thought to be a practical site for presentation, as it may be encumbered with gloves and tools, or may be moving around which may make a sensation difficult to perceive. Typical turnout gear (including protective garments, helmet, boots, radios, respirators, air tanks, and tools) might weigh as much as 110 pounds/50 kilograms. Suggestions were made to present tactile cues within the facemask itself, to provide users with the best chance of perceiving and responding to the alerts, without needing to spend time donning additional equipment. Vibrations were mocked-up and presented using motors positioned on the face in the later workshops. Participants in Group #3 suggested that while this would gain attention, a "super simple" wearable (such as a wrist watch) might appeal for users to keep on at all times and thus always have them during emergencies.

In terms of visual feedback, suggestions were made to present cues via LED strips, as these required limited space so could be

presented within the facemask itself. To better differentiate cues from other indicators within the facemask, Group #5 and #6 members suggested color and spatial location could be used for mappings. For example, the left-most LED of a pair could indicate threat type, while the brightness of its neighbor would encode the intensity of the threat. Combinations were examined in the sessions using feedback from participants. Recommendations were also made to lower the brightness to reduce the occurrence of glare.

In terms of auditory and tactile mappings, the second team suggested associating the pitch and amplitude respectively, to the severity of the situation (i.e. unsafe temperatures, presence of a hazard). This design suggestion was then strengthened by third group, that different levels of threat should be presented via these channels, rather than a continual increase in intensity which may be ignored after a period of time. In the later workshops, participants experimented with auditory cues designed as pitch sweeps, which were found to be more discernible. A continuous tone signal was found to be too similar to ‘smoke detector’ or PASS alarms, which may be ignored or misinterpreted in a fireground.

Through a process of iteration, the groups suggested to represent three types of alerts: acute external heat threat (such as reaching the temperature range at which flashover may occur), core body temperature heat threat, and cardiac rate threat. A minimum number of levels were suggested for each signal to be presented to users (e.g., “ok”, “danger”) because firefighters said that they would not alter their behavior unless the alert was critical. However, a mid-range “caution” level was added as two of the alert types indicate internal body conditions that could be modified by some degree with biofeedback training: suggesting that this alert level could lead to an action. Firefighters did not want any alerts that would not lead to an action. The choice of three-level alerts was primarily appealing because it was consistent with the encoding of existing warnings on the face mask. Visual feedback was preferred for threat level as it can be displayed all the time peripherally without interfering with primary firefighting tasks or irritating the user (which constant tones or vibrations would). This capitalizes on a basic human factors experience: for visual displays a person can look away, but not for auditory or tactile displays. Auditory and tactile alerts would provide information about the specific issues associated with the threat.

3.3.3 Development of Prototypes

The alerts were provided to participants using an Arduino Ruggeduino board, controlled via USB connection to a laptop, powering three output devices. The output devices included a vibration actuator, bone conductance audio speaker, and LED strip. The laptop connection allowed a proctor to control playback of alerts through an interface authored in Max/MSP (a visual programming environment for interaction design). The interface passed alert commands via a serial port connection to the Arduino hardware.

The three output devices were placed on the participants at locations that would allow effective communication while wearing a typical SCBA mask. This whole-face type of mask is impractical for study use for several reasons. It is heavy and its webbing makes it difficult to put on and take off. The used SCBAs we procured also had partial respirators in place, which were both difficult to breathe through and difficult to clean in between trials. To work around these limitations, while still

imposing realistic task and head-mounted actuator conditions, we substituted a commercial safety facemask-equipped helmet for the SCBA, which allowed mounting the actuators in the same locations. For example, the bone conductance speaker was attached by athletic tape to the cheekbone of the participants. This location allowed good sound conductance by placement over bone mass with proximity to the ear, along with relative comfort for the participant. Similarly, the vibration motor was taped above the brow of the participant, but low enough on the forehead to allow the SCBA’s outer seal to make the required airtight fit against the skin of the forehead. The LED strip was fitted inside the mask along its lower left edge, in the same position in the user’s peripheral vision as it would be in the SCBA. This allowed the LED strip to be visible hypothetically even in smoke-filled, zero-visibility conditions, but out of the direct line of sight where it might cause glare or distraction (see Figure 4). The facemask was covered with an adhesive plastic layer to mask the user’s ability to view directly ahead, providing a similar experience to firefighters whose vision may be impaired by the situation/environment.

Once the hardware and interaction control integration of the system was completed along with determining the optimal placement of the output devices, the signals were iterated for efficacy. This included altering the haptic and auditory signal designs to make the alerts both as simple and distinct from one another as possible (to ease participant training and recognition tasks) as well as making the elevated-level alerts as salient as possible. This iteration process also included selecting audio alerts that were both distinct from one another and from other alerts that might be present at a fireground and complicate recognition (such as radio tones, fire department air horns, smoke detector alarms, and SCBA low-air sirens). To assist participants in effective recognition of the alerts, the duration, pitch, and amplitude of the tones was made consistent across emergency types. For example, critical-level audio and tactile alerts for external temperature share the same duration and interval pattern, which is different from that of the cardiac rate and internal temperature alerts. Interval was also utilized in the signal designs to communicate priority, with alerts being repeated more quickly to convey urgency as the alert level increases. The alert designs are shown in Table 1.

Figure 4: At left, positioning of tactile actuator on the user's brow and audio speaker on the cheek. At right, placement of the LED display in the user's lower left peripheral view.

3.4 Evaluation of Alerts under Situationally

3.4.1 Approach

The main objective of the study is to examine the perception and identification of alerts to represent critical cues for firefighters. More specifically, we aimed to determine: how reliably users could identify the alert type and level, how quickly they could do

this identification and the cognitive load, when placed under constraining conditions. Cues which performed well could then be tested under more realistic conditions.

3.4.2 Study Design

A within-subjects study was designed. Independent variables included signal design. Cues would be presented with three stages indicating escalating levels of severity (all-OK, caution, and critical), through three different channels (visual, auditory and tactile). These would be used to convey threats identified in the prior step, which are described in the paragraph below. The dependent variables included recognition rate, recognition time and perceived level of cognitive workload. A custom questionnaire was developed to assess levels of perceived cognitive workload (Likert scales 1–5).

A set of prototypes described in 3.3.3 were used to present alerts. Mappings to these alerts were created representing threats relating to core temperature, ambient temperature and cardiac distress (termed ‘type’), alongside the level of intensity (ok, warning, critical) also informed through our earlier studies (Table 1). The alert type and level combinations were presented as a single feedback signal that was played constantly. From the design meetings it was decided that: visual feedback should be mounted inside the face shield at the height of the hose entrance (presented via LED strips); the audio feedback would be placed on the outer edge of the face shield around the cheek; and the tactile feedback placed on the top edge of the face shield on the forehead.

The study was conducted within a controlled laboratory setting. All participants donned a mask with limited viewing capabilities (i.e., smoke simulation screen). To provide a sense of realism under simulated conditions, audio from the scene of a fire was downloaded and presented through speakers at a rate commensurate with firefighting environments. Research suggests that this would be 82–109 dBA [12].

3.4.3 Hypotheses

H1: When the user is situationally-impaired, performance accuracy of visual feedback representing threat level will be higher compared to tactile and auditory feedback.

H2: When the user is situationally-impaired, performance accuracy of auditory and tactile feedback representing type of threat will be higher compared to visual feedback.

H3: When a user is situationally-impaired, perceived cognitive workload levels will be higher when tactile cues are presented compared with visual and auditory cues.

3.4.4 Participants

Twelve participants (aged 18-39) were recruited from a university student population. None reported significant issues with visual, auditory or tactile processing.

3.4.5 Procedure

Participants were trained on the visual, audio and tactile alerts formulated through the design meetings. Participants were then asked to don the faceshield with the visual display mounted inside it. Presentation of the alerts was blocked by sensory mode (visual, audio and tactile). Two repetitions of a block of trials presenting all alerts for a particular sensory mode in random order was performed. Participants were able to replay each cue as many times as necessary before verbally recording their responses for the value of each parameter of the cue. A verbal questionnaire was then presented after each cue was played to rate its perceivability

and to record levels of perceived cognitive workload for each condition. Similar measures and procedure have been used to assess these factors for tactile cues in [36]. Post hoc, participants were asked to rank the effectiveness of cues, and describe the ways in which feedback could be made more perceivable.

3.4.6 Results

Our first hypothesis (H1) related to whether visual alerts representing threat level would be higher compared to tactile and auditory feedback, as participants in design sessions had thought visual feedback to be more effective, while other types of feedback would be beneficial for communicating alert type. Findings from a Wald Chi Squared test suggested the presence of an effect by modality ($\chi^2(2) = 12.592$, $p=0.02$). Pairwise analysis revealed that visual cues depicting level were recognized with higher rates of accuracy (99.41%, SD 2.06%), compared to auditory (92.86%, SD 10.10%, $p=0.028$) and tactile cues (85.71%, SD 21.1%, $p=0.014$), providing support for H1.

A Wald Chi Squared test was performed on type. Findings also showed the presence of an effect by modality ($\chi^2(2) = 69.683$, $p=0.00$). Pairwise analysis revealed that auditory cues depicting type (98.21%, SD 4.44%) were recognized with lower levels of accuracy compared to visual (100%, SD=0.00%, $p=0.00$). Similarly, tactile were recognized at lower levels (73.22%, SD 27.77%). H2 was rejected.

Our third hypothesis (H3) examined whether cognitive workload was most affected by tactile cues, as firefighters had highlighted this type of cue was least practiced. In order to determine the impact of modality on cognitive workload, a further Wald Chi Squared test was performed, revealing the presence of an effect ($\chi^2(2) = 12.847$, $p=0.02$). Further analysis from a pairwise comparison revealed that levels of workload were higher in the tactile condition (1.95, SD 0.71), compared to auditory alerts (1.38, SD 0.32, $p=0.02$) and visual alerts (1.35, SD 0.37, $p=0.00$), allowing us to accept H3.

An effect was identified for response time by modality ($\chi^2(2) = 22.397$, $p=0.02$). Findings suggested that responses to visual alerts were faster (4.56s, SD 1.2s) compared to auditory alerts (6.6 s, SD 1.9s) and tactile alerts (10.58s, SD 4.19s). Each cue was presented two times to participants in the study. The impact of repetition was examined on accuracy, however no effects could be detected ($p>0.05$). Interestingly, when examining the impact of repetition on response time, findings highlighted the presence of a significant effect ($\chi^2(2) = 22.397$, $p=0.02$), confirming that less time was taken on the second attempt.

3.4.7 Discussion

Errors were most commonly made when attempting to discern cautionary vs critical tactile and auditory alerts. Modification of the interval-based approach for coding alert level might improve accuracy in that task for those modalities, as the difference between mappings was found to be negligible. Participants offered suggestions for this. These included simply making the cues shorter to allow smaller intervals, which would reduce the overall amount of required attention. Additionally, participants suggested adding amplitude as a parameter for conveying urgency, by making critical-level alerts louder/stronger/brighter than caution-level cues.

In terms of subjective feedback, some participants mentioned, assuming they were relying on the alerts for their safety, that the tactile and audio cues were effective for redirecting their attention because of their salience and immediate perceptual impact, but

also challenging to learn and remember. There was also concern that exertion and background noise might interfere with reliable identification of tactile and audio patterns. Subjective comments relating to tactile cues aiding SA were generally positive. Tactile feedback clearly offers a number of unique features that apply to rigorous real world alerting problems (e.g. [34]). It affords a “private channel” for feedback that doesn’t distract others nearby, and is an alternative for passing cues when users’ vision and hearing are blocked [18]. However, effective information encoding of tactile cues is generally more limited than visual and auditory channels [32], and requires careful consideration of alert design and actuator placement on the body, especially in real world scenarios wherein exertion or external vibration may cause interference [33]. In firefighting related studies, encoding for wayfinding [4] and temperature sensing tasks [35] has been promising but limited. Given this, the poorer performance of tactile feedback relative to visual and auditory channels is expected.

Reasons for the poorer performance using tactile feedback could in part be attributed to the limited level of familiarity, compared to users’ abilities to discern auditory and visual cues which are well-practiced tasks. Pancake motors were chosen for presentation as they are lightweight and easily programmable. However, these are known to have their own limitations. For example, frequency and amplitude cannot be controlled independently. Researchers note that when tactile feedback is presented to the user, simply turning or movement of the location where the motor is affixed (i.e., the face) disrupts the sensation from the actuator [28]. Van Erp and McGrath [33] suggest that eccentrically rotating motors (e.g. pancake motors) may take time to spin up to full intensity. The sensations evoked can be perceived as having a ‘soft start’. Further work would need to be conducted with a range of technologies, to better understand the potential of tactile feedback.

Tactile alerts were designed with the intention of being easy to discern. However, participants performed most poorly interpreting these cues. Levels of cognitive load were high when tactile feedback was presented. Similar issues were uncovered in other firefighting-related studies where vibrational cues were presented [29, 35]. Although cognitive load was measured, it is believed that each sensory system has its own sensory memory. This may give tactile cues more of an advantage when visual and audio tasks are being performed at the same time as the alerts. On the other hand, the visual and audio alerts are designed to be disruptive (e.g., the visual alerts use flashing LEDs which draw the eyes in for the critical level), so this is unclear. Currently we are performing another design iteration to improve the poorer performing alerts in each sensory modality. We will then rerun the study described in 3.4, prior to proceeding to the step described in 3.5.

3.5 Testing with Realistic Tasks in Fire

3.5.1 Approach and Study Design

The aims of this step are to investigate how a smaller set of alerts can be perceived in more realistic simulated settings. To assess the efficacy and usability of different types of feedback, firefighters are currently being recruited for a within-subjects study which will take place at a Fire Training Academy, where settings can be better simulated. The experimental testing will be blocked by sensory modality, counterbalanced across participants.

The testing environment will closely simulate real world conditions except for any dangerous hazards. This means, in

addition to the real world tasks and increase in activity level above base levels, participants will be required to wear turnout gear throughout, and poor visibility and hearing conditions will be created.

For each alert set, training will first occur to teach the mapping from the alerts to their meaning (“run”, “hide”, “escape”, which were chosen to be memorable rather than precisely map onto needed firefighter alerts). Then 3 tasks will be performed, again being counterbalanced. The tasks will be: (1) climbing stairs, (2) moving a hose line and (3) searching a room; these are similar to those which firefighters may face in real world conditions, and have been validated by other researchers as methods for testing equipment use with firefighters [5]. Each task will be required to be performed for 4 minutes.

The three alerts will be distributed randomly throughout each 4 minute test period. In order to respond to an alert, participants are expected to rotate back from their current position to the door of the room and voice the alert which was presented. This will be measured objectively by mounting an orientation sensor on the fire helmet of the firefighter and recording its output at 100 Hz. Time taken will be determined as the time from presenting the cue until the participant is facing the door. Accuracy will be determined by vocalization of the correct alert. Immediately after the response, the participant will be prompted to give a rating of how busy he/she was at the moment of the alert on a Likert scale (1 to 5). This assesses the cognitive load using the Instant Self Assessment of Workload [27].

4. REVIEW OF APPROACH ADOPTED

A number of observations can be made about the methods utilized in this study. Firstly, the contextual interview process, while lengthy, was critical to **understanding the rigorous physical and cognitive demands** that firefighting would place on equipment and the design of alerts. Moreover, this challenging work environment makes the users themselves understandably resistant to trusting a new technology for communication and safety decision making until it demonstrates suitability to the conditions. This insight and iterative user feedback were vital in establishing the need for relative simplicity and salience in the prototype alert designs.

At the same time, it was difficult to gain consensus among participatory design sessions on some questions. It also became clear that different units often have different gear and technology needs. Participants **candidly discussed a number of constraints on any potential additions to their standard equipment**. Primarily they cited the arduous work conditions that can damage equipment through constant exposure to water, dirt, and wear and tear. “We break stuff,” one firefighter concisely explained. Also, gear is donned extremely quickly when responding to alarms, so any additions that would slow that routine were viewed skeptically. This was especially true for wearable items that would need to be put on underneath turnout gear or require recharging. Metal and plastic items like watches (or heavy-duty pancake tactile actuators) are deemed a liability because they can heat up and burn the skin. However, in addition to identifying these potential functional stumbling blocks, participants also **called out the realistic value of other design possibilities**. For example, firefighters appreciated the basic idea of tactile alerting, using a separate sensory channel for localized alerts when vision and hearing are busy, despite the lower performance of those prototypes in our testing. These concerns echo research findings showing that placement of tactile actuators on the body changes

signal perception and identification performance greatly [11], particularly when the user is exerting or dealing with distraction [14] or exertion that causes perceptual interference [26].

A second observation about the process involves the firefighters' view of being included in the design process. They generally expressed interest and supported designing effective cues for the improved safety and wellbeing of their community. **Firefighters were willing to participate on multiple occasions due a greater sense of buy-in from using a participatory design approach.** Cues could be discussed in terms of perceivability, meaningfulness, and whether these would indeed be respected when engaged in service, and could be modified accordingly within each design session.

Thirdly, **testing of the cues using simulated settings offered important insight into ways the alerts would impacted by real world distracters** (e.g. background ambient noise and similar alert sounds, and complete visual occlusion by smoke). Studies have shown that evaluation of cues under "simulated realistic settings" (e.g. similar to those in 3.4 where ambient sounds and visual masking was applied) produces design better suited to the needs of users facing SIIDs [15].

Fourthly, for **ecological validity**, it would have been helpful to test within an active firefighting environment. However, the hazardous and dynamically-changing nature of the scene of a fire, combined with the practicalities of running a study presenting multiple cue prototypes, would make the process very challenging at best. Environmental chambers at fire training academies offer the best of both worlds; the ability to control variables, yet offer enough of a sense of realism to better determine the efficacy of interfaces. As described in 3.5, we aim to conduct tasks performed by firefighters in this environment to identify whether cues resist SIIDs and match the needs of their users.

5. CONCLUSION AND FUTURE WORK

Our study highlights the benefits of using a structured multi-step approach to the design of alerts for individuals with situational impairments. Peripherally-displayed visual alerts were most effective, relative to tactile and auditory channels, in conveying perceivable and meaningful alerts grounded in real world needs of firefighters. These alerts focus on critical situationally-induced impairments and disabilities experienced in this domain. Further inquiry that adjusts the alert signals' parameters to evoke better identification performance and user acceptance and testing under more rigorous conditions similar to real world challenges will be necessary to more exactly specify appropriate settings. The next logical step in the research is to refine cues, and evaluate in the environmental chamber as specified in the approach. Resulting cues could then be tested within field-based settings to determine their impact for establishing SA and making decisions.

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Rate	Visual			Audio			Vibration		
	OK status	Caution alert status	Critical alert status	OK status	Caution alert status	Critical alert status	OK status	Caution alert status	Critical alert status
Cardiac rate	Six LED strip, with pairs of blue, magenta, and cyan (corresponding to emergency types; blue=cardiac rate, magenta=external temp., and cyan=internal temp). The 1st of each pair is steady lit to display OK status.	The 2nd LED of a pair would flash on for 1 sec., with a 3 sec interval. For example, the 2nd blue LED would flash on for 1 sec. with a 3 sec interval for cardiac alerts.	Rate of the 2nd LED flashing would increase. For example, for critical cardiac alerts the 2nd blue LED would flash on for 1 sec, with a 1 sec interval.	[If required] One 500ms pureTone beep, then 30 second pause , while system is running OK.	chirpUp sequence (about 1.5 sec duration), with 3 sec. interval between repeats , while alert condition persists.	Continuously repeating chirpUp sequence, with 1 sec interval between repeats , while critical condition persists.	[If required] One 500ms pureTone pulse, then 30 second pause , while system is running OK.	Approx. 1.5 sec. duration chirpUp sequence, with 3 sec. interval between repeats , while alert condition persists.	Continuously repeating 1.5 sec. chirpUp sequence, with 1 sec interval between repeats , while critical condition persists.
External Temp.	One magenta LED would be steady lit to show nominal operaton.	2nd magenta LED would flash on for 1 sec. with a 1 sec interval.	2nd magenta LED would flash on for 1 sec, with a fast 250 ms interval.	[If required] One 500ms (pureTone) beep, then 30 second pause , while system is running OK.	2 sec duration tripleTone sequence, with 1 sec. interval between repeats , while alert condition persists.	Continuously repeating 2 sec. duration tripleTone sequence, with 250ms interval between repeats , while critical condition persists.	[If required] One 500ms pureTone pulse, then 30 second pause , while system is running OK.	2 sec. duration triple pureTone sequence, with 1 sec. interval between repeats , while alert condition persists.	Continuously repeating 2 sec. triple pureTone sequence, with 250ms interval between repeats , while critical condition persists.
Core Temp.	One cyan LED would be steady lit to show nominal operaton.	2nd cyan LED would flash on for 1 sec. with a slow 3 sec interval.	2nd cyan LED would flash on for 1 sec, with a fast 500 ms interval.	[If required] One 500ms pureTone pulse, then 30 second pause , while system is running OK.	2 sec duration 'rough' sequence, with 4 sec. interval between repeats , while alert condition persists.	Continuously repeating 2 sec. 'rough' sequence, with 2 sec interval between repeats , while critical condition persists.	[If required] One 500ms pureTone pulse, then 30 second pause , while system is running OK.	2 second duration staircaseMew sequence, with 4 sec. interval between repeats , while alert condition persists.	Continuously repeating staircaseMew 2 sec. sequence, with 2 sec interval between repeats , while critical condition persists.

Table 1: Descriptions of three-level (OK, caution, and critical) alert prototypes for visual, auditory, and tactile channels, for three types of scenarios (elevated cardiac rate, external temperature, and core body temperature).

1. What types of alerts and signals do you use currently to remain aware of your situation?
2. Where are these alert devices worn?
3. Can you describe instances you recall where you had difficulty communicating with others?
4. Can you describe instances you recall where you had difficulty knowing where you were?
5. Can you describe instances you recall where you had difficulty keeping track of time factors?
6. What things do you have to keep track of while you're in a fire scene?
7. What makes it hard to keep track of those things, and what helps?

Table 2: Example of questions asked of firefighting personnel participants during semi-structured contextual interviews.