A Field Study of Multimodal Alerts for an Autonomous Threat Detection System

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Abstract. Every year, inattentive or impaired drivers strike law enforcement officials, emergency personnel, and other workers by the roadside. Preventative efforts include making at-risk parties more conspicuous to oncoming motorists in order to prompt safer driving behaviors. In contrast, this work evaluates active alerting mechanisms designed to induce defensive action from at-risk roadside personnel once a hazardous situation has been autonomously detected. This paper reports on field investigations with state police to capture their cognitive requirements for this dynamic environment, as well as the design of four alert prototypes for a high noise, low-light environment such as a highway shoulder. We discuss implications for such future autonomous systems and argue that such active defensive alert mechanisms could improve roadside safety and save lives.

Keywords: Autonomous alerting, safety · Law enforcement · Wearable computing · Ubiquitous computing · Haptics · Multimodal alerts

1 Introduction

In the United States between 2000 and 2009, 120 law enforcement officers were struck and killed by vehicles while performing duties such as directing traffic, assisting motorists, or stopping on a highway shoulder [24]. For example, on October 19th, 2012, a Nassau County highway patrol officer exited his vehicle on an expressway to investigate a crash and aid an injured person. Soon after, he was struck and killed by another car [4]. On December 29th, 2012, an interstate officer was hit and knocked over a guardrail after stopping another vehicle on the highway [23]. In June of 2013, despite emergency lighting, a Massachusetts state trooper was rear-ended by a drunk driver while making a roadside stop [8]. Had he been outside the car, the collision could have been fatal. Similar traffic threats affect other first responders and roadside personnel as well. In 2008, 29 of 114 firefighters killed on duty in the U.S. were killed in vehicle accidents. Between 1992 and 1997, at least 67 EMS providers perished in ground transportation-related events [25].

While numerous precautionary steps can be taken to protect roadside personnel, drivers are fallible [12]. Unlike most other passive mitigations developed to warn

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drivers of the presence of roadside personnel, this paper explores an active defensive alerting system for at-risk individuals, which incorporates technology to communicate danger.

Automatic identification of anomalous driving behavior is becoming feasible as sensors and computer vision systems improve. An on-cruiser, backward-facing computer vision system has been proposed to monitor oncoming traffic for police officers stopped roadside [13]. The system works by means of two cameras processing video at high and low resolution to track vehicle trajectories as they approach the cruiser. If the system detects a dangerous vehicle trajectory, an imminent danger signal could be delivered to the officers (Fig. 1). This monitoring system is augmented by computer-controlled laser road flares to divert traffic [27]. Autonomous hazard recognition systems such as this could act as a line of defense when other passive signals fail. However, the design of the warning signal requires careful consideration of the unique human factors for this user group.

Fig. 1. Chain of communication from autonomous detection of dangerous vehicle to user notification

This paper describes the design and testing of alerts that can communicate the danger recognized by a machine vision system to a person at risk. It was designed to be easy to use, unambiguous, and efficient in mobilizing the user to take preventive action. It was also important that the design was technically and fiscally feasible, and that potential users were willing and inclined to use this mechanism. This work has the potential to save hundreds of lives and provide a more effective alternative to existing alerting mechanisms.

The contributions of this paper are as follows. First, we report on the results of a field investigation to characterize police officers' operational environment, focused on highway safety. We then introduce four personal defensive alerting devices for such an environment as well as an evaluation experiment to assess their relative effectiveness. Finally, we provide insights on the practical implementation of defensive alert systems from a focus group, which included state police officers.

2 Background

2.1 Hazardous Highway Conditions

The factors that contribute to hazardous traffic conditions are manifold. First, motorists can be distracted while driving or be unfit to drive. In 2010, there were a total of 195,879 Driving Under the Influence (DUI) arrests in California alone [6]. Poor highway engineering can endanger police officers and other personnel on the road as well. The Arizona Crown Victoria Police Interceptor Blue Ribbon Panel and the New York State Police recommend that officers position their highway stops parallel to the highway and a sufficient distance from both violator vehicles and the edge of the highway [1]. Unfortunately, these types of stop locations are not always available. Highway engineers are often forced to reduce shoulder width or remove emergency breakdown lanes to help mediate high traffic volume [1]. In addition, highway traffic can be loud, visually demanding, and constantly changing. Weather conditions and terrain can reduce visibility of the surrounding area, making it harder to find escape routes, and temperature can cause discomfort and impaired tactile discrimination, especially in the cold [18]. These conditions impair an officer's ability to respond to threats, with little margin to escape an imminent collision.

2.2 Highway Safety Policy and Practice

A number of national agencies, including the American Association of State Highway and Transportation Officials and the National Safety Commission as well as international groups such as the International Association of Chiefs of Police, are working to minimize such hazards. In 2007, forty-three states had passed "Move Over" laws, which require oncoming traffic to clear the lane closest to a stopped officer [15]. However, the laws were not reliably enforced and in a survey taken that year, 71 percent of Americans reported no knowledge of these laws [15]. The Michigan Give 'em a Brake Safety Coalition supports the establishment of modified speed limits in work zones, and they have also campaigned through bumper stickers and over the radio [14].

2.3 Highway Safety Devices and Technology

In addition to policies, many types of visual, auditory, and haptic devices and technologies are used to raise driver awareness of unusual road conditions.

Visual signals. Traffic cones, flares, signs, message boards, and reflective markings are all used to control and divert traffic. Police uniforms often include retroreflective garments such as jackets and raincoats to help improve their conspicuity, and the Federal Highway Administration requires that such garments comply with American National Standards for High Visibility Safety Apparel and Headwear to ensure their visibility [11]. Additionally, studies have shown that retroreflective striping on police cruisers is particularly effective, including fluorescent colors during the day and contrasting colors to make objects stand out from the background [25]. Using LEDs, colors and light patterns can be varied based on the amount of ambient light [1].

Auditory signals. Sirens and horns, today a quintessential feature of emergency vehicles, exemplify the auditory modality of warning signals on the road. While valuable when cutting through traffic and effective at grabbing attention, these loud, conspicuous warnings can cause physical discomfort at close range, be obstructive to covert police work and unnecessarily disturb communities. For this reason, sirens are typically used only for brief periods, and rarely on stationary vehicles.

Haptic signals. There are also haptic methods currently in place for protecting against vehicle accidents. For example, Sonic Nap Alert Patterns (SNAPs) are indentations in the road surface that produce a loud noise and vibrations in a vehicle driving over it [28]. The use of SNAPs on the Pennsylvania Turnpike over five different projects produced a seventy-percent reduction in "drift off road" accidents. These types of haptic patterns, now more loosely referred to as "rumble strips" have also adapted to be raised features in plastic, ceramic, or asphalt materials, and have been used in various locations such as parking lots and between highway lanes. Rumble strips have also proved to be "more cost effective than many other safety features including guardrails, culvert-end treatments, and slope flattening [9]." These haptic mechanisms, however, are geared toward motorists and are permanent features installed on the ground. There has been little work looking at more dynamic mechanisms.

3 Field Investigation and Design Considerations

To address the safety issues of individuals conducting roadside stops, we conducted a field investigation in which we spent two evenings on "ride alongs" with state troopers during actual highway patrol [16]. This allowed us to identify important considerations for designing a defensive alerting system. In addition, our design was informed by previous research on alerts. Further details on the ride alongs and related research are described below.

3.1 Ride Alongs

Police officers are highly trained individuals, skilled in fast decision-making, safety procedures, and emergency response. They are trained to be familiar with their equipment and to be prepared for a wide range of situational circumstances. To gain a better understanding of their operational environment, we conducted two ride alongs with a sergeant from the State Police. We were interested in understanding the cognitive requirements of the job by observing officer behavior and in characterizing all other haptic, visual, or auditory stimuli the officers experienced, with the purpose of gauging the sensory load of the environment. Decibel readings were taken around the vehicle on the shoulder of the road and notes of equipment and uniforms were collected.

During the ride alongs, we sat in the passenger seats of a police cruiser and observed the officer at work. The ride alongs were conducted in late fall and after sunset, so the environment was cold and dark. We were given reflective jackets to wear as an additional safety measure. Over the course of each ride along, the officer stopped in four different roadside locations, both on the highway and in more suburban settings. At these stops, while the officer attended to the infraction and stopped party, we would exit the vehicle to collect data using digital cameras, video cameras, a decibel meter, and pen and paper. We also interviewed the officer before, during and after the ride along for clarification and further details.

Timeline of a Roadside Stop. From observations during the ride-alongs and an informal cognitive task analysis with the officer, we were able to gain an understanding

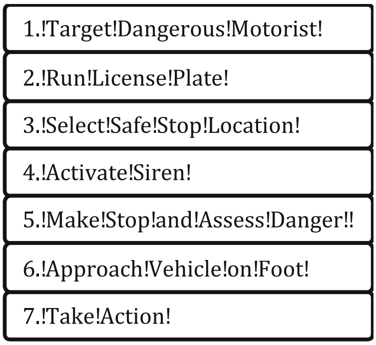

Fig. 2. Sequence of events in a roadside stop. Officers are trained to take these steps while driving, attending to oncoming traffic, and planning for emergency situations.

of the timeline of a roadside stop. Figure 2 summarizes the sequence of events observed each time the officer conducted a stop.

A roadside stop occurs when an officer targets a motorist on the road. As an officer begins to tail a subject vehicle, the targeted motorist will usually know that he or she is being followed by a police officer. However, the identity of the motorist is unknown to the officer. Inside the cruiser, each police officer has a computer interface on which he or she can run the license plate to match plate numbers with the registered owner of the vehicle, potentially the dangerous driver at hand. It is possible, however, that the current driver is not the owner. The car may be borrowed, leased, or even recently stolen and not yet reported. Once the license plate has been analyzed on the computer, the police officer will select a safe location to make the stop. At this point, the police siren may be activated, and the officer will make the stop and assess danger. Sometimes the target vehicle's driver will comply and sometimes the driver will not. For example, the driver may panic and stop his vehicle in the middle of the road or on the opposite side of the highway where no breakdown lanes exist. The motorist may become hostile or try to escape the situation. This latter possibility becomes more of a concern the longer the vehicle takes to come to a stop. As he is driving, the driver may be readying a concealed weapon or searching for a personally advantageous location to stop where the officer's attention may be diverted.

The officer must then approach the vehicle on foot, from up to 100 yards away. At this time, his or her attention is always divided between the stopped individual and oncoming traffic, both of which can pose serious threats to safety. Officers are trained to always look for escape routes in their environment, make their presence known to oncoming traffic, but also to conceal themselves from the targeted driver. If and when the officer must move to a safe location, time is critical. For example, a car traveling at 70 mph will travel 100 yards in 2.9 s. Based on an assessment of the situation, the officer chooses between wearing reflective gear or standard jackets, plans movement around the stopped vehicles and will then write a citation or take other action. Most of this behavior is taught through training and practiced until it is routine.

Table 1. Summary of ride along sound levels

Source	Max reading (dB)
Inside vehicle	69.0
Highway shoulder	83.3
Suburban neighborhood	71.0
Horn	85.5
Air horn	90.5
Sirens (Wail, Yelp, Piercer)	92.9, 90.5, 90.7

Noise in Roadside Environment. Adecibel meter was used to measure sound levels in various locations over the course of the ride along. Readings were also taken of other warning signals currently in use. The results are summarized in Table 1. Outside the vehicle in traffic, maximum decibel readings varied between 71 and 84 dB, mostly from vehicles rushing past. Inside the vehicle, the readings reached up to 69 dB. The cruiser's built-in sirens, gauged from about 30 feet away from the vehicle, reached decibel readings in the 90 s. All sirens are automatically turned off when the car is in park. The officer also carries an on-person radio and multiple other radios inside his vehicle.

Officer Uniform and Equipment. Uniforms consist of combat boots, a long-sleeved shirt and slacks (or shorts in the summer). All on-person items are carried on an external waist belt or cross-chest belt. Officers might wear several other layers of clothing (e.g. a vest, jacket, or undershirt) and their standard-issue equipment can include a variety of other items such as radios, cell phones, and firearms, for various situations.

3.2 Additional Design Considerations

Alert Perception. Humans are generally capable of selectively attending to individual channels of stimuli even in the presence of other competing stimuli [19]. However, an emergency alert that can tap into unengaged cognitive resources will have the best chance of capturing attention. For example, in a loud setting, one might choose to use a non-auditory alert for better chance of detection. But even an easily detected alert can be inaccurately identified, especially in a high-pressure environment or when used with other similar alerts. In light of these challenges, we can manipulate the content of the signal to optimize the user's perception and response to the alert. For example, certain sounds may have preexisting connotations for humans that would accelerate their reaction time. A siren would more quickly and intuitively be identified as an oncoming emergency vehicle than a foghorn or a doorbell. Furthermore, physical characteristics such as frequency and volume can also enhance detection and reaction time. These considerations are further discussed below.

Alert Modalities. Roadside alerting requires a modality of warning that would be effective in all types of lighting and weather conditions and which would capture attention as quickly as possible. We explored the characteristics of three different modalities of warning: visual, auditory, and haptic.

Visual alerts. On the road at night, traffic headlights can cause much light pollution and glare and at different times of the year, fog, frost, dew and dirt can also significantly degrade visibility [26]. Moreover, crash warning system guidelines published by the National Highway Traffic Safety Administration specifically recommend visual warnings for "continuous lower-priority information" and discourage their use for "conveying time-critical information" [20]. Considering the operation environment of the highway, we concluded that a visual alert would not be appropriate.

Auditory alerts. Auditory signals are effective as warnings because they act on a sense that is not easily ignored, and could "be detected automatically and routed through on a priority line to the brain [17]." Three different types of auditory sounds can be used as warning signals: abstract tones, auditory icons, and verbal messages [2, 7, 26]. An abstract tone is typically composed of a single or multiple tones, which can be pure or harmonically complex. These tones can be continuous, they can be pulsing, or they can otherwise vary temporally, but the distinct pattern of sound, whatever it may be, must be identifiable to humans and will require learning. It has been found that warnings that consist of single continuous tones or similar temporal patterns are easily confused [7].

Auditory icons are sounds that typically have pre-existing associations with the warning audience [10, 26]. They are typically composed of real-world sounds that have a relationship with the circumstances they represent. For example, using the sound of skidding tires to notify the user of a vehicle crash [26]. Because of this relationship, auditory icons are easier to learn and identify than abstract tones.

Finally, verbal auditory messages, like verbal visual messages, use language to signal warnings. They have similar benefits, costs, and challenges. Incoherent or long messages will delay reaction times and in a high noise environment. Verbal messages can also cause a language barrier when the user population speaks different languages. However, if the appropriate language is used, verbal messages require the least learning, which could be suitable for an infrequent warning or one that appears in stressful situations that might cause listeners to forget the meaning of a more abstract alert [26].

Aside from the content of the sound, the physical characteristics of the signal can also be used to manipulate perception. Research has shown that "fundamental frequency, harmonic series, amplitude envelope shape, delayed harmonics, and temporal and melodic parameters such as speed, rhythm, pitch range, and melodic structure all have clear and consistent effects on perceived urgency [3]." These characteristics also play an important part in the conspicuity and discriminability of the signal, two features that the National Highway Traffic Safety Administration has indicated are most important in the design of imminent collision warnings [20].

The human auditory system is much better at perceiving changes in sounds rather than absolute frequency or intensity [17] and furthermore, warnings sounds will generally be more resilient against environmental noise if they are composed of multiple sinusoidal tones [26]. Regarding alert amplitude, guidelines suggest that high urgency warnings should be 10–30 decibels higher than the masked threshold, a measurement of listener hearing threshold based on frequency and decibel level [20, 26].

Haptic alerts. Haptic warnings have not been studied or used as widely as auditory alerts in roadside environments. However, touch is an underutilized sensory channel and research has shown promising prospects for haptic alerts in comparison to visual and auditory warnings. In a study on collision avoidance, it was observed that reaction times to rear-end collision warnings was significantly shorter using tactile warnings than using visual warnings in a simulated driving environment and potentially also shorter than auditory warnings in real driving situations [21]. Rumble strips have now been installed all over the United States have drastically reduced drift-off-road accidents [9, 26, 28]. Although the roadside environment for officers and other workers is different than that for drivers in their cars, these studies suggest that tactile cues can be useful in circumstances that are perceptually taxing on the visual and auditory system.

Auditory or visual cues are often better indicators of orientation and location. They are both distal senses, capable of containing information about the distance of an event [22]. However, if auditory and visual cues are impractical, haptic alerts can also be used to orient attention using directional spatial tactile cues. In a study, drivers were warned of front-end collisions through a haptic vibration on the stomach and rear-end collisions through a vibration on the back. In cases where directionally appropriate cues where given, responses were 66 ms faster [22].

Haptic warnings are recommended in conjunction with warnings of other modalities to present redundant information [5, 20]. The combined message can create a sense of enhanced importance and enlarge the audience for which the warning will be effective, for example, persons with disabilities in perceiving other modalities [26].

4 Alerting Mechanism Requirements

Based on knowledge gathered from the ride along and the literature review, the requirements for the warning system were finalized, and are listed below.

(1) For the best chance of detection, the alert must excite a sense that is not otherwise engaged or over stimulated in the operational environment.
(2) The alert must produce the desired effect in less than 3 s. It is crucial that the speed of hazard detection and communication to the officer is maximized.
(3) The alert signal must be succinct but descriptive enough to trigger both fast and accurate recognition.
(4) The alert must be more urgent than, and distinct from, other signals the officer may already have in use.
(5) The alert must be effective up to 100 yards away from the police cruiser, since this is a typical distance officers travel from their car.

In addition to these technical requirements, we are also interested in usability issues. That is, the proposed alarm should be relatively easy for the target user community to transition into use. To this end:

(6) The proposed implementation must be practically feasible in terms of cost and additional equipment.
(7) The alert must be safe, comfortable, and easy to use.
(8) The target users must be willing to use the device.

4.1 Prototype Design

Based on our research and field investigation in the traffic operation scenario outlined above, we explored the use of two auditory and two haptic alerts [16]. The two auditory alarms, which varied in sound pattern and other tonal characteristics, were designed to emanate from the cruiser loudspeaker system. The haptic alerts varied in location of wear. The designs of the prototypes are outlined below.

Auditory Prototype Design. The State Police cruisers currently use three of ten preprogrammed siren tones on the SA314 series of Whelen box amplifier sirens, commonly referred to as *Wail*, *Yelp*, and *Piercer*. From a practical standpoint, it would be a relatively effortless and low-cost choice to activate one of the currently unused siren tones. For this reason, we chose two of the remaining seven signal tones as prototypes for the officer alerting mechanism. The first, *Pulsed Airhorn* consists of a repeating two pulse tone, which repeats about every second. The second, *Woop*, is a repeating single tone that increases in pitch over a period of about 250 ms. These two particular signals were selected for their distinguishability from the sirens currently in use and roughly evaluated on urgency by pitch and period. Other available signals had longer periods (lowering the perceived urgency), or were similar to *Piercer*, *Yelp*, and *Wail*, sirens already in use.

These proposed sirens also have several desirable characteristics consistent with our prototype requirements and communicated the appropriate semantics for a high priority alert. First, both sirens have varying tonal characteristics, which are important for alert discrimination and recognition. The human auditory system is much better at perceiving changes in sounds than pure tones [17]. In terms of sound intensity, it is suggested that the signal have a 10 to 30 dB increase over the ambient environmental noise with a maximum of 90 dB [20]. Our experience during the ride along showed that highway sound can reach levels around 80 dB, so our proposed signal should be 90 dB. The Whelen siren is capable of reaching this volume at close range.

Haptic Prototype Design. The haptic warning device designed for this system is a small wearable device that delivers a vibration signal when triggered. This trigger can be activated wirelessly from a computer and works in all weather conditions. The haptic device was engineered in the lab. The system diagram is shown in Fig. 3.

To achieve wireless communication, we use XBee wireless radio frequency modules with both a 300-foot and one-mile range. When a hazard is detected by the machine vision system, a serial command is sent to the transmitting XBee from the computer, which will then transmit a trigger signal to the receiving XBee. The receiving XBee is connected to an Arduino Fio, a smaller version of the Arduino microcontroller specifically designed for wireless applications. The Fio powers an

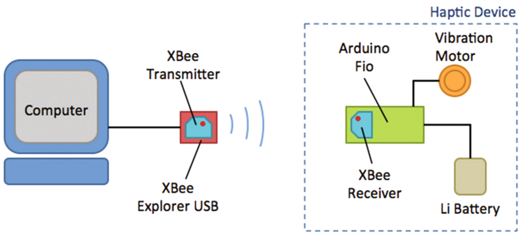

Fig. 3. Haptic system diagram.

eccentric rotating mass motor rotating at 12000 RPM to cause device vibration. These types of motors are similar in mechanics and intensity to those used in cellphones, game controllers and other vibrating devices. To power the motor, the system requires a small circuit—a transistor, resistor, and diode combination (not pictured in Fig. 3). The device is encapsulated in a custom-made case using a 3D printer (Fig. 4). The case features a small belt loop through which an elastic band can be threaded.

In experimentation, we were interested in testing this device on the wrist and on the waist. Ideally, a haptic device would be integrated into something that the officer already wears such as a watch, or belt. The wrist and waist were thus chosen to mimic this kind of integration and also for their sensitivity relative to other locations on the body. In both these locations, the motor was placed in contact with the skin.

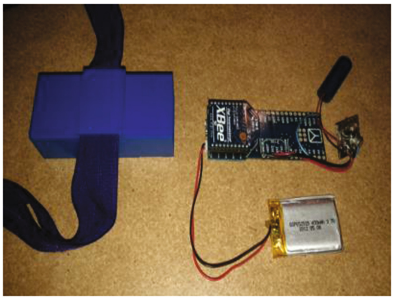

Fig. 4. Haptic device hardware, consisting of Arduino Fio, battery, and vibration motor and fabricated case.

5 User Evaluation

To assess the usability and effectiveness of the proposed prototypes, two studies were conducted: a human subjects experiment, and a focus group assessment with members of the user community—the State Police.

5.1 Human Subjects Experiment

In this experiment, we were interested in identifying which of the four prototypes, *Wrist Haptic*, *Waist Haptic*, *Pulsed Airhorn*, or *Woop*, would induce the fastest response, and which was most preferred by users. We set up a lab environment to replicate a high noise, low-light environment, and collected data on response times and subjective feedback in order to compare the effectiveness of each alert type with one another [16].

Design. The experiment was a four condition within-subjects experiment. That is, each participant interacted with each of the four alert types at the time of experimentation.

Independent and Dependent Variables. The experiment consisted of four randomized and counterbalanced trials. These trials were identical with the exception of the alert type used: *Wrist Haptic*, *Waist Haptic*, *Pulsed Airhorn* siren, or *Woop* siren. Thus, the *alert type* was the independent variable. During each session, we recorded the alert type, time at which the alert was triggered, and the time between the alert trigger and response to the alert (a key press). We also surveyed each participant on various aspects of the alarm to collect a subjective response. Thus, the dependent variables were *response time* and *subjective feedback*.

Participants. Forty volunteers (17 male) were recruited and screened to exclude those with known hearing impairments.

Apparatus. The study was conducted in a sound-proof room. To simulate the operating environment, recordings of ambient noise taken during the ride along were played over stereo speakers located on the right and left sides of the room. These speakers were connected through an amplifier box to a dedicated laptop, which controlled the audio playback. The decibel level of this playback varied between 70–77 dB. In our research and design phases, we concluded that highway noises may reach up to 80 dB and the optimal alarm decibel level might be 90 dB (a 10 dB increase over the max environment level). In our study, however, these levels were slightly reduced for hearing safety reasons. A third speaker was placed in front of the participant and connected to a second laptop to be used for the auditory signals. This second laptop was also connected to a wireless transmitter that could trigger the haptic alert. It ran software that controlled the type of alert, time at which it was triggered, and data logging over the course of the procedure. The room was illuminated by only a small lamp on the ceiling to replicate street lighting at night. An iPad 2 was provided to perform a secondary task.

Task. In runs in which the participant was outfitted with a haptic warning device, he or she was instructed to press a key on the laptop placed in front of him or her when the warning mechanism vibrated. In the two other sessions, the participant performed the same action in response to an auditory signal played from the speaker located in the front of the room. During all sessions, each participant was instructed to stand in the center of the room and play any of several games on an iPad to provide cognitive stimulation, as a proxy for cognitive demand an individual may experience outside of the alerting mechanism itself. The selection included the games, “Supermagical”, "Angry Birds", "Unblock Me", "Candy Crush", "Icomania", "Jetpack", "Blitz", "Temple Run 2", and "CollapseBlast". The purpose of this secondary task was simply to distract the participant from focusing their attention on hearing or feeling the alert. This kind of sensitivity to a particular channel of perception would detract from the authenticity of the lab environment. We chose iPad games, a visual and kinetic task, to mimic simple, common police assignments such as writing citations. These particular games we chosen from popular games for iPad to ensure an engaging selection.

Procedure. Each session was preceded by a practice trigger in which the participant was given the opportunity to experience the alert in the upcoming session but not respond to it. Once the test session was started, playback of the ambient highway noise began, and the participant was directed to begin playing an iPad game of choice while standing facing the alarm speaker. The alarm signal was automatically triggered by the computer at a preselected time.

Each alert was triggered only once during a test session. To select alert trigger times, a sequence of forty times between thirty seconds and eight minutes were randomly selected, one for each participant, and a random permutation of these forty times was used for each type of alert. Thus, the average trigger time for each alert type across all experiments was identical.

The time at which a key press was detected in response to the alert was automatically recorded and the test session ended ten seconds after the alarm was triggered. Following each session, each participant was asked to complete a questionnaire to gather subjective information about his or her interaction with the warning signals.

5.2 Officer Assessment

Following the experiment, we conducted a focus group with members of the State Police to understand their perspectives on the proposed warning prototypes [16]. Findings from this are discussed in the next section.

6 Results and Discussion

Of the forty participants, ten were missing response time data for at least one of the four conditions due to test bed and subject errors. For example, in cases where an alert malfunctioned or the subject did not respond to the alert in the appropriate way, accurate readings were not taken.

6.1 Response Time

Response time is the key measure as the warning needs to induce a reaction within seconds. We ran a one-way repeated measures ANOVA using response time as the dependent variable and the alert type as the independent variable with 4 levels. There was a significant effect of alert type on response time ($F(3,87) = 27.5$, $p < .0001$) indicating that some alert types induced a significantly faster response than others.

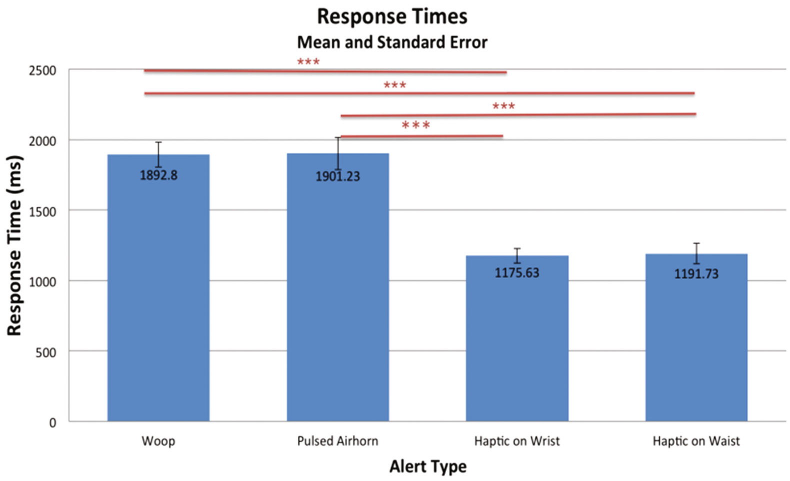

Fig. 5. Mean and standard error of response times in each condition. Red indicates significance: *** p < .001.

A post hoc Tukey's pairwise comparison revealed the significant differences between *Woop* and *Wrist Haptic* = ($p < 0.001$), between *Woop* and *Waist Haptic* ($p < 0.001$), between *Pulsed Airhorn* and *Wrist Haptic* ($p < 0.001$), and between *Pulsed Airhorn* and *Waist Haptic* ($p < 0.001$). Other pairs showed no significant differences. These results indicate that the modality of warning had a significant effect on the response time. More specifically, responses to haptic signals were about 0.7 s faster than responses to the auditory signals. Moreover, considering that two of each signal modality were studied, the effect seems repeatable in experimentation. Figure 5 illustrates the mean and standard error of the four conditions.

6.2 Subjective Data

In terms of subjective data, study participants were asked to rate several features of the haptic and auditory alerts using a five point Likert scale. Specifically, subjects rated the intensity of the volume and pitch for the auditory alerts, the comfort of vibration, wear, and movement wearing the device for the haptic alerts, and detectability, signal urgency, warning appropriateness, and warning effectiveness for all four alerts. According to Wilcoxon matched pairs signed-rank test, there was no significant difference in ***volume*** ratings between the two auditory signals and no significant difference between the haptic alerts in ***comfort*** *of vibration* or *comfort of wear*. However, a Wilcoxon matched pairs signed-rank test showed a significant effect of the type of auditory signal on ratings of ***pitch*** ($W = 78$, $Z = 6.19$, $p < 0.005$, $r = 0.565$). Pitch was rated from "Too Low" to "Too High." The mean and standard error of the pitch ratings are plotted in Fig. 6. On average, subjects felt that the *Woop* siren was higher in pitch than the *Pulsed Airhorn* and tended to rate it closer to the "Too High" end of the scale. For each of the four prototypes, subjects were also asked to rank ***detectability*** on a scale

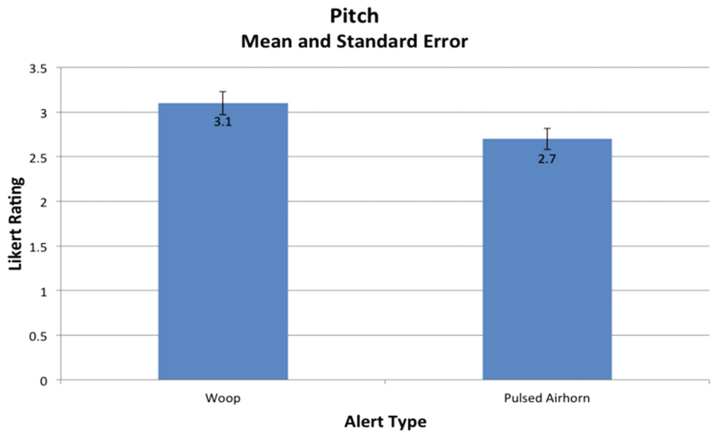

Fig. 6. Mean and standard error of pitch ratings in each auditory alert condition.

from a one, “Very Difficult to Detect” to five, “Very Easy to Detect.” A Friedman test revealed no significant difference between the four conditions. However, a significant effect was found of alert type on ratings of ***urgency*** (X^2 (3) = 33.945, $p < 0.0001$). Urgency was rated from “Very Relaxed” to “Very Urgent.” The *Woop* signal was rated as significantly more urgent than the other three indicating that it would be easiest to detect (Fig. 7). A post-hoc test using Dunn’s Multiple Comparisons Test showed significant differences between *Woop* and *Pulsed Airhorn* ($p < 0.01$), between *Woop* and *Wrist Haptic* ($p < 0.001$), and between *Woop* and *Waist Haptic* ($p < 0.001$).

Finally, we found a significant effect of alert type on ***effectiveness*** rating (X^2 (3) = 21.514, $p < 0.0001$) with significant differences between *Pulsed Airhorn* and

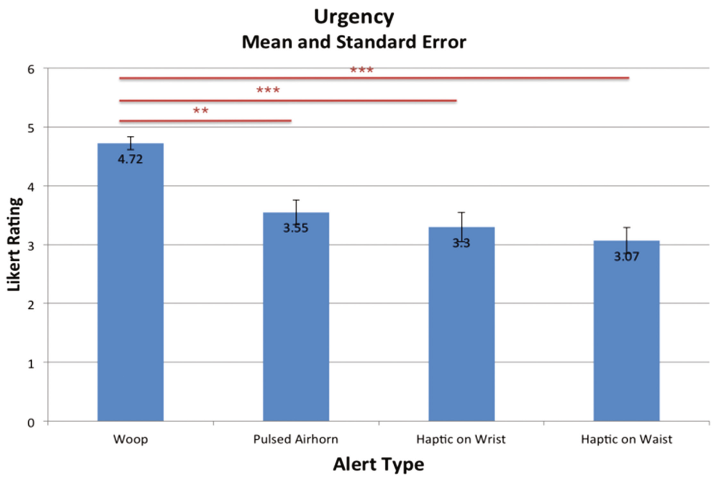

Fig. 7. Mean and standard error of urgency in each condition. Conditions that were significantly different are indicated in red: ** p < .01, *** p < .001.

Waist Haptic ($p < 0.05$), between *Woop* and *Wrist Haptic* ($p < 0.05$), and between *Woop* and *Waist Haptic* ($p < 0.01$). In these comparisons, the auditory sirens were rated higher than the haptic conditions as seen in Fig. 8.

In addition to these Likert scale ratings, the subjective survey concluded with a request for rankings on all four prototypes based on preference ("1" being the most preferred and "4" being the least preferred). A Friedman test here revealed a significant effect (X^2 (3) = 11.427, $p < 0.01$). Dunn's multiple comparisons test only showed a significant difference between *Pulsed Airhorn* and *Waist Haptic* ($p < 0.05$) in which *Pulsed Airhorn* was, on average, rated higher than the haptic signal located on the waist. Overall, *Pulsed Airhorn* was the most preferred. The results are summarized in Fig. 9.

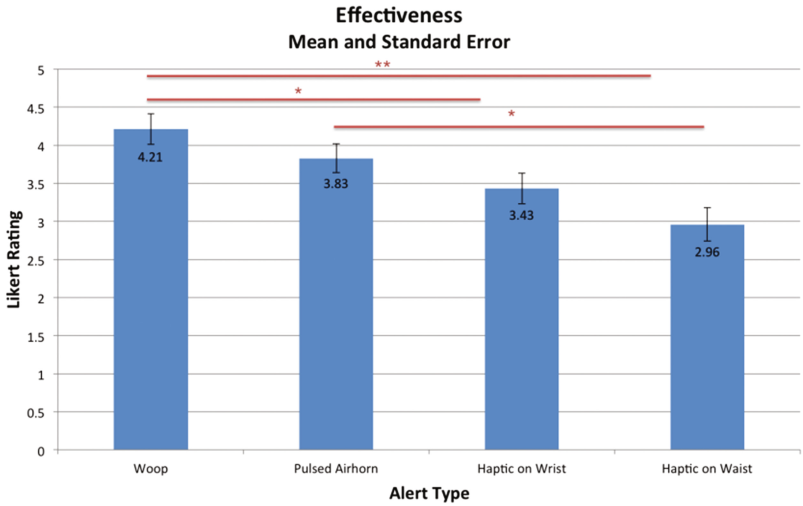

Fig. 8. Mean and standard error of effectiveness across conditions. (* p < .05, ** p < .01).

6.3 Comments

In general, comments varied in terms of whether subjects preferred the auditory or haptic signal. There was some general consensus, however, on various aspects of the individual prototypes.

For the haptic warning on the waist, the vibration was generally perceived as detectable and comfortable although many participants likened the vibration to a cell phone vibration or that of other similar devices. One participant stated, "The vibration frequency wasn't 'relaxed' but seemed along the same 'force' as a hand held massager so doesn't exactly bring emergency to mind." Some even felt that the vibration was "ticklish." It seems that because of its similarity to sensations we have naturally learned to associate with other devices, the haptic alert loses its novelty and hence its perceived urgency. Another common response to the haptic device was that it was at least mildly uncomfortable to wear, typical of an early prototype. This wearability issue should be

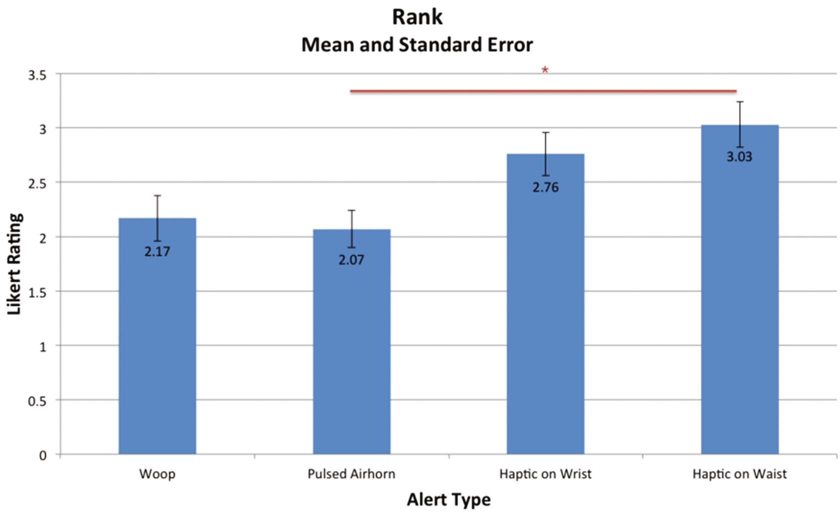

Fig. 9. Mean and standard error of rank rating in each condition. Red indicates significance: * $p < .05$.

easy to improve in further revisions. For example, the current device was designed with pointed corners, which could be rounded for better ergonomics and the hardware could be modified to be less bulky to wear. Eventually, the device can be integrated into an existing device or garment.

Some responses to the haptic device on the wrist were similar to those with the haptic on the waist in terms of the quality of the vibration and wear. It was described as "a little unwieldy" and "enough to signal/alert without stressful disturbance." In general however, many subjects compared the device on the wrist to a watch, a location that felt more natural than the waist. One common sentiment was that the vibration on the wrist was "much more comfortable than on the stomach." An important advantage of incorporating vibration into a device such as a watch would be that the vibrating mechanism would be much more likely to maintain contact with the skin.

In regards to the two auditory alarms, subjects tended to perceive the volume of both auditory alarms as "definitely audible" but also very close to the ambient noise. Although the sounds were controlled at 90 dB, about 10 dB higher than the ambient noise, it was common for subjects to observe that either auditory signal was, "loud by itself but not when the background noise was on." In regards to the *Woop*, one subject commented, "Pitch was slightly on the high side but I feel that it stimulated an appropriate response," while many responded to the *Pulsed Airhorn* with remarks such as, "Could be higher."

In regard to the two sirens, comments included, "Catches my attention very well," and, "Couldn't have done a better job." However, a common observation for both auditory signals was that they sounded similar to regular highway noises such as "truck horns" and "an actual siren." If this concern proves to be an issue in the field, it could be mitigated by engineering new and more unique sounds for the operational environment.

6.4 Focus Group Findings

Following the conclusion of the user study, we conducted a focus group with four members of the State Police force to demonstrate the prototypes and gather feedback from experts in the field. The experience of the four individuals ranged from 17 to 31 years on the State Police force.

In response to the haptic signal, an officer wearing the device during the demonstration commented that the vibration "caught my attention right away" and all four agreed that the intensity was appropriately strong and different from that of a cell phone vibration. There were, however, varying opinions on the optimal location of wear. As a watch, some felt that it would be best in terms of maintaining the effectiveness of the device, but that most officers don't wear watches and that it would easily be forgotten. Another suggestion was to instead, integrate the vibration into the duty belt because, "you are always going to put it on." However, there were concerns as to how easily the vibration would be felt through layers of clothing or when standing or sitting in different positions.

The officers also suggested putting the device in a pocket and/or modifying uniforms to have holes where the motor could be placed in contact with the skin. If integrated into the clothing, there would be a need for multiple devices for each officer – one for each uniform. Another idea was to wear the device as a necklace and the other individuals seemed to agree that this was a viable option. When asked whether officers would be inclined to wear the device on a regular basis, the general consensus was positive. In discussion of the haptic device, we also learned that in terms of battery life, the haptic device would need to run for up to 16 h (the length of a double shift).

In response to the auditory alarms, all four officers agreed that they preferred the *Woop* over the *Pulsed Airhorn*. The *Pulsed Airhorn* was "too similar to the air horn we already use." With the auditory alarm, there was also the concern that it would go off in a situation in which an officer would not want to bring attention to himself or herself (for example when watching a scene before going in). However, one of the officers acknowledged that the siren would not go off unless the emergency lights were on, based on the programming of the cruisers, and then the others seemed to agree that this was acceptable. The officers also agreed that in all cases, the warning should automatically turn off after a ten-second timeout.

Next, when asked if a multimodal warning incorporating the *Woop* signal and haptic device would be useful, the answer was a resounding yes. The auditory signal would "always be there" since it would be a part of the cruiser hardware and the haptic signal would be supplemental.

Overall, the officers were enthusiastic about the prototypes. One of the individuals, serving as director of fleet operations and responsible for equipment, stated, "It's a great tool, I really do think," and concluded saying that, "If we can absorb that cost, it's a no-brainer."

7 Future Work

There are some features that we did not implement in the current prototypes that are worth investigating in future work. The existing prototypes could easily be integrated with each other or other modes of warning to create a multimodal alerting mechanism. With such a warning, it would be worthwhile to study whether a warning that uses multiple modalities can improve response time over a single modality.

In terms of modifying the existing prototypes presented in this paper, several changes could be made to improve feedback from the usability studies. First, we did not investigate the design of a new sound with the desirable qualities of signal urgency and conspicuity for these environments. It is possible that a unique sound tailored to the environment could produce superior response times.

Second, the haptic device could be upgraded in two ways. First, it currently delivers a continuous vibration but may benefit from a modification in intensity of the signal or in a change in vibration pattern. In addition, a more comfortable device design could improve user acceptance. Ideally, the haptic signal could be integrated into a device that the user already wears on a regular basis, such as a belt and based on the conversation with the state police, there is also work to be done in pinpointing the best method and location of wear.

8 Conclusion

Based on fieldwork and background research, and in close collaboration with state police, four alert prototypes were designed and evaluated for use in a high noise, low-light environment such as a dimly-lit highway shoulder. Two of these alerts were auditory sirens and two were haptic vibrations, one placed at the wrist and one at the waist. Haptic vibrations, which we hypothesized would be more salient in a loud and visually stimulating environment, produced statistically significantly faster responses than the auditory alerts. However, there were no statistical differences between the two haptic and the two auditory alerts, suggesting robustness to the specific alarm type.

Subjectively, the subjects had a slight preference for the auditory alerts and perceived them as significantly more urgent than the haptic alerts. However, both the subjects and state police officers responded positively to the haptic alerts overall. The discrepancy in the findings, objective data leaning towards haptic and subjective data leaning toward auditory, could be attributed to cognitive fluency with auditory sirens over haptic alerts. Subjectively, participants favor auditory alerts in this scenario because they are more familiar and feel easier to process even if the data shows otherwise. In practice, while the auditory alerts offer more permanence and durability, the haptic alerts are a more novel and thus more conspicuous stimulus in the operation environment. It was proposed by members of both groups that a multimodal alert using both signal types could be highly effective.

In a traffic environment, most existing safety technologies focus on passive danger prevention rather than active warning which can incorporate autonomous safety technology as proposed in this work. This research has shown that once alerted through a haptic device, a person in this low-light setting gains, on average, an additional 0.7 s in response time as compared to an auditory alert, which could mean the difference between life and death. However, the fidelity and reliability of the overall system, i.e., the sensors and algorithms that detect a possible oncoming threat, will determine whether these alerting schemes are successful. If such a system experiences many false positives, users may become frustrated and learn to ignore the system. Highlighting the importance of systems engineering, the overall testing of the integrated system, which is still pending, will determine the ultimate success of these alerts.

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References

1. Ashton, R.J. Solutions for safer traffic stops. Police Chief (2004)
2. Belz, S.M., Robinson, G.S., Casali, J.G.: A new class of auditory warning signals for complex systems: auditory icons. Hum. Factors **41**(4), 608–618 (1999)
3. Burt, J.L., Bartolome, D.S., Burdette, D.W., Comstock, J.R.: A psychophysiological evaluation of the perceived urgency of auditory warning signals. Ergonomics **38**(11), 2327–2340 (1995)
4. Cergol, G.: On-Duty Nassau County Patrol Officer Struck, Killed by Car on LIE. NBC, New York (2012)
5. Cummings, M.L., Donmez, B., Graham, H.D.: Assessing the Impact of Haptic Peripheral Displays for UAV Operators (2008)
6. Daoud, S.O., Tashima, H.N.: 2012 Annual Report of the California DUI Management Information (2012)
7. Edworthy, J., Stanton, N.: A user-centered approach to the design and evaluation of auditory warning signals. Ergonomics **38**(11), 2262–2280 (1995)
8. Feathers, T.: Trooper injured when alleged drunk driver crashes into cruiser in Saugus. boston.com (2013)
9. Federal Highway Administration. Boosting Roadway Safety with Rumble Strips (2002)
10. Haas, E.C., Schmidt, J.: Auditory icons as warning and advisory signals in the US Army Battlefield combat identification system. HFES **39**, 999–1003 (1995)
11. International Safety Equipment Association. American National Standard for High-Visibility Safety Apparel and Headwear (2010)
12. Joint Transport Research Centre of the OEDC and International Transport Forum. Towards Zero: Ambitious Road Safety Targets and the Safe System Approach Summary Document (2008)
13. Karraker, J.: Detecting, Tracking, and Warning of Traffic Threats to Police Stopped Along the Roadside. M.Eng. Thesis, MIT EECS, Cambridge, MA (2013)
14. Michigan Department of Transportation. New Work Zone Sign: Give ‘em a Brake Safety Coalition Warns Motorists to Pay Close Attention (2006)
15. Patterson, R.D., Mayfield, T.F.: Auditory warning sounds in the work environment. Phil. Trans. R. Soc. Lond. **327**, 485–492 (1990)
16. Powale, P.: Design of an Alerting Device for Roadside Personnel, June 2013

17. Provins, K.A., Morton, R.: Tactile discrimination and skin temperature. J. Appl. Physiol. **15** (1), 155–160 (1960)
18. Reisberg, D.: Cognition. Norton & Company Inc., New York (2007)
19. Richard, C.M., Brown, J.L., McCallum, M.: Crash warning system interfaces: human factors insights and lessons learned (No. HS-810 697) (2007)
20. Scott, J.J., Gray, R.: A comparison of tactile, visual, and auditory warnings for rear-end collision prevention in simulated driving. Hum. Factors **50**(2), 264–275 (2008)
21. Spence, C., Ho, C.: Tactile and multisensory spatial warning signals for drivers. IEEE Trans. Haptics **1**(2), 121–129 (2008)
22. The Associated Press. Officer escapes injury in traffic stop accident. The Record (2012)
23. U.S. Department of Justice and Federal Bureau of Investigation, C.J.I.S.D. Law Enforcement Officers Killed and Assaulted (Table 61: Law Enforcement Officers Accidentally Killed; Circumstance at Scene of Incident, 2000–2009) 2009
24. U.S. Fire Administration. Emergency Vehicle Visibility and Conspicuity Study (2009)
25. Wogalter, M.S. (ed.): Handbook of Warnings. Lawrence Erlbaum Associates, Mahwah (2006)
26. Wood, N.E.: Shoulder rumble strips: a method to alert "Drifting" drivers. In: Proceedings of the 73rd Annual Meeting of the Transportation Research Board (1994)
27. Wu, B.: A Controllable Laser Projector for Diverting Traffic. M.Eng. Thesis, MIT EECS, Cambridge, MA (2013)
28. National Campaign Launches Effort Educating Drivers to 'Move Over' and Protect Officers on Roadways. Move Over, America (2007)