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Multimodal urgency coding: auditory, visual, and tactile parameters and their impact on perceived urgency

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Abstract. Through a series of investigations involving different levels of contextual fidelity we developed scales of perceived urgency for several dimensions of the auditory, visual, and tactile modalities. Psychophysical ratings of perceived urgency, annoyance, and acceptability as well as behavioral responses to signals in each modality were obtained and analyzed using Steven's Power Law to allow comparison across modalities. Obtained results and their implications for use as in-vehicle alerts and warnings are discussed.

Keywords: Auditory warnings, tactile warnings, perceived urgency, in-vehicle displays, driver behavior

I. Introduction

Urgency mapping is critical to effective warning design [1, 2]. It is also essential to overall display design since minor alerts and indicators should not interfere with time critical warning information. Modern workstations (e.g., vehicle dashboards and cockpits) have the potential to present an extensive amount of information in visual, auditory, and tactile modalities. Tasks such as driving and piloting impose high visual load requirements, making auditory and tactile modalities of particular interest. An extensive body of literature now exists to guide the hazard matching designs for auditory and visual signals [1, 3] and these guidelines have received empirical validation [4-6]. In order to effectively incorporate new developments in tactile signaling systems, it will be essential to consider how tactile signals are perceived in relationship to visual and auditory signals.

The aim of the set of investigations described here was to provide a means of determining how perceived urgency is scaled across visual, auditory and tactile modalities. Particular focus was placed on examining the perceived urgency of tactile signals since little, if any research currently exists in this domain. A series of experiments were designed to determine scales of perceived urgency across several parameters of each modality with varying levels of context. A validation study was then carried out in a driving simulation context by using the scales developed in the initial experiments to design collision warnings of three levels of urgency in each of the three modalities. Due to space limitations, we will concentrate here on the first two sets of psychophysical experiments examining

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auditory, visual, and tactile signals presented in low to medium-level simulated driving context.

2. General Methods

The general approach was to conduct a series of psychophysical experiments and apply Stevens Power Law to allow comparison of perceived urgency, annoyance, and acceptability across and within modalities. This approach and basic procedure has been used successfully in previous research developing urgency scales in the auditory modality [e.g., 7, 8]. Stimuli were presented via a custom program developed in MATLAB with Psychtoolbox [9, 10]. For each experiment, participants were presented with stimuli of a specific modality (visual, auditory, or tactile) and asked to rate the perceived urgency, annoyance, and acceptability of each. Participants were instructed to imagine they were in a driving context while rating these items on a 1-100 scale, 1 being the least urgent, annoying, or acceptable and 100 being the most. The relevant stimuli were presented one at a time and participants were asked to rate each on their perception of its perceived urgency by placing a cursor on a slider scale between 1-100. After indicating their placement for perceived urgency they used a similar procedure to rate the stimuli's annoyance and acceptability level. For each modality, the stimuli were presented in a randomized order. Following completion of one presentation of each level of each stimulus in the set, the set was randomized again for subsequent presentation until each stimulus had been presented three times. Ratings were averaged across the three presentations and were then used to compute the final rating.

2.1 Experiment 1

Participants. Psychophysical ratings were voluntarily obtained from 92 college undergraduates (37 male) between the ages of 18 and 47 years.

Auditory Stimuli. Auditory stimuli were presented in a sound attenuated laboratory on an Optiplex 745 Dell PC with a SoundMAX Integrated Digital HD Audio Driver Analog Device sound card. All auditory stimuli were presented through a pair of Sennheiser stereo headphones. Participants received a fixation cross on a black screen for 500 milliseconds followed by an auditory stimulus. The three auditory parameters investigated were, fundamental frequency, intensity and pulse rate. Fundamental frequency and pulse rate stimuli were created following the specifications of Hellier et al. (1993), whereby varying durations of silence separated several standard or basic pulses. The basic pulse used -based on Paterson (1984)- was a 200 ms sine wave (20 ms on/offset) with 15 harmonic components at 300 Hz fundamental frequency. Because we were interested solely in main effects, only one characteristic of the stimulus was manipulated at a time while all others were held constant to the basic pulse as described above. Unless intensity was being specifically manipulated, the basic pulse was presented 75 dB SPL.

Fundamental frequency (F_0) stimuli consisted of 6 basic pulses of the same frequency played in succession with no silence between pulses for a total duration of 1200 ms. The 20 ms on/offset allowed the pulses to be discerned without the need for silence between pulses.

Stimulus intensity was varied in a similar fashion. Each stimulus consisted of 6 basic pulses at 300 Hz with no silence between pulses for a total duration of 1200 ms. Using a Brüel &Kjær Sound Level Meter, we verified the intensity of each stimulus through the headphones. Decibel measurements were taken from the individual pulses rather than the entire stimulus to avoid including the decreasing intensity of the onset and offset in our measurement. There was no evidence of intensity disparity between the left and right channel. Seven intensity levels were examined including the standard 75 dB SPL tone and then three levels lower (66, 69, and 72 dB) and three levels higher (78, 81, and 84 dB).

Pulse rate stimuli consisted of between 4 and 12 basic pulses at 300 Hz, the inter-pulse interval (IPI)- or silence between pulses- varied from 475 to 9 ms. Pulse-to-pulse duration is defined as the duration from the start of one pulse to the start of the next pulse (pulse duration + IPI). The duration of each stimulus approached, but did not exceed, 2500 ms so each stimulus varied slightly in total duration. Pulse rate was derived via a formula based on one previously used by Hellier et al. (1993):

2500ms/pulse-to-pulse time (1)

2500 ms represents the total approximate duration of each stimulus and pulse-to-pulse time varied among 7 levels. 2500 ms was used as the total duration to standardize the rates for all stimuli although the total durations of the stimuli varied slightly. For example, a stimulus with a pulse rate of

3.69 would consist of 4 basic pulses of 200 ms each separated by 475 ms of silence. Because following the last pulse was simply 275 ms of silence the total true duration of this stimulus is 2225 ms rather than 2500 ms.

Visual Stimuli. Visual stimuli varied in background color, signal word, and pulse rate. The background colors were red, orange, yellow and green. Signal words were "brake", "danger", "notice", and "warning". The colors and signal words (Danger, notice, and warning) were chosen based previous work by Wogalter, et al. [6]. The colors were made on a Dell Latitude D820 laptop using an RGB color scale. Each RGB color was then transformed to nanometers using a code based on the Bradford matrix color transformation (see appendix for stimuli). All stimuli were presented on an image of a vehicle dashboard on a Dell 24" ST2420L monitor.

Similar to the auditory stimuli, the visual stimuli consisted of a basic visual "pulse" (background, signal word). The pulse rates examined were derived using the same formula.

Tactile Stimuli. Tactile stimuli were presented through a single C2 tactor (Engineering Acoustics: www.eaiinfo.com) and a RadioShack amplifier that was modified to act as a microcontroller. Through this set up, the tactor responded as a speaker. Tactile stimuli were generated by playing audio files through the computer's sound card and output via the tactor. The tactor was affixed to the top of the participants arm approximately 1 inch above their wrist. An athletic sweatband (5.75 cm length; 15 cm diameter) was used to hold the tactor in place. A single disposable layer of plastic film was wrapped around the participant's arm beneath the tactor for hygienic purposes and to prevent any perspiration from coming in contact with experimental equipment. White noise was played in the background to avoid confounding the acoustic properties of the tactor with its vi- bro-tactile sensation.

Table 1
Parameters examined in each modality

Auditory
- Frequency
- Pulse Rate
- Intensity or "loudness" (dB level)

Visual
- Color (text and background)
- Word Choice
- Flash Rate (visual pulse rate)

Tactile
- Pulse Rate

Pulse rate was the only vibrotactile parameter examined in this series of investtigations. This is partially due to physical characteristics of the tactor. For example the tactor is best suited to presenting a single sine wave of 250 Hz. The length of the pulse remained 200 ms with 20 ms on/offset. Due to space limitations the results are combined with Experiment 2 below.

2.2 Experiment 2

Experiment 2 utilized the general experimental protocol implemented in Experiment 1 with the primary exception that participants experienced and rated stimuli while engaged in a simulated driving task presented via a medium fidelity driving simulator (RealTime Technologies, Inc.). Participants performed a car following task while intermittently being presented with stimuli to rate. The lead car was yolked to the participants' vehicle and thus maintained a consistent headway with speed being determined by the participant's vehicle. Participants were instructed to maintain performance on the driving task at all times and to make their ratings as soon as they safely could without disrupting their driving performance.

Other than adding the contextual fidelity of asking for ratings while participants were engaged in the driving task, Experiment 2 had several other notable differences. One difference from Experiment 1 was that in Experiment 2, the time interval between presentations of stimuli ranged randomly within an interval of 10-15 seconds, with an average of 12 s. This manipulation was implemented to allow participants to maintain adequate driving performance. An additional difference was that in Experiment 2, response time for the initial rating was obtained. One final difference was that in Experiment 2, all participants provided ratings for each of the three modalities, rather than only one modality.

Participants. Participants were 29 college undergraduate and graduate students (8 male, 21 female), ranging from 20 to 30 years of age (mean, 20.25 y). All participants had normal visual and auditory acuity based on self-report and all possessed a valid driver's license.

Visual Stimuli. The visual stimuli were modified slightly from Experiment 1 by only manipulating one parameter at a time rather than more than one (e.g., signal word and background color). This was done to more closely resemble the manipulations to the auditory stimuli. Additionally, the total presentation time in Experiment 2 was changed from 3 seconds to 2.5 seconds. When color was varied the word "Warning" was held constant as in Experiment 1 but with no pulse rate. When signal word was varied the color was held constant as yellow, with no flash rate. Additionally, seven pulse rates corresponding to the auditory and tactile pulse rates were examined while holding word and color constant ("Warning" on a yellow background).

Auditory Stimuli. The auditory stimuli for this experiment were the same as Experiment 1, with the exception that we only examined pulse rate for the auditory modality in Experiment 2.

A summary list of each of the parameters examined in the current series is provided in Table 1.

3. Results

The subjective rating results for perceived urgency, annoyance, and acceptability were computed in the same way in all experiments in this series. First, we log transformed all of the ratings to normalize the data. Then we computed Stevens Power Law for the log transformed values to allow comparison across modalities and parameters. Specifically, we used the formula

$$S = KI^a$$

Where S equals the subjective rating, K is a constant determined by the unit of measurement, I is the physical stimulus parameter (i.e., pulse rate, intensity) and ^{a} is the power exponent that determines the slope of the line and the relationship between the subjective ratings and the physical parameters. Using this formula, log(S) = a log(I) + log(K).

The results of raw or untransformed values for ratings of perceived urgency for the parameter pulse rate in the visual, auditory and tactile modality are illustrated in Figure 1.

4. Discussion

We used a modified version of a magnitude estimation procedure discussed by Stevens [11, 12] and previously employed by Hellier, et al. [8]. The

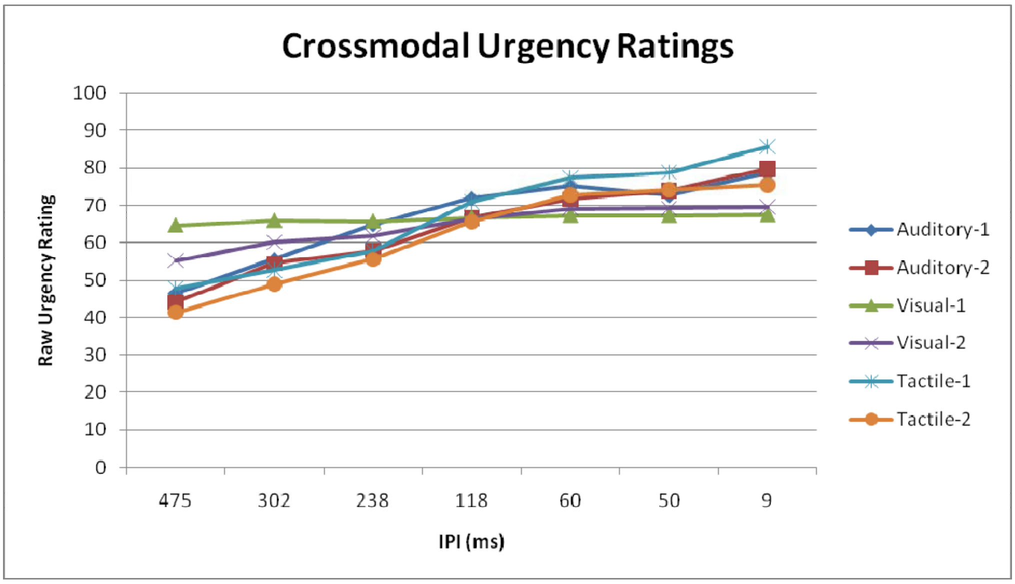

Figure 1: Psychophysical Ratings of Perceived Urgency in Experiment 1 (low context) and 2 (medium context). Note that interpulse interval (IPI) is a function of pulse rate. Since total duration of the stimuli were held relatively constant, faster pulse rates resulted in shorter duration IPIs.

methods and paradigm of psychophysical scaling using log-log transformations as recommended by Stevens yielded scales of urgency, annoyance, and acceptability that could be compared across visual, auditory, and tactile modalities and across various key parameters within each of those modalities. A wide range of urgency levels were obtained in each of the modalities. Parameters could be determined that resulted in nearly equivalent perceptions of urgency level across each of the three modalities.

Importantly, the results obtained in this series of investigation are some of the first ever obtained for perceptions of urgency for vibro-tactile stimuli. The current results indicate that the tactile modality is well suited for presenting information of varying urgency levels to the drivers. Participants generally rated the tactile stimuli as no more annoying, and at least as acceptable, as stimuli presented in the auditory and visual modality.

The urgency ratings obtained in Experiment 1 (low context) were generally validated in Experiment 2 (medium context) providing at least partial support for the use of scales obtained in laboratory settings for the design of warnings for field use

In future research it would also be beneficial to validate the predicted urgency levels obtained in the current experiments to different types of driver interface applications (i.e., alerts for signals of varying hazard level – low tire pressure versus imminent collision). For example, it would be of interest to determine if low urgency alerts would result in both appropriate response and acceptability for low urgency situations (i.e. low fuel) relative to pairings of high urgency alerts with high urgency situations (i.e., collision situations of various types).

A few limitations are worth noting. In the current series, due to practical constraints only a limited number of parameters in each of the modalities could be examined. Future research examining additional parameters, such as pulse duration and pulse pattern, is warranted. Additionally, the current series of investigations examined urgency scaling for unimodal stimuli. Future applications of this work (particularly for high criticality signals) will likely involve presentation of stimuli in two or more modalities simultaneously (e.g., tactile and auditory, visual and tactile). Previous research in basic laboratory settings provides support for the redundant target effect [13, 14] indicating that presenting redundant information in two modalities results in faster response time than either modality alone. However, this laboratory finding has yet to be adequately confirmed within a driving context. Further, there is little if any information regarding the impact of multiple modality presentation on perceptions of urgency and annoyance. Further work in this area is warranted. Presenting stimuli in multiple modalities may result in redundant, additive, or multiplicative effects on urgency.

In conclusion, the objective of this experiment – to determine urgency scaling within and across visual, auditory, and tactile modalities – and specifically, to develop and test a methodology for determining these cross modal scales was achieved. Further, the tactile modality appears well suited for displaying a wide range of criticalities levels to automobile drivers.

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