Effects of Looming Auditory FCW on Brake Reaction Time under Conditions of

Distraction

by

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ABSTRACT

In 2013, 1.8 million US drivers were responsible for rear-end collisions with other vehicles (NHTSA 2014), for which driver distraction has been identified as the main factor (Campbell, Smith & Najm, 2003; Knipling, Mironer, Hendricks, Tijerina, Everson, Allen & Wilson 1993; Wang, Knipling & Goodman, 1996). The ubiquity of cell phones and their use behind the wheel has played a major role in distracting these drivers. To mitigate this, some manufacturers are equipping vehicles with forward collision warning (FCW) systems.

Generally, warnings that are perceived as being urgent produce lower response times. One technique for increasing perceived urgency of a warning is called looming, where the signal increases in or more dimensions over time. Looming warning signals have been shown to produce low response times, likely because the recipient perceives the signal as a potential approaching threat, prompting defensive reactions (Graziano and Cooke, 2006).

The present study evaluates the effect of veridical (intensity increases at the rate of closure with the lead vehicle) and high urgency (intensity increases at a rate of Time to Collision minus 0.5 seconds) looming FCW, as well as a static FCW, on drivers' brake reaction times in the presence of a secondary texting task. Participants' brake reaction times were recorded as they followed a lead car in a driving simulator, encountering multiple sudden-braking events across the five conditions (a control condition as well as four counterbalanced conditions using a secondary texting task). In the four conditions with a secondary task, participants received no FCW, static FCW, veridical FCW, and

high-urgency FCW, respectively. Performance data was analyzed using a repeated measures ANOVA, and a series of pairwise comparisons were then made using Bonferroni corrected pairwise t-tests.

The presence of a visually and manually distracting secondary task (texting) seems to diminish the performance of the looming signals as compared to previous studies that did not use a distraction component. While looming FCW do seem to effectively lower BRTs when the driver is distracted, it is recommended that further research investigate the relationship between secondary task types and their respective levels of distraction, and the effectiveness of auditory looming FCW.

Dedication

I would like to dedicate this thesis to my parents Michelle and Steve, and my

brothers Chris and Andrew, for a lifetime of love and support;

to my grandparents John and Marilyn Folvig, whose generous love and financial support

made this graduate endeavor possible;

and to my grandparents Don and Mary Jo Becker, who did not live to see me finish this

degree, but from an early age instilled in me a ceaseless appetite for knowledge and

passion for creative problem-solving.

I love you all.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

In the United States in 2013, there were over 5.6 million motor vehicle accidents, 1.8 million (32.2%) of which were rear-end collisions with other vehicles (NHTSA 2014). It has been shown that driver distraction is the main factor in these collisions (Campbell, Smith & Najm, 2003; Knipling, Mironer, Hendricks, Tijerina, Everson, Allen & Wilson 1993; Wang, Knipling & Goodman, 1996). This is due in part to the increasing number of interactions integrated with the vehicle's own systems, and partly due to the use of a range of electronic devices, most notably cell phones. In 2010, a study found drivers engage in over 30 non-driving visually-intensive tasks while behind the wheel (Klauer, Guo, Sudweeks & Dingus 2010)

Drivers engaging in these visually and attentionally-demanding tasks while driving usually exhibit associated risky driving behaviors, including using one or no hands on the steering wheel, erratic lane positioning and departures, and inattention to the driving task (Stutts, Feaganes, Reinfurt, Rodgman, Hamlett, Gish & Staplin, 2005). Clearly, driver distraction is a problem, and it's one that may be alleviated somewhat by the intervention of future collision warning systems, or FCW.

An FCW system is an in-car system that warns the driver of an impending collision. This is of particular use to distracted drivers who have lost visual contact with the road ahead, and would otherwise be unaware of the danger. Ideally, the FCW warns the driver with enough time to react in order to avoid the collision. While FCWs are becoming more ubiquitous in new cars, they are not all the same. There are three main modalities through which most FCWs are delivered: vision, audition and touch. Among

these modalities, many variations may occur, including inter-modality combinations, and intra-modality differences. For example, auditory warnings may vary in frequency, intensity, inter-pulse-interval (IVI) and pulse duration, abstract vs. semantic sounds, and more.

While conceptually brilliant, FCW system implementation has been imperfect. It has been noted that they are prone to false alarms, and that these false alarm events happen much more frequently than situations in which the FCW might be useful (Zador, Krawchunk & Vaos, 2000). Repeated false alarms may undermine the driver's perception of system reliability, as they reduce trust in the system, annoy the driver, and ultimately have the opposite intended effect of decreasing driver compliance with the system (Abe & Richardson, 2004; Ervin, Sayer, LeBlanc, Bogard, Mefford, Hagan, Bareket, & Winkler, 2005; Lerner, Kotwal, Lyons, & Gardner-Bonueau, 1996). At the same time however, they discourage dangerous behavior by preventing overreliance on the system (Parasuraman, 2000; Parasuraman & Riley, 1997) so some level of FCW false alarms are probably helpful. It's important for drivers to know the limits of their FCW system, like if a car is stopped at the top of a hill or around a sharp turn. Some of these limits may be learned through false alarms. On the other hand, in some instances, the system is inhibited specifically to prevent an abundance of false alarms, like not operating under 50kph, or not warning of stationary objects (Ervin et al. 2005).

As a consumer product, it is important not to underestimate the importance of the annoyance factor. The system won't function properly at all if the driver refuses to purchase or use it. A Field Operational Test study by Reagan, Triggs, Young, Tomasevic,

Mitsopolous, Stephan & Tingvall (2006) demonstrated that even with a detailed system description in addition to training drivers on system operation in normal situations, drivers were still disinterested in the system because of frequent false alarms. Some adjustments, then, are still needed.

In addition to amending the circumstances in which FCWs are triggered, there exists ample opportunity to fine tune the use of the three main warning modalities and the variations within them. There are inherent strengths and weaknesses of delivering warnings in each modality within the context of driving. Visual warnings may not be noticed by a driver when they are distracted, or may be difficult to notice in unfavorable lighting conditions. As much as 95% of the information we receive when driving is identified visually, leaving little bandwidth for processing visual FCWs (Shinar & Scheiber, 1991). On the other hand, people react more quickly to auditory signals, and they are highly linked to arousal and activation systems in the brain. Some studies have examined the use of semantic vs abstract sounds. For instance, Sullivan and Buonarosa (2009) tested semantic, less-urgent-semantic, and abstract sounds, and found that the semantic sounds produced the fastest reaction time and highest recognition rate. These verbal warnings may also be more effective than static/abstract auditory warnings at indicating the direction of a threat (Chang et al., 2008), but they are not as effective in time-critical situations when the user is unfamiliar with the warnings.

However, abstract or otherwise, all auditory warnings risk not being perceived due to ambient noise or physical impairments. There is also the phenomenon of inattentional deafness, in which cross-modal stimuli are not recognized when the other

system is under high stress (high visual load means people usually don't hear auditory warnings and vice-versa). While using a multimodal FCW can increase the probability the driver will detect at least one of the warnings, inattentional deafness is highly likely under moments of high cognitive load; 79% of drivers failed to notice an auditory signal when presented at the same time as visual targets while under high visual load (Macdonald and Lavie, 2011). Due in part to these limitations, some researchers and FCW designers have gravitated toward multi-modal displays that include a vibrotactile element. The simplest tactile warning delivers one or more vibratory pulses to the user (Haas & Van Erp, 2014). Murata, Kanbayashi and Hayami (2014) found, after examining isolated and multimodal cues, that auditory and audio-tactile cues introduced shorter reaction times to hazards. Ho, Reed and Spence (2007) found that multimodal audio and vibrotactile cues (on the torso) produce faster reaction times than either unimodal presentation. Even when presented unimodally, vibrotactile signals have been shown to produce faster response times than auditory signals. Furthermore, in a study by Scott and Gray (2008), it was discovered that a tactile warning (delivered through three tactors on the drivers' abdomen) produced a faster brake reaction time than equivalent auditory or visual modalities.

Tactile feedback circumvents the inattentional deafness problem, because vibrotactile signals don't use the bandwidth of visual/auditory channels, which are occupied with driving. As a bonus for passenger comfort, tactile devices deliver warnings directly to the driver, rather than everyone in the cabin. There are studies which seem to extoll the virtues of tactile warning methods, as well as a few studies that show there are

limitations to its effectiveness. After pooling data from multiple studies, the NHTSA rated the effectiveness of different tactile feedback methods/locations. Brake and accelerator pedals were rated poor to fair, since the driver's foot may not always be in contact. Steering wheel warnings were rated as poor and seat vibrations were rated as fair to good. However, these ratings are not totally generalizable. For example, the steering wheel rating was poor because the signal was too small for the driver to notice, not because the steering wheel is inherently a poor place to give a warning (Chu, Han, Park, Seo & Choi, 2012). Reaction times have been shown to be reduced using vibrotactile stimuli in various different locations (Carlander, Eriksson & Oskarsson, 2007; Mohebbi, Gray & Tan, 2009; Scott & Gray, 2008). It seems as long as the vibrotactile stimulus is perceived, the location of the stimulus is less important. In the study by Chun et al. (2012), the average participant reaction time from onset of FCW was 1.75sec with no FCW, 1.48sec with a steering wheel FCW and 1.54s with a seatbelt FCW. Both FCW conditions were significantly different than the control condition, but were not significantly different from each other. Braking distance was reduced by 6.13m in the steering wheel condition and 4.73m in the seatbelt condition.

As with any modality, there are inherent problems with a vibrotactile delivery method. There are situations in which a vibrotactile warning may not be received by the driver. These include: One-handed drivers (Walton & Thomas, 2005), drivers wearing thick gloves (McGehee & Raby, 2002), and too much ambient vibration in the car, which may increase sensory noise to the point that the vibrotactile signal may not be detected by the driver (Ryu et al, 2010). It has also been shown that, in the case of steering wheel vibrotactile FCWs, moving the wheel while the warning is presented could cause the

driver to miss the signal due to tactile change blindness (Gallace, Tan & Spence, 2005; Gallace, Auvray, Tan & Spence, 2006; Spence & Gallace, 2007; Gallace & Spence, 2008). Lastly, vibrotactile stimuli are not an ideal way to communicate orthogonal information. For example, a vibrotactile signal with three .5 second pulses, separated by .2 seconds, at a given intensity will not be reliably identified as different from another signal of the same intensity and pulse width separated by .5 seconds, or a signal with the same pulse width and duration but of an increased intensity. Changing one dimension of the signal will not be consistently differentiated from other, similar presentations of that signal. Peoples' ability to differentiate between levels of physical feedback (like rhythm, spatial patterning, and/or distinctive intensity) is limited (Brown et al., 2006; Jones, Kunkel, & Piateski, 2009; Gallace & Spence, 2014).

While overly complex unimodal warnings or notifications should be avoided, time-sensitive warnings are an ideal candidate for vibrotactile use. Drivers do seem to be able to discern directionality from vibrotactile cues. The presentation of a directional vibrotactile cue has been shown to direct a driver's visual attention to the indicated side, possibly resulting in a quicker response (Butter et al., 1989; Spence & Driver, 2004; Ho, Tan & Spence 2005; Ferris et al., 2006; Ngo & Spence, 2010; Gallace & Spence, 2014). Ho, Tan and Spence (2005) found that vibrotactile cues which originated from the direction of the threat decrease driver reaction times (compared to cues that originated from the opposite direction). However, not all FCW systems support multi-directional threat detection. Luckily, even non-directional tactile warnings are effective in heightening driver alertness (Posner & Petersen, 1990; Cummings et al., 2007; Lees,

Cosman, Lee, Vecera, Dawson & Rizzo, 2012; Haas & Van Erp, 2014), which can help reduce reaction times even when the threat is not directly ahead.

While almost any detectable FCW will reduce reaction times when compared to a lack thereof, all FCWs are not created equally. By changing certain aspects of a warning signal within each modality, it is possible to effect changes in the way the signal is perceived, which in turn may cause the user to react differently (i.e., more quickly).

One important metric when examining FCWs is perceived urgency. Kaufmann et al. (2008) have created some urgency guidelines: High (Immediate action required) which is best represented by audio-tactile pairings; medium (no immediate action required) which should use visual-tactile modalities, and low priority (no immediate relevance to driving task) which should use audio-visual pairing. The Kaufmann study did not examine all modality combinations, however. Furthermore, the perceived urgency of unimodal warnings can also fluctuate. It is worth noting here that for real-world applications, there is another important metric that is strongly connected to perceived urgency, and that is perceived annoyance. Generally, when perceived urgency increases, so does perceived annoyance. In a study by Politis, Brewster & Pollick (2013), the more modalities a warning utilized, the more annoying it was perceived to be. In that case, the effect of increased urgency was greater than the effect of annoyance, but that relationship does not hold for all methods of increasing urgency.

There are certain ways to increase urgency in unimodal presentations while minimally increasing annoyance ratings. Baldwin et al. (2012) and Lewis and Baldwin (2012) constructed a crossmodal urgency scale, in which pulse rate was found to be an effective measure of urgency across all modalities. Audio intensity and frequency were

also effective for audio signals, and color and word choice were effective for visual signals. Increases in urgency of auditory signals also saw increases in annoyance, but the tactile and visual modalities did not see the same increase in annoyance. Regarding auditory warnings, Marshall, Lee and Austria (2007) demonstrated higher pulse duration and lower pulse interval can increase urgency and annoyance ratings of audio alerts.

Gonzales, Lewis, Roberts, Pratt and Baldwin (2012) found that while increasing fundamental frequency, pulse rate and intensity of warning sounds all increase perceived urgency, pulse rate increased annoyance much less than the other two. Edworth, Loxley and Dennis (1991) showed that higher fundamental frequency, higher speed and larger pitch range increase perceived urgency of auditory warnings. Pratt, Lewis, Peñaranda, Roberts, Gonzalez, and Baldwin (2012) reported a similar effect using vibrotactile cues. Increasing the pulse rate increased perceived urgency while having less impact on perceived annoyance ratings. Baldwin and Lewis (2014) also found that decreasing IPI (inter-pule interval) was effective at increasing ratings of perceived urgency, with a greater impact on perceived urgency than annoyance.

The location of tactile warnings can also affect urgency. For instance, tactors activated near a subject's shoulders produce higher urgency ratings than those of the lower back or waist (Li & Burns, 2013). Politis et al. (2013) conducted a comprehensive study in which multiple FCW urgency levels were tested in all modality combinations. It was discovered that more urgent signals generated quicker and more accurate responses. There was a general trend which indicated the more modalities used in the FCW, the more urgent (and annoying) the warning was perceived to be. It was also found that

multimodal displays that included a visual component tended to be rated more urgent than the other two modalities, while conditions with a tactile component were perceived to be more annoying. However, while the study was broad enough to include all modality combinations with urgency and annoyance ratings, there are still issues when it comes to generalizing the results to the real world.

One such issue is that the delivery method of each FCW modality was static. The vibrotactile signal was produced from a waistbelt, which may have different annoyance ratings than warnings produced from a steering wheel. The visual signal was extremely prominent on the simulator display, and could not be replicated as such in a real automobile. The driving task was limited to steering tasks (demanding a much lower cognitive and visual load), there was no driver distraction component, and behavioral metrics like brake reaction time were not recorded. In short, there are additional factors of FCW that affect perceived urgency and driver performance. While the stimuli in the aforementioned studies were static, the addition of dynamic qualities is one such way to boost perceived urgency.

A method of employing dynamic warnings is the incorporation of looming stimuli. A looming signal is one whose intensity increases in one or more dimensions (pitch, brightness, volume, perceived proximity, etc.) over time, or in some cases, in relation to the closing velocity of the vehicle. It is thought that looming stimuli are treated as a potential threat, lowering response times and prompting defensive reactions (Graziano and Cooke, 2006). During a driving task, a looming auditory warning was shown to produce quicker Brake Reaction Times than a static auditory warning (Gray

2011). This effect is thought to occur because the brain interprets the dynamic sound as the sound-emitting object approaching the driver (Shaw et al., 1991).

It is this sensation of an approaching object that facilitates lower BRTs (Hall & Moore, 2003; Leo, Romei, Freeman, Ladavas & Driver, 2011). The looming effect does not seem to be as strong with tactile cues when presented in the same way as auditory or visual stimuli. Increasing intensity tactile cues have been shown not to produce quicker BRTs than static tactile cues (Jones & Sarter, 2008) Though it worked for audio warnings, increasing the vibrotactile intensity as a function of Closing Velocity (as opposed to a constant, linear increase) did not produce significantly shorter BRTs as compared to non-looming signals (Gray, Ho & Spence 2014).

The looming perception does not seem to function for vibrotactile cues in the same way it does for audio/visual stimuli. It is thought this is because humans do not perceive distance through tactile sensations, so there is no natural reaction to increasing intensity suggesting an object is getting closer. If the sensation is perceived tactually, the object must already be close, so manipulating intensity alone will not produce the desired effect. Thus, there have been other attempts to reproduce the looming effect through vibrotactile stimuli using methods besides increasing intensity.

Several studies by Ho et al. (2014), which used three tactors on drivers' abdomen, evaluated the effects of directional cues toward and away from the head created using apparent tactile motion. While the toward-head activation condition produced a significant decrease in braking response times, it was not significantly different than the away-from-head condition, potentially implying it is the movement itself that speeds response time, but directional information is still not conveyed. However, in this study,

the rate of apparent motion was the same for all conditions. Gray et al. (2014) conducted a similar study, but varied the inter-tactor interval so that the rate of apparent motion varied as a function of closing velocity. The results showed that when linked to closing velocity, a FCW simulating motion towards the head produced quicker BRTs than the away-from-head condition, as well as both static conditions (toward- and away from head).

Because the studies by Ho and Gray used signals that travelled up the body, rather than toward it from the direction of travel when driving, Meng, Ho, Gray & Spence (2014) tested dynamic tactile warnings emanating from the hands (steering wheel) and the waist. After testing static signals to the hands, waist, and hands and waist simultaneously, they also examined a dynamic hands-waist cue (toward torso) and waist-hands cue (away from torso). The dynamic toward-torso cues were significantly more effective at lowering BRTs (as compared to a no warning condition) than any other condition. This is likely because of the congruency of the warning direction with the threat direction. The perceived directional encroachment into peripersonal space triggers a quickened defensive response from the driver (Graziano and Cooke, 2006). Vibrotactile cues that only increase in intensity, or whose simulated direction of movement do not simulate such encroachment, and are therefore not perceived as a threat.

While various FCW modalities and their component characteristics have been studied a great deal, the majority of this research has involved conditions in which participants are only engaged in the driving task i.e., there are no distracting secondary tasks involved. A study by Mohebbi et al. (2009), which examined the effects of static auditory and tactile FCW during hands-free phone conversations, found the effectiveness

of both the tactile and auditory warnings (as measured by change in brake reaction times) was reduced when the driver was engaged in a hands-free cell phone conversation with the auditory warning producing BRTs that were not significantly different than a no-warning condition. However, in that study participants were able to retain visual contact with the road ahead, and dynamic warning signals (i.e. looming) were not used. Similarly, Ahtamad, Spence, Meng, Ho, McNabb & Gray (submitted) found that tactile FCW were rendered less effective when drivers were engaged in a secondary task that involved the sense of touch, namely texting using a smartphone. Thus, the FCW warnings developed to date seem to be least effective in situations they are needed the most i.e., when the driver is distracted.

To date, previous research has not examined whether looming auditory FCW are effective under conditions in which the driver is engaged in an attentionally-demanding secondary task. Therefore, the primary goal of the present study was to compare auditory looming FCW, static auditory (i.e., constant intensity) FCW, and no-warning conditions when drivers were asked to perform both car-following and smartphone texting tasks. As first shown by Gray (2011), it is also possible to speed brake reaction times to auditory looming warnings by using a rate of increase of sound intensity that is faster than the actual closing velocity with the lead vehicle. Therefore, a secondary goal of the present study was to compare these high urgency looming warnings with veridical warnings for which the rate of increase of intensity was matched to the closing velocity. The experiment was designed to test the following predictions:

(i) BRTs will be significantly faster for all warning conditions as compared to the no warning condition

(ii)   BRTs will be significantly faster for the two looming FCW conditions (high urgency and veridical) as compared to the static auditory FCW

(iii)   BRTs will be significantly faster in the high urgency FCW as compared to the veridical FCW

Methods

Participants

Twenty undergraduates from Arizona State University participated for partial fulfillment of an introductory psychology research requirement. All were fluent English speakers with normal or corrected-to-normal vision with a valid driver's license, and were smart phone users. Participants were at least 18 years old. The study protocol was approved by the Institutional Review Board of Arizona State University.

Apparatus

The DS-600c Advanced Research Simulator by DriveSafety™ was used. This simulator is comprised of a 200 degree wraparound display, a full-width automobile cab (a Ford Focus) and a motion platform. Tactile and proprioceptive feedback cues are provided via dynamic torque feedback from the steering wheel and vibration transducers mounted under the driver's seat. The motion platform provides coordinated inertial cues for the onset of longitudinal acceleration and deceleration. The data recording rate is 60 Hz. Figure 1 shows the driving simulator used by Arizona State University.

Warnings

All FCW signals were presented at 2000Hz, and emanated from the car stereo speakers. 2000Hz has been shown to fall within the range of frequencies that produce the

lowest detection thresholds (Goldstein, 2006). Following Gray (2011), warnings were triggered by the algorithm developed by Hirst and Graham (1997):

$$D_w = TTC_{thres} \times \frac{dD}{dt} + \text{SP} \times V_F.$$

In this equation, D_w is the distance from the lead vehicle at which the warning is activated, dD/dt is closure rate (which is determined by the speeds of both vehicles), and V_f is the following vehicle's speed. SP (speed penalty) and TTC_{thres} (time-to-collision threshold) are values that can be set within the system. The essential goal of this algorithm is to warn the driver earlier when he or she is traveling at a higher approach velocity (thus requiring a greater stopping distance). In the present study, the recommended values of 0.4905 for the SP and 3.0 for TTC_{thres} were used (Hirst & Graham, 1997).

For veridical looming warnings, the intensity is increased according to

$$I_w \approx a + kD^{-2},$$

where the value of D at each instant is determined by the driver's speed at the onset of the warning. Values of a = 50 and k = 30,000 were chosen to make the intensity of the warning approximately 60 dB at a simulated distance of 100 m (the largest distance at which drivers receive a warning in the present study) and to ensure that the intensity level is never greater than 85 dB. This 60 dB value was chosen as the minimum warning intensity to ensure that in all cases, the warning signal is considerably greater than the combined intensity of the noise of simulated engine, road, and traffic (approximately 50 dB). The sound level of 10 dB to 15 dB above ambient noise is what is typically

14

recommended for auditory warning signals. The static auditory warning signal had a constant intensity equal to the mean intensity of the looming signals (75dB). In the high urgency looming condition, the drivers were presented with a change in intensity that would correspond to an approach with a TTC value that is 0.5 s less than the actual value (i.e., that would be indicated by the rate of expansion of the lead vehicle).

Procedure

Participants were asked to perform a car following task identical to that used in several previous studies (e.g., Scott & Gray, 2008; Gray, 2011). Specifically, drivers followed a red lead car on a rural, two-lane road and were instructed to drive in their own lane and not pass the lead car. Drivers were instructed to maintain a 2.0s time headway (TH) with the lead car. If the drivers followed too far behind the lead car, the words "Speed Up!" appeared in red text on the driver's display. There was no analogous "Slow Down!" warning so that drivers were free to maintain any TH below 2.0 sec. Drivers were given a 10-min practice drive (with no secondary tasks) to become familiar with the driving simulator and the car following task.

The lead car was programmed to unpredictably (to the driver) change speeds at variable intervals. The lead car travelled between 55 and 65 mph (with an average speed of 60 mph) with its speed determined by a sum of three sinusoids. The lead car was programmed to make 8 unpredictable (to the driver) full stops at a -6 m/s^2. The behavior of the lead car made it very difficult for the driver to predict when the lead car would speed up, slow down, or stop, creating multiple possible rear-end collision situations. Intermittent opposing roadway traffic was included to more closely simulate real-world

rural driving conditions. If the participant contacted the lead vehicle (i.e., crashed) an audio file of a crash sound was presented for a duration of 500 milliseconds and the lead vehicle disappeared from the screen.

Each driver completed 5 driving tracks corresponding to the 5 experimental conditions: (i) a baseline condition in which there are no FCW and the participant did not perform the secondary texting task, (ii) a no warning condition in which there were no FCW and the texting task was added, (iii) a static auditory FCW condition with the texting task, (iv) a veridical looming auditory FCW condition with the texting task, and (v) a high urgency looming auditory FCW condition with the texting task. Following the procedure used in previous research (e.g., Scott & Gray, 2008), condition (i) was always presented first. The order of the rest of the conditions were partially counterbalanced across participants, so that each remaining condition was presented 2nd, 3rd, 4th and 5th an equal number of times.

Each track had 8 unpredictable full stops of the lead car, and required roughly 10 minutes to complete. The location of the stops was randomly varied across tracks. Participants took 5 minute rest breaks between conditions to minimize simulator sickness and fatigue.

After the practice and baseline driving condition participants were given instructions about the texting task, as well as a brief description of the FCW system. For texting tasks, participants used their own smart phone. The task was identical to that used in previous research (McNabb & Gray, 2015). Specifically, participants were told to

imagine that they are selling their own car on Craigslist and a potential buyer was

contacting them to ask questions. The experimenter then sent several questions (e.g.,

"what is the make, model and year of your vehicle?", "how long have you owned it?"

etc.) to which the participant was required to write a text response as they typically would

respond.

After completing the 5 conditions, participants were debriefed and given credit for their

participation.

Data Analysis

Mean brake reactions for the different conditions were first analyzed using a

repeated measures ANOVA. A series of pairwise comparisons, corresponding to the

hypotheses described above, were then made using Bonferroni corrected pairwise t-tests,

$\alpha = 0.008$.

Results

Table 1 shows the mean Brake Reaction Time in the four warning conditions plus the

baseline, just driving condition. All assumptions were met for the repeated measures

ANOVA, which revealed a significant effect of warning condition on participants' mean

Brake Reaction Time, $F(4,76) = 4.9$, $p = 0.001$, $\eta_p^2 = .21$. Paired Samples t-tests (with

corrected p value of 0.007) revealed that brake reactions times were significantly faster

for the two looming FCW as compared to the no-warning condition: High Urgency

Looming FCW, $t(19)=3.9$, $p = 0.001$, and Veridical Looming FCW, $t(19)=3.3$, $p = 0.004$.

There was no significant difference between the Static Auditory FCW and the no-

warning condition, p=.031. There was no significant difference between brake reaction times for the Static FCW and either of the Looming FCW (p's both >0.3). Nor was there a significant difference between the two looming warnings, p=.68. Finally, there was no significant difference between the just-driving baseline condition and the no-warning condition, p=.38

Discussion

The goal of the present study was to investigate the effectiveness of looming auditory FCW under conditions of driver distraction. It was predicted that these warnings would significantly reduce brake reaction times (as compared to no warning) and be more effective than a static constant-intensity auditory FCW. The results partially supported our predictions. Only the two looming FCW conditions resulted in a significant reduction in brake reaction time (by 206 ms on average for the High Urgency Warning and by 182 ms on average for the Verdical warning) as compared to the no warning condition. These values are lower than those reported by Gray (2011) for identical warnings used when there was no secondary task, 320 ms for High Urgency and 240 ms for Veridical, again showing that the addition of distracting secondary tasks reduces FCW effectiveness. Similar to previous research using cell phone conversations as a secondary task (Mohebbi et al., 2009), the static auditory FCW did not result in a significant reduction in brake reaction time in the present study. This was not expected due to the fact that the secondary task in the present study (texting) was primarily manual/tactile and did not involve an auditory component.

18

In the present study, it was also predicted that the High Urgency FCW would result in significantly faster brake reactions times as compared to the Veridical FCW. This prediction was not supported as pairwise conditions revealed no significant difference between any of the warnings. However, it should be noted that while the difference between the warning conditions was not statistically significant, the mean BRT data did trend in the predicted direction, as the High Urgency condition produced the lowest BRTs, followed by the Low Urgency condition, and finally the Constant Tone which had the highest BRTs of the three.

The lack of a significant difference between the three FCW could be due to a number of reasons. While it's possible the study lacked statistical power due to a relatively low sample size, this seems unlikely as the number of participants was similar to that used in previous studies by Gray and colleagues. A second possibility is that the lack of False Alarms (i.e., instances in which the FCW is activated but a collision is not actually imminent) in the present study decreased the relative effectiveness of the looming stimuli. In most previous studies by Gray and colleagues (e.g., Gray, 2011) in 20% of the conditions the FCW was activated at a time to collision of 7 sec, which required no response from the driver. When presented with False Alarms, the participant must decide whether to apply the brakes or ignore the FCW. When looming is present it is informative, as the rate of increase of intensity can be used to aid in the decision about whether to brake or not. However, the lack of false alarms in the present study means no decision was required: the participant applied the brake because it was the correct action to take 100% of the time. Therefore, the value of the looming signal may have been

reduced in the present study. In the real world, the presence of too many False Alarms means the system will be annoying and therefore disabled (or not purchased), or the driver will brake hard whenever the warning is detected, which will cause needless, unexpected and likely dangerous braking, both of which are undesirable behaviors. However, the presence of *some* false alarms requires the driver to make a decision before braking, rather than assume the FCW is an infallible signal to apply the brake. Finally, it may be the case that looming auditory warnings are simply less effective when the driver is distracted (perhaps because some cognitive resources are required to process the looming signal). It is recommended that further studies are conducted to examine the relationship between distraction and the effectiveness of looming FCWs.

There was another unexpected result from the present study that deserves further consideration: the lack of significance in BRT between the just –driving baseline and the no-warning condition in which participants were texting. The lack of significance between these conditions indicates that the secondary task may not have been as distracting as intended. This was most likely due to a practical limitation of the texting task. The driving simulator is housed in a large concrete building. The secondary task involved the experimenter texting back and forth with the participant using their respective cell phones, but signal strength was severely diminished inside the building. While the experimenter never ran out of material to maintain a constant conversation, the weak cell signal meant there was a significant delay in the time it took to send and receive messages. This delay was frequently 30 – 60 seconds for each message, to and from participants. This meant the participant was not constantly or near-constantly

engaged with their phone, as was the intention when the texting task was selected. Participants were therefore not always fully distracted when lead car braking events occurred, across all conditions other than the control condition. It is recommended that future studies re-examine the effect of distraction on FCW performance using a more consistent secondary task (which could be accomplished simply by texting over a strong wireless network).

Practical Implications

The results of this study indicate that looming FCW seem to be an effective mitigation against the serious problem of driver distraction. While the effectiveness of the looming warnings was reduced in the presence of a secondary texting task, the reduction in BRTs in the looming conditions over the no-warning condition remains significant. However, despite the evidence suggesting perceived urgency can be increased by reducing the perceived time to collision (i.e. increasing the rate at which the looming signal intensifies), the presence of a distracting secondary task seems to temper this effect. Manipulating the urgency of looming FCW signals may therefore be a fruitless pursuit if the goal is to further reduce distracted driver BRTs.

Future Research

It is recommended that future research be conducted using similar experiments to further understand the impact of FCW on distracted drivers. Using an eye-tracker to know where the driver is looking when an FCW is presented would clarify the level of

distraction introduced by the texting task. This would help ensure the secondary task is sufficiently distracting. The relationship between driver distraction and FCW effectiveness could be further explored using other secondary tasks that vary attentional demand between modalities (e.g. reading a book or identifying differences between pictures, or finding an object in the console by touch). Finally, future studies could examine other methods of increasing the perceived urgency of looming signals, and their effectiveness in reducing BRTs of distracted drivers.

Table

Condition	Mean Brake Reaction Time (seconds)
Control	1.082
No Warning	1.123
Constant	0.978
Low Urgency	0.941
High Urgency	0.917

Table 1 – Mean BRTs

Figures

Figure 1 - DS-600c Advanced Research Simulator at ASU

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