Warning a Distracted Driver: Smart Phone Applications, Informative Warnings and

Automated Driving Take-Over Requests

by

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ABSTRACT

While various collision warning studies in driving have been conducted, only a handful of studies have investigated the effectiveness of warnings with a distracted driver. Across four experiments, the present study aimed to understand the apparent gap in the literature of distracted drivers and warning effectiveness, specifically by studying various warnings presented to drivers while they were operating a smart phone. Experiment One attempted to understand which smart phone tasks, (text vs image) or (self-paced vs other-paced) are the most distracting to a driver. Experiment Two compared the effectiveness of different smartphone based applications (app's) for mitigating driver distraction. Experiment Three investigated the effects of informative auditory and tactile warnings which were designed to convey directional information to a distracted driver (moving towards or away). Lastly, Experiment Four extended the research into the area of autonomous driving by investigating the effectiveness of different auditory take-over request signals. Novel to both Experiment Three and Four was that the warnings were delivered from the source of the distraction (i.e., by either the sound triggered at the smart phone location or through a vibration given on the wrist of the hand holding the smart phone). This warning placement was an attempt to break the driver's attentional focus on their smart phone and understand how to best re-orient the driver in order to improve the driver's situational awareness (SA). The overall goal was to explore these novel methods of improved SA so drivers may more quickly and appropriately respond to a critical event.

DEDICATION

I dedicate all my hard work to my family. To my parents, especially, that encouraged me from a young age to pursue an education and have been there for all my accomplishments as well as my failures. To my husband, who stood by my side for the past ten years and supported me even in every way imaginable, even when I felt like giving up. Lastly, I dedicate my work to my three young daughters. I hope that one day I may inspire them to work hard and achieve whatever they want in life, even if it seems impossible. Thank you all so much for all you have done for me, I would not have been able to do any of this without you!

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Background

According to the Center of Disease and Control (2015), every day in the United States, nine people are killed and 1,153 people are injured in crashes that involve driver distraction. Distracted driving is defined as the diversion of attention away from the activities critical for safe driving and towards a competing activity (Lee, Regan & Young, 2008; Regan & Strayer, 2014). Ironically, due to a limited capacity of available cognitive resources, distracted drivers are unable to recognize their own driving errors (Kane & Engle, 2003; Watson & Strayer, 2010). Furthermore, drivers self-assessments combined with their driving performance under distraction suggest that drivers tend to be overconfident in their distracted driving ability (Horrey, Lesch & Garabet, 2008; Peters & Peters, 2001). The combination of one's inability to recognize driving errors and one's high confidence of their ability to drive distracted contributes to the large number of distracted drivers on the road. In fact, distracted driving is responsible for up to 30% of total crashes (NHTSA, 2013) although, this estimate may be low due to inaccurate classification of the term distracted driving (Regan & Strayer, 2014). Regardless, Wilson and Stimpson (2010) reported that fatalities involving driver distraction rose 28% since 2005. They proposed that an alarming increase in driving distraction may be attributed to the growing number of drivers using a smart phone, specifically, texting on a smart phone while driving.

Prior to the introduction of cell phones, contributors of distracted driving consisted of tasks such as listening to music, talking with passengers, eating,

daydreaming or in some cases even grooming. Although these various distractions have been shown to have a negative impact on driving performance (Stutts, Feaganes, Rodgman, Hamlett, Reinfurt, Gish & Staplin, 2003), the introduction of the cell phone in 1995, exacerbated distracted driving (Strayer & Johnston, 2001; Horrey &Wickens, 2006; Caird, Willness, Steel & Scialfa, 2008). From 1999- 2008, the percentage of Americans that owned a cell phone jumped from 33 to 91% (Wilson & Stimpson, 2010). Due to this boom in cell phone usage over such a short period of time, extensive research on the impact of cell phone usage on driving performance was imperative. Research suggests that (though not entirely consistent) cell phone use while driving may be more detrimental to driving performance than engaging in a conversation with a passenger, (Drews, Pasupathi & Strayer, 2008; McEvoy, Stevenson & Woodward, 2007), hands-free cell phones provide no benefit over handheld cell phones in preventing distraction (Stayer & Johnston, 200l; Caird et al., 2008) and additionally, drivers talking on a cell phone are more likely to experience inattenional blindness resulting in missed signs, vehicles and even pedestrians (Strayer, Drews & Johnston, 2003; Strayer, Cooper & Drews, 2004; Nasar, Hecht & Wener 2008). In a meta-analysis including 33 driving studies involving cell phone use, a reliable, perhaps underestimated, increase in reaction time (RT) of .25 sec to an event (relative to driving alone baseline conditions) was demonstrated while the control of lateral position remained relatively unaffected (Caird et al., 2008). Driving performance has been shown to be negatively affected when drivers use a cell phone for calling, however, more recent evidence suggest that the distraction problem has been further intensified with the advancement of cell phone technology (e.g., the text message).

Text messaging is both a convenient and popular form of communication that requires little to no effort once practiced. Due to the lack of effort required of a person to text message, drivers are led to believe they can simultaneously and successfully text and drive. Text messaging requires both *manual dexterity* to hold and press the correct keys, and *visual attention* to ensure accurate typing and comprehension. The attentional demands associated with texting and driving have dangerous repercussions for public safety. Over the past decade, numerous driving and texting studies have been conducted to assess the dangers imposed on drivers (Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; Hosking, Young & Regan, 2009; Caird, Johnston, Willness, Asbridge, & Steel 2014; Young, Rudin-Brown, Patten, Ceci & Lenne, 2014). More recently, Caird et al. (2014) conducted a meta-analysis of 28 experimental texting and driving studies. The analysis revealed that both typing and reading text messages while driving produces increased brake reaction times (BRT's), increased collisions, as well as having an adverse effect on the control of lane position, speed and time headway (TH) (i.e., the temporal gap between the driver's vehicle the vehicle they are following). These effects were found when the driver was both typing and reading text messages. A similar pattern of performance degradation was found regardless of what phone interface was used to text message e.g., participants using either a touch-screen interface of the smart phone (lacking tactile feedback) or a hard numeric keypad interface of a standard cell phone (Young et al., 2014). Additionally, although slightly less detrimental to overall driving performance, He, Chaparro, Nguyen, Burge, Crandall, Ni and Cao (2014) recently reported that text messaging using speech-based interfaces also had negative impacts on driving performance. Overall, these studies together provide evidence that

cell phones, and now specifically smart phones, contribute to a major source of distraction behind the wheel.

Smart phones are not just a "phone" but rather a conglomerate of technological devices including a phone, camera, video camera, GPS, computer and entertainment system with over 1 million applications (app's) available for download. With a constant 4G network, drivers can stay connected to social media apps such as Facebook, Instagram, or Twitter all while simultaneously operating a vehicle. As of 2014, over 65% of American's own a smart phone (PRC, 2015) with the majority of them being young adults (18-49 years old). To date, surprisingly, only a handful of studies have looked at the negative effects of smart phone use while driving (Basacik, Reed & Robbins, 2012; Saiprasert, Supakwong, Sangjun & Thajchayapong, 2014). Basacik et al., (2012) asked participants in a driving simulator to either update their Facebook status or use Facebook messenger while driving. Relative to an only driving control condition, Facebook use while operating a vehicle resulted in a significant increase in the RT to target stimuli (by 0.4 s on average) as well as an increase in the number of lane departures, increased variability of TH, and increased amount of time with eyes off the road. Further exploration of the type of task or app platform a driver engages in on their smart phone may reveal the potential for different consequences on distracted drivers.

Unfortunately, in today's technology based society, drivers often use their smart phones to talk, text or connect to social media apps, making distracted driving seemingly inevitable. This issue has become a growing concern for roadway officials, policymakers and automotive industry leaders. Various attempts to mitigate driver

distraction have been demonstrated through instantiating laws that restrict various smart phone uses while driving, e.g. texting, or talking (Sundeen, 2005), developing advanced infotainment systems using voice-based interactive technologies (Cooper, Ingebretsen, & Strayer, 2014), as well as detecting driver distraction or drowsiness with the use of an eye-tracker (Smith, Shah, & Lobo, 2003; Sahayadhas, Sundaraj & Murugappan, 2012). Whereas these attempts to mitigate distracted driving may initially deter drivers, the results may not be a lasting solution (McCartt & Geary, 2004). Progressively, car assistive technologies, while typically integrated in luxury vehicles, have been successful in reducing rear-end or lane changing collisions (Ben-Yaacov, Maltz & Shinar, 2002). These assistive technologies include, but are not limited to, collision avoidance warning systems, lane departure warning systems, blind spot warning systems, and rear back-up camera warnings. Of specific interest to the current review is how effective warning systems are when a driver is facing distraction?

Distraction

In order to have a clear understanding of distraction, both as a cognitive process and as it relates to driving, it is necessary to first recognize the cognitive role of attention. Attention is defined as a cognitive process that allows a person to selectively concentrate or attend to specific information in their environment by allocating resources that are able to process modality specific information (Friedenberg & Silverman, 2011). Metaphorically expressed, Posner, Snyder and Davidson (1980) ascribe one's visual attention to an "attentional spotlight" beam that continually scans the environment and allocates processing power to stimuli within the beam of focus. The precise cognitive

mechanisms and processes performed by the central executive system in maintaining attention and processing visual and cognitive information within one's "spotlight" has been studied and modeled (Kane & Engle, 2002; Baddeley & Hitch, 1974). Results of these studies reveal that attention is necessary for processing information and is an essential component to both working memory and long term memory models, but due to the increased resources required to maintain attention, attention is by nature limited (Kahneman, 1973). Attentional limitations, throughout cognitive psychology research, are exemplified in studies that simulate inattention, divided attention (multi-tasking) as well as mind-wandering tasks (De Pisapia & Braver, 2006; McVay & Kane, 2009). In an applied driving context, the same attentional limitations a driver experiences tend to contribute to overall driver distraction and driver inattention (Strayer & Drews, 2007; Watson & Strayer, 2010). Furthermore, Regan and Strayer (2014) created a driver inattention taxonomy that attempts to clarify the various levels of driver inattention through categorizing various instances of driver distractions. They suggest that distraction is only ONE of the many factors that can contribute to a driver's inattention on the roadway. Consequently, as smart phone and advanced infotainment system technologies progress, drivers become more apt to be distracted visually (i.e., looking away from the roadway) or distracted cognitively (i.e., thinking about a new alert message). As both a driver's visual and cognitive attention demands increase, overall driver distraction and inattention thereby increase. Due to this increase in driver distraction, a model (Distract-R) was developed that accounts for a drivers attentional limitations as they interact with various vehicle interface designs and smart phones. This

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model attempts to analyze and predict a driver's behavior and attention as they interact with current available technologies,

Modeling the Effect of Distraction in Driving

Distract-R was developed by Salvucci, Zuber, Bergovaia and Markley (2005) and is based on the Adaptive Control of Thought cognitive model (ACT-R) to generate driving performance predictions. The Distract-R model is based on a modified version of the ACT-R model, referred to as the ACT-Simple framework, which eliminates the recall and learning aspect of the original ACT-R model. The ACT-Simple framework is based on basic perceptual and cognitive operations required for a driver to perceive and complete a secondary task while driving.

Distract-R consists of five major components that include *interfaces, tasks, drivers, scenarios* and lastly the *results* which are presented in a visual simulation. The *interface* component allows a visual prototype to be created and includes the dial, microphone, and display buttons. For example, each operation on the interface such as speak, press, or listen requires 300ms of processing time. Also, prior to each operation, a 1200ms cognitive operator "think" is added. Furthermore, the prep and execution models are based on assumptions, based on Fitt's Law models; such that, prep time for each task consists of 100ms intervals and execution times for each specific task. The *tasks* component allows the designer to specify the order in which various tasks are to be completed, such as, the process for placing a call or turning a knob on the radio. The *driver* component allows different parameters to be chosen such as, age (young versus old), steering style (how aggressively the driver corrects vehicle to center), and stability

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(based on how unsafe the driver is). Likewise, the *scenario* component allows for environment parameters such as speed of the vehicle and behavior of the lead car. Once all components are satisfied the designer can run the model which outputs *results* in the form of BRT, task time, lane violations data at a rate 1000x's real observed time. This data generated output can be used as a baseline for potential causes of driving errors and then matched and compared to real human data. If this model is match to real observed data then this model has high predictive ability.

While Distract-R is a relevant and efficient way to test new interface designs for drivers, with the introduction of the smart phone, the model itself needed to be updated. In order for the Distract-R model to account for visual and touch interfaces that are consistent with today's smart phones, Lee (2014) extended the Distract-R model. Particularly, one of his major contributions to advance the Distract-R model was introduction of a Saliency Map model. The Saliency Map model fills the visual attention gap by allocating resources associated with task switching and eye-glance behavior while engaging in dual tasks. This updated Distract-R model has been shown to be a better model for making predictions about driving performance based on the smart phone tasks that a driver is using such as playing music, text messaging or navigating an application.

Warnings

Even when a driver's attention is fully focused on the task of driving, drivers have been shown to be prone to perceptual errors and risky behaviors. For example, drivers fully engaged in driving tasks frequently are unable to accurately judge distance or speeds on the roadway (e.g., Denton, 1980; Gray, 2005), have a tendency to follow too

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closely to the car in front of them (vanWinsum & Heino, 1996) and tend to have an over inflated sense of confidence about their driving abilities (Horrey et al., 2008). These types of driving inadequacies, along with the high rate of distracted drivers on the roadway increases one's chances of being involved in an accident.

For many, autonomous vehicles offers a pragmatic solution to this serious problem however, there are still many issues that need to be solved before autonomous vehicles will be commonplace on roadways. These unforeseen issues include, but are not limited to, issues regarding the situation awareness of drivers with regards to the driver taking over control from the automation (e.g., Zeeb, Bucher & Schrauf, 2015), the high costs of purchasing and converting all vehicles to automation, as well as the political issues associated with accident responsibility (Jones, 2002) i.e., the driver or car manufacturer responsible if an accident does occur. For these reasons, warnings offer a more practical approach to mitigate accidents due to the low cost and easier implementation to vehicles.

Driver warnings are intended to improve safety by way of influencing a person's behavior as well as act as a supplement, rather than substitute, for a good design (Salvendy, 2012). Successful warnings need to be able to quickly alert a driver of an event and more importantly orient the driver's attention to the location of the event (Meng & Spence, 2015). Additionally, more advantageous warning systems may be able to convey information about the situation such as the urgency required, or the even the direction in which a driver should expect a potential collision (Gray, Ho & Spence, 2014). Drivers, who are distracted, specifically, by reading or writing text messages may benefit most from warnings of potential collisions.

Various warning modality types e.g., visual, auditory and tactile warnings, have been shown to be effective in both alerting and orienting a driver's attention (Edworthy, 1994; Lee, McGehee, Brown & Reyes, 2002; Gray et al., 2014), refer to (Table 1) for a summary of each warning modalities pros and cons. Visual warnings provide drivers with pertinent information about a specific situation, although due to a driver's overloaded visual demand, visual warnings are typically not as effective when presented in isolation (Lee et al., 2002; Scott & Gray, 2008). Auditory warnings that consist of auditory icons i.e., screeching tires, have been shown to immediately capture attention of external events, especially in cases of high cognitive workload, (Edworthy, 1994; Ho & Spence, 2005) although due to competing sounds, auditory warnings may potentially be masked or conversely, if too loud or unreliable, may become annoying (Bliss & Acton, 2003). Tactile warnings, unlike auditory and visual warnings, can be implemented without substantially increasing a driver's workload, thus improving reaction times to potential collisions (van Erp & van Veen, 2004; Scott & Gray, 2008) although due to the physical contact within a person's peripersonal space as well as being a rarely used warning modality type, tactile warnings in a critical event may actually shock or confuse drivers. Crossmodal warnings, which are combinations of different modality types, such as, audiovisual, audiotactile and visuotactile bimodal warnings, as well as trimodal (auditory + visual + tactile) warnings provide the most promising results. Research has shown bimodal and trimodal warnings that account for spatial location and timing tend to elicit faster BRTs to critical events than the same warnings presented in unimodal fashion (Fitch, Kiefer, Hankey & Kleiner, 2007; Santangelo & Spence, 2007; Lee & Spence, 2008).

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Although data gathered in driving simulators has been shown to be reliable and generalizable to real world driving (Kluver, Herrigel, Henrich, Schoner & Hecht, 2016) warning drivers in the lab may differ from real world situations (Ho, Gray & Spence, 2014). Warning a driver in a lab setting inherently creates a learned response to the warning in which a driver can prepare and expect a critical event therefore improving overall reaction times. In a real driving situation, a driver may rarely encounter warnings leading to longer reaction times in the event of a critical situation. Because of this potentially low occurrence with warnings it is imperative to implement intuitive and easily understood warning systems. Successful warning systems need to account for not only warning modality but location, timing and pertinent information that is specific to a driver's environment and situation. I next review each of the different warning modalities in more detail.

Visual Warnings

Driving is predominantly a visual task requiring a great degree of visual attention. In order for a driver to successfully navigate the roadway, they need to be able to visually identify and process other vehicles, nearby pedestrians, current traffic conditions, as well as interpret traffic signals and warning signs (Strayer et al., 2004). Visual demands placed on the driver are not limited to demands outside of the vehicle, but are also present within the vehicle. In-vehicle visual demands consist of, but are not limited to, visual interfaces including the dashboard, displaying vehicle information such as the speedometer and fuel level, the center console, providing entertainment, navigation and climate control information, as well as rear and side mirrors. Additionally, as technology advances, in-vehicle distractions can come from portable technology sources such as a driver's smart

phone, laptop or tablet. As would be predicted given that driving is primarily a visual

task, visual warnings have been shown to be the least effective modality used to warn a

driver. Scott and Gray (2008) provided clear evidence of this notion by conducting a

study that directly compared auditory, tactile and visual unimodal warnings to a no-

warning condition. Results showed that visual warnings (dashboard flashing lights) were

not as effective in reducing BRT's as the auditory tones alone or tactile vibrations

embedded in the seatbelt.

To circumvent the problem of drivers missing visual warnings, head-up displays

(HUDs) have been developed. HUDs project on the windshield so that warning signals

and other driving information (e.g., speed) is in the driver's field of view when they are

looking at the road. HUDs main goals are to minimize the amount of total time spent

looking away from the roadway and effectively reduce information access costs

associated with task switching (Sojourner & Antin, 1990). While HUDs can be beneficial

to a driver, the HUDs overlay of information may obstruct or clutter the driver's field of

view, and in an unexpected situation may hinder any benefits (Horrey, Wickens &

Alexander, 2003). HUDs as well as in-dashboard displays have also used icons to warn

drivers symbolically (e.g., an image of two cars colliding) or via text messages (e.g., the

word "Stop!"), (Edworthy, Stanton & Hellier, 1995). Although fairly limited, previous

research on visual warnings in this context has demonstrated similar comprehension rates

for both visual symbols and textual words (Hawkings, Womack & Maunce, 1993;

Hanowski & Kantowitz, 1997). Specifically, Hanowski & Kantowitz, (1997) found that

overall, participants had better comprehension for shorter messages and symbols

categorized as "very high comprehension" and younger drivers, as compared to older drivers, were more accurate in interpreting a message's meaning.

Visual warning comprehension is vital in order to effectively assist drivers in avoiding hazardous events. Visual warnings may not be detectable or discernible in a moment of urgency due to the high visual workload in driving. For this reason, visual warning research has looked at the impact of multiple sources of visual warnings as well as combining visual warnings with other warning types (Selcon, Taylor & McKenna, 1995; Lee et al., 2002). For instance, Selcon et al. (1995) found redundancy of warnings, visual verbal + visual spatial e.g., a written word on the correct side of a display, was more beneficial in reducing response time to an event than a single source e.g., written word in the center of the display. Similarly, rear end collision warning studies demonstrated success in implementing a symbolic visual warning (e.g., a vehicle colliding with the rear of another vehicle), with an auditory warning tone (Kiefer, 2000; Lee et al., 2002). Furthermore, although visual warnings can provide drivers with pertinent information about a specific situation, visual warnings unaccompanied by another modality may not be sufficient to successfully warn drivers.

Auditory Warnings

Auditory warnings, in a driving context, may be a beneficial modality to capture a driver's attention and provide critical information of external events (Ho & Spence, 2005). Auditory warnings can be detected and identified quickly resulting in decreased reaction times to an external event, especially in cases of high cognitive workload (Edworthy, 1994; Belz, Robinson & Casali, 1999; Graham, 1999). Auditory warnings in general need to be loud enough for people to hear them, especially drivers who with

hearing limitations and those in cars with competing auditory stimuli (e.g., music, passengers, traffic noise, or cell phone conversations). However, the audio warnings should not be so loud as to trigger a startle response (Patterson, 1989; Edworthy, 1994).

Auditory warnings are either verbal or nonverbal and each type has advantages as well as limitations. Verbal warnings (e.g., speech) covey critical information to a driver in stressful situations though, depending on the length of the verbal warning or the competing auditory sounds, verbal warnings may take longer to fully process or could even be misunderstood (Aldrich & Parkin, 1989). Nonverbal warnings can be further broken into synthetic/abstract sounds (e.g., tones or beeps) that represent a particular meaning, or representational *auditory icons/earcons* (e.g., car horn or skidding tire sound) that represent a naturally occurring sound (Graham, 1999) or looming warnings that convey critical information through increasing or decreasing the intensity of a sound (Gray, 2011).

Abstract auditory warnings are easily learned and in certain situations and have been shown to improve reaction times to an external event (Graham, 1999; Mohebbi Gray & Tan, 2009). However, when abstract warnings are presented in new situations they may be indistinguishable or confusing (Belz et al., 1999). Similarly, auditory icons have been shown to be effective in alerting a driver to an external event (Ho & Spence, 2005). However, auditory icon warnings have the potential to be confused with naturally occurring stimuli and have been shown to elicit inappropriate responses in some situations (Gray, 2011). An alternative which seems to capture the benefits of both abstract and auditory icon warnings are informative warnings that provide an optimal solution in warning a driver about an impeding collision. For example, looming auditory

warnings which use an abstract signal that increases in loudness at a rate that matches the

closing velocity have been shown to result in speeded reaction times and appropriate

responses (Gray, 2011). However, though auditory warnings have shown success in

alerting and informing a driver of a critical situation, auditory warnings alone may not be

the most beneficial modality.

Tactile Warnings

Tactile warnings are used to alert someone of a potentially dangerous situation

through the sense of touch. Tactile warnings, with respect to warning drivers, have

included vibrations via tactors or applied force feedback systems that have been delivered

to the driver through the gas pedal, steering wheel, driver's seat, seatbelt, or even on the

body such as, a driver's thighs, waist or back (Ho, Gray & Spence, 2014). Overall, tactile

warnings can be broken down into three types, basic (non-directional), directional and

meaningful signals. Basic (non-directional) tactile warnings are the most simple and

consist of vibrational pulses that do not provide the driver any additional information

about the external collision itself (e.g., Scott & Gray, 2008). Directional tactile warnings

stimulate different parts of the driver's body to signal events in different locations. For

example, torso/back stimulation to stimulate front-end/rear-end collision (Ho, Reed &

Spence, 2006), left/right leg stimulation to signal lane departures to each side (Navarro,

Mars & Hoc, 2007) or warnings which attempt direct attention to multiple spatial

locations (Gray et al., 2014) e.g., stimulation to left shoulder to get driver to look up and

to the left. Lastly, meaningful tactile looming warnings can convey proximity

information about the driving environment through manipulation of the dynamic qualities

of the vibrations (i.e., signals toward-head or toward-torso and rate of apparent tactile

motion, Gray et al., 2014; Ho et al., 2014). Research has investigated whether there is an intuitive natural mapping to tactile warnings and if meaning can be conveyed by a tactile warning through manipulating perceived urgency (e.g., changing the intensity, varying the inter-pulse interval or simulating motion (Ho, et al., 2006; Lee & Spence, 2008). Ho et al.,(2014) found that the use of three tactors was beneficial in decreasing BRTs as compared to only using one or two tactors, although the direction of the three tactors, upwards, downwards or randomized did not convey any additional benefits. Conversely, in a separate study, when the tactors displayed an upward and towards motion that was dependent on the closing velocity to the lead car, BRTs were significantly reduced (Gray, et al., 2014).

The success of tactile warnings are based on the "tap on shoulder" principle, to which stimulating an individual's personal space can lead to immediate identification of an event. Also, tactile warnings alert a driver privately, in a non-obtrusive manner (i.e., passengers are unaware) which may be a contributing factor to why participants generally rate them as being less annoying than other warning types (Fitch et al., 2007). Another benefit to tactile warnings is that the tactile sense is the most accessible and unburdened sensory modality available during driving. Unlike auditory and visual warnings, it has been proposed that because the sense of touch is relatively less involved in the task of driving, tactile warnings can be implemented without substantially increasing a driver's workload. Evidence in support of this idea comes from studies that have shown that as compared to other warning types, tactile warnings elicit faster reaction times to a potential collision (van Erp & van Veen, 2004; Fitch et al., 2007; Scott & Gray, 2008; Meng & Spence, 2015).

Equally, there are some drawbacks in an applied setting to using only tactile warnings. Whereas the "tap on the shoulder" principle is beneficial in creating an immediate response, the response is not sensitive to spatial localization as an auditory or visual warning. For example, when someone reaches over and taps a person on the wrong side of the shoulder and then quickly moves out of the way, the person is "tricked" into looking in the wrong direction. With regards to tactile warnings, if a tactile warning is given to the waist of a driver in a critical situation a driver may be more likely to look down at their waist rather than to an event outside of the vehicle. Secondly, tactile warnings depend on stimulating a person's body and may not be detected by the driver if heavy clothes are worn (i.e., jeans and/or a coat in the winter), if both hands are not placed on the steering wheel, or if a seatbelt is not worn. Lastly, due to the low occurrence of potential collisions encountered by the driver, a vibrotactile warning presented to a driver in an emergency situation may ironically result in confusion and longer reaction times (Ho et al., 2014). Although tactile warnings can quickly alert a driver, a combination of warning modalities may be the best option to best warn a driver.

Crossmodal Warnings

As discussed previously, warning drivers via unimodal presentation (e.g., auditory, visual or tactile modalities have been shown to reduce response time in driving situations (e.g., a potential lane departure or rear-end collision). Again, though reliable, these findings may not be suitable in an applied driving context. For example, if the modality used to warn a driver is masked, as in the case of the sounds from a noisy car masking an auditory warning or the vibrations from a bumpy dirt road masking a tactile warning, a driver might better benefit from a bimodal or even trimodal warning signals

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(Lee & Spence, 2008; Ho, Santangelo & Spence, 2009; see Ho & Spence, 2008, for a review).

Crossmodal links may exist between sensory information processing pathways (Holmes & Spence, 2005) such that, the use of bimodal audiovisual, audiotactile and visuotactile warnings, as well as trimodal warnings (auditory + visual + tactile), have been shown to elicit faster BRTs to critical events (Fitch et al., 2007; Santangelo & Spence, 2007; Lee & Spence, 2008). Specifically, auditory and visual channels have been shown to share attention pathways, resulting in no attention task switching costs (van Erp & van Veen, 2004; Ho & Spence, 2005) and complementary audio-visual warnings, rather than redundant warnings, can be more effective at reducing BRTs to a potential collision (Fricke & Thuring, 2009). More recently, with the introduction of tactile displays, studies combining tactile with auditory or with visual warnings have reduced BRTs. For instance, Ho, Reed and Spence (2007) found that drivers had faster brake responses to a potential rear-end collision event when a bimodal audiotactile warning (a 500 sec car horn and 500 sec vibration to the participant's waist) was used as compared to only using one modality warning type. Similarly, visuotactile displays increased reaction time to navigation messages by 15% as compared to reaction times in a visual only condition (van Erp and van Veen, 2004). Furthermore, an added benefit to using all three modalities was demonstrated by Lee and Spence (2008). In this study, participants in a simulator were asked to operate a touch-screen device consisting of both visual and tactile information as well as being warned via an auditory tone, while simultaneously asked to avoid potential collisions with the lead car. Findings demonstrated participants

had faster responses to the lead car when the trimodal warnings were presented from the same location, as compared to bimodal or unimodal warning conditions.

Although crossmodal warnings may benefit drivers of potential collisions, precautions in their design need to be taken into account. Recent data suggest that in order for crossmodal warnings to be successful, they need to be congruent in both spatial location and time, and this congruency may be more necessary for audiovisual warnings as opposed to audiotactile warnings. This theory is based on the concept that audiotactile warnings may be inherently nonspatial therefore not requiring congruency in spatial location (Ho et al., 2009). With that being said, Ho et al. (2009) found that bimodal audiotactile warnings presented to participants left or right thigh and corresponding ear were actually more effective in capturing spatial attention suggesting that congruency for audiotactile warnings is indeed important. Overall, regardless of what warnings modalities are to be used especially in the context of warning a driver, it is vital the modality of the warning and modality combinations are appropriate to the situation.

Other Warning Considerations

Successful warning systems not only need to be presented in the appropriate warning modality but they also should be sensitive to timing, location, as well as what information they convey to a driver. In order for a warning to be most effective it should be presented in the correct sensory modality and if an additional modality is to be used they should be complementary and additive, not just redundant (Spence & Driver, 1997; Ho & Spence, 2005). Timing of the warnings themselves is critical especially if simultaneous warnings are to be given, as well as considerations as to how far in advance

the warnings are given (Lee et al., 2002; Spence & Squire, 2003; Straughn, et al., 2009).

Ideally, the warning should be spatially congruent with the other warnings as well as

congruent with the critical event (Ho & Spence, 2008). Lastly, if the warnings are to be

informative, attention as to what information should be conveyed to a driver is essential.

Information that may be conveyed includes verbal messages, as well information

containing the urgency of a situation or the direction in which a potential collision may

occur. This can be achieved by manipulating the rate of change or simulated motion

direction of a warning signal. I next review timing, location and information of the

warnings in more detail.

Timing

Warnings about a critical event, particularly one as common a potential rear-end

collision, are extremely time sensitive (Lee et al., 2002; Abe & Richardson, 2006; Ferris,

Penfold, Hameed & Sarter, 2006; Straughn, et al., 2009). A poorly timed warning could

not only annoy or disturb a driver it could counteract any benefits of the warning

(Parasuraman Hancock & Olofinboba, 1997). For instance, warnings that are presented

too far in advance may create a false alarm situation leading to alarm mistrust (Bliss &

Acton, 2003) or the driver may forget the warning altogether (Hanowski &

Kantowitz,1997). Conversely, warnings that are presented too late may not give a driver

enough time to appropriately interpret or react to the situation, most likely resulting in an

abrupt, ingrained, and possibly incorrect response such as slamming on the brakes or

violently turning the steering wheel (Graham, 1999).

For these reasons, research has been conducted to identify the optimal warning

time relative to the collision event. Results of rear-end collision warning studies have

shown that a fixed time to collision (TTC) warning of two to five seconds prior to a potential collision may be advantageous (Maretzke & Jacob, 1992) although, due to individual differences in drivers, specifically in their driving speeds, a fixed TTC may not be as effective as an algorithm based warning that takes into account both TTC and the drivers speed in relation to a lead car (Burgett, Carter, Miller, Najm & Smith, 1998). Generally speaking, potential collision warnings that are presented earlier rather than later tend assist drivers the most (Lee et al., 2002; Abe & Richardson, 2006; Straughn et al., 2009). In a rear-end collision warning simulator study performed by Lee et al. (2002) it was found that compared to the no warning condition an early warning helped prevent 80.7% of collisions. Similarly, Abe and Richardson (2006) found that early warnings, especially in the case of short time headways, reduced driver BRTs as well as increased drivers trust with the warning system. Furthermore, Straughn et al., (2009) showed a benefit to early pedestrian collision warnings, by giving an early (4 second TTC) as opposed to giving a late (2 second TTC). These findings suggest that the early warning signals may have allowed drivers to shift their attention to the critical event allowing for a driver to evaluate and more appropriately respond to the situation. These findings together indicate that in order for a driver to more appropriately respond to a critical situation an early warning may be more suitable.

In conjunction to how far in advance a warning is given, if multiple warnings are to be given, the specific timing of each warning modality source needs to be considered. In warning system research, optimal spacing of multimodal warning signals has been studied in an attempt to create the most efficient warning systems. Visual, auditory and tactile sensory information sources travel at different rates and have different processing

times in the human perceptual system thus leading to slight perceived temporal offsets when they are physically presented at the same time (Stein & Meredith, 1993). For example, the neural processing of auditory information is faster than the neural processing of visual information because the latter involves a chemical process (Dixon & Splitz, 1980). Also, tactile information given to the fingertips is processed quicker than tactile information given to the torso due to more receptors located in a person's fingertips (Stein & Meredith, 1993). Although these processing differences between modalities exist, people are generally unaware of the differences due to our brains ability to integrate information from the different senses. This smooth integration allows the perception of synchrony of information presented in different modalities (Spence & Squire, 2003). In order to achieve a warning system that appears synchronous, a slight delay (100ms or more) in the presentation of each warning modality, as well as the appropriate presentation order of each modality i.e., the visual warning precedes the auditory warning, has been shown to be necessary. Conversely, recent work in an applied driving context, demonstrates that surprisingly synchronous warnings may be more optimal. Ho, Gray and Spence (2014) found evidence that synchronous audiovisual cues facilitated head turning and steering wheel turn response times, whereas asynchronous audiovisual cues did not. The explanation for these inconsistent findings may be that the mechanism responsible for an orienting a response rather than an alert response is more sensitive to temporal synchrony. These findings highlight why it is imperative that designers of multimodal waring systems consider both accurate timing of the warning as well as timing of each warning modality.

Location

An effective warning may alert a driver, but a more effective warning can both alert AND orient a driver's spatial attention to the correct location (Ho & Spence, 2008 for a review). In order for a warning to be most advantageous to a driver it is necessary that the warning signal be both spatially congruent with the critical driving event (e.g., the location of the object that will hit) and spatially congruent with additional warning modality types (Ho & Spence, 2008). Spatially congruent warnings that have been shown to effectively orient a driver's spatial attention to a specific location have consisted of flashing lights displayed in a critical direction, spatially predictive auditory tones i.e., a tone given to the left speaker indicative of the left side of a vehicle, as well as tactile stimulations administered to various locations on a drivers body i.e., torso/back to indicate a front-end/rear-end collision (Ho & Spence, 2005; Ho et al., 2006; Scott & Gray, 2008, Ho et al., 2009).

Although spatially congruent warnings have been shown to be successful in alerting and orienting a driver, the reliability of the signal to indicate the location of the event may be equally as important. Ho and Spence (2005) investigated this theory by having participants in a driving simulator complete a cognitively demanding rapid serial visual presentation (RSVP) task while responding to a reliable or unreliable auditory warning indicative of either a front-end or rear-end collision. The spatial congruency of the auditory warnings was manipulated as well as the reliability of the warning in correctly indicating the direction of the critical event. Findings showed that spatial congruency of the auditory warnings contributed to improved response times to a critical event but equally important were that response times improved as the reliability of the

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warnings increased from 50% to 80%. These results are consistent with previous findings

on warning reliability, such that, as the reliability of a cue increases to 100% valid,

reaction times tend to improve (Bliss & Acton, 2003).

As previously discussed, under conditions of high driver workload unimodal

warnings are not as effective as multimodal warnings. With that being said, more

research is needed on multimodal warning systems. Overall findings on multimodal

warnings propose that, in order for the warnings to be valuable to a driver, each warning

modality should be delivered from a congruent spatial location (Ho & Spence, 2005; Ho

et al., 2007; Fitch et al., 2007; Lee & Spence, 2008; Ho et al., 2009). In fact, many

studies have demonstrated that driver's reaction times to a critical event are facilitated by

delivering the warnings from spatially congruent locations, although studies have rarely

considered the effect of warning a driver from spatially incongruent locations. To assess

the impact of warning signals delivered from incongruent spatial locations, Ho et al.,

(2009) designed and conducted two experiments that incorporated either unimodal and

bimodal audiotactile warnings that were spatially congruent (spatial tactile vibration and

auditory cue) or spatially incongruent (central tactile vibration with spatial auditory cue).

Results revealed that bimodal audiotactile cues presented from similar spatial directions

were more effective than the use of solely unimodal cues. Additionally, it was observed

that bimodal cues, with no regards to spatial direction, provided no additional benefit to a

driver, suggesting that incongruent bimodal cues may actually eliminate any observed

facilitation effects. Ultimately, research findings indicate that when designing a vehicle

warning system it is essential that the warning signal be spatially congruent to the critical

event as well as reliable and if multimodal warnings are to be used, it is imperative that they originate from the same spatial location.

Information Conveyed

Vehicle warning systems have been shown to successfully alert a driver about a critical event as well as orient a driver to the location of the event. Of present interest is the warning systems ability to convey pertinent information about an event itself, such as urgency or direction of a potential collision. Research addressing this specific topic has attempted to convey meaning into the warning systems by manipulating various features of the warning signal such as the intensity, frequency, and the rate of change of intensity (Gray, 2011; Gray et al., 2013; Ho et al., 2014). For instance, auditory warnings have been shown to convey urgency to a driver by manipulating the sounds intensity or by manipulating the rate of change of intensity with respect to the TTC. Gray (2011) revealed that when the sound intensity of an auditory warning increased as a function of the decreased distance between a driver's vehicle and a lead car (looming auditory warning), the driver's reaction time to a collision was improved as compared to other auditory warnings that varied in only their speed or frequency. Additional results observed that looming auditory warnings were so naturally informative that by altering the rate of change of intensity to the TTC, drivers could be influenced to respond early or late to an impending collision. These results, taken together, suggest that looming auditory warnings may be the most effective way to inform drivers of a potential collision due to the natural mapping of the looming auditory signal to real-world events.

Building on the findings of the effectiveness of informative auditory warnings, Ho et al., (2014) recently extended this idea into the vibrotactile warning domain. However,

results showed that vibrotactile looming signal (i.e., a vibration from a single tactor that increased in intensity as a function of the distance to the lead vehicle) alone did not provide participants any advantage over other non-looming vibrotactile signals (e.g., a constant intensity vibration). Interestingly, whereas looming virbotactile warnings themselves did not improve a driver's response to potential collision, it was found that simulating motion either upwards, downwards or randomized with three tactors, across the driver's body did in fact improve performance. Because the randomized tactor simulation, which lacked directional information, improved performance to a similar degree as the directional tactile signal, the findings of this study suggested that vibrotactile dynamic warnings could not be used to convey meaning to a driver.

To further explore this question, Gray et al. (2014), had participants in a driving simulator wear three dynamic tactors that delivered a vibrotactile signal that was dependent on the closing velocity (CV) with the lead car and provided upward or downward motion information. Results of this study concluded that BRTs were significantly improved when the vibrotactile warnings were CV-linked and even more facilitated reaction times were shown when the vibrotactile cues were presented in an upwards motion, moving towards the drivers head. Overall, these applied driving studies provide evidence that information can indeed be conveyed to a driver through the use of auditory looming sounds or dynamic collision linked vibrotactile cues.

Distraction and Warnings

Despite the abundant research showing the effectiveness of collision warnings (reviewed above), one question that has not be studied in detail is whether these warnings will remain effective under conditions of high driver distraction. Generally speaking, auditory warnings can be successful in reducing reaction times to a potential collision, though this effectiveness begins to diminish when a driver is distracted. Mohebbi et al. (2009) exposed this limitation by having drivers talk on a hands-free cell phone while receiving either auditory or tactile warnings of an impending rear-end collision. Results indicated that the task of talking on a cell phone rendered the auditory collision warning completely ineffective (i.e., it no longer reduced BRT as compared to a no warning condition) and reduced the effectiveness of the tactile collision warning (i.e., although it resulted in significantly lower BRTs as compared no warning, this difference was reduced). The authors proposed that this difference between modalities is that talking on cell phone increases auditory attentional demands without effecting tactile attention. In a follow up study, Ahtamad, Spence, Meng, Ho, McNabb & Gray, (*under review*), recently investigated the effect of a task relying primarily on the sense of touch (texting with a smart phone) on warning effectiveness. Results revealed that texting rendered vibrotactile warnings (either abstract or informative) ineffective (i.e., no reduction in BRT relative to a no warning condition). Although various real-life scenarios may mitigate the success of a warning system, such as loud music masking an auditory warning or a bumpy road masking a vibrotactile warning, these few distraction and warning studies highlight that warning a driver that is distracted by their smart phone may consequently render any warning virtually ineffective. Due to these unsettling findings, it is essential to investigate

further what warnings or combinations of warnings, if any, might successfully alert a driver that is indeed engaged in smart phone operations.

Distraction and Autonomous Vehicles

Autonomous vehicles, while an exciting design and obvious solution for many of today's roadway problems associated with distracted drivers, do not come without problems of their own. For instance, the most dangerous circumstance, a driver who is not in full control of the vehicle physically and has not been monitoring the driving situation cognitively receives a request from the vehicle to take immediate control to a time sensitive or critical event. Due to the likely opportunity for some type of control failure in autonomous vehicles, research in this area has focused on understanding what level of situation awareness may be most effective in assisting the driver to safely regain control of the vehicle (Louw, Merat & Jamson, 2014; Louw & Merat, 2014). Overall findings have demonstrated that drivers should be encouraged to remain driving "in the loop" both cognitively and physically (Louw, et al., 2014) because drivers that take advantage of fully automated systems (i.e., attending to their iPad) tend to react slower and more aggressively to critical events, thus increasing their risk for potential collisions (Merat & Jamson, 2014). While the findings suggest that the best case scenario in autonomous driving is that drivers remain as supervisory agents, these findings do not seem achievable in an applied setting. Specifically, because supervisory drivers that are physically and cognitively in the "loop" appear to defeat the main intent of an automated vehicle. For this exact reason, it is necessary to reveal the most effective way to break a driver's attention and redirect them to the "loop" (i.e., roadway) as quickly as possible

when they have been acting as a supervisory agent. The most favorable solution to this problem would be to develop a warning system that is effective enough to both alert a driver of a critical event but additionally provide enough information to the driver that they can properly assess the situation and appropriately react.

Summary

The seemingly inevitable fact that a large proportion of drivers will use a smart phone while driving creates immense problems for public safety. Of the various attempts to mitigate this serious problems, warnings, such as collision avoidance warning systems, lane departure warning systems, blind spot warning systems, and rear back-up camera warnings have aimed to provide an inexpensive method to reduce accidents, as well as diminish fatalities and high financial losses associated with preventable accidents. Though warnings can be easily added into most vehicles, their effectiveness has shown to be highly sensitive to the design parameters. First, it is essential that the correct warning modality types are used and if crossmodal warnings are used the signals for each modality is properly combined. Second, it is imperative that the location, timing, and information to be conveyed by the warning are considered. Additionally, due to most driver's lack of experience with warning systems (and likely reluctance to go through a training period before driving a new car off the lot), systems need to be intuitive and quickly understood in order to ensure the driver makes an appropriate response to a critical situation.

Even if all of these requirements have been successfully met and the warning system has been implemented, a major area of concern is how effective a warning may be

when a driver is distracted especially given that the bulk of research in this area used low workload conditions. The limited amount of research that has examined warning effectiveness when a driver is distracted, being a secondary task, suggests that warnings may not provide any benefit in reducing potential collisions in such situations. That being said, it is vital that future research be conducted that not only looks at the use of warnings on distracted drivers but research that is aimed to discover the best warning implementations systems to quickly disengage a driver from specific sources of distraction, (i.e., their smart phones). Equally, as autonomous vehicles become more commonplace, distraction research needs to be focused on what warning modalities or combinations of warning modalities can quickly alert and re-orient the attention of a distracted driver in the event of a critical incident. These as well as other research questions need to be addressed due to a heightened number of distracted drivers on the public roadways, consequently, jeopardizing everyone's safety.

Current Study

  While various collision warning studies in driving have been conducted, (Table 1) only a handful of studies have incorporated the effectiveness of warnings with a distracted driver. Interestingly, to date, only one study has researched the effectiveness of warnings with a driver that is distracted by a smart phone. The present study (across four experiments) aims to understand the apparent gap in the literature of distracted drivers and warning effectiveness, specifically by studying various warnings on drivers while they are operating a smart phone.

Table 1. Driver Warning Modality Research Summary

Modality Type	Pros	Cons
Visual	• Easily implemented • Projected in driver line of sight	• Driving requires too much visual competition • Images may be misinterpreted
Auditory	• Quick attention capture • Effective in alerting driver to an external event	• May be masked • May be result in inappropriate response (i.e., braking) • May be annoying
Tactile	• Minimal workload on driver • Typically rated as less annoying	• May cause confusion, shock due if rarely experienced • May be masked
Crossmodal	• Due to multiple sources, more likely to not be masked • Visual & auditory pathways may have no task-switching costs	• Need to be congruent in location • Need to be congruent in timing

CHAPTER 2

EXPERIMENT ONE: Staying Connected on the Road: A Comparison of Different

Types of Smart Phone Use in a Driving Simulator

Abstract

Previous research on smart phone use while driving has primarily focused on phone calls and texting. Drivers are now increasingly using their phone for other activities during driving, in particular social media, which have different cognitive demands. The present study compared the effects of four different smart phone tasks on car-following performance in a driving simulator. Phone tasks were chosen that vary across two factors: interaction medium (text vs image) and task pacing (self-paced vs experimenter-paced) and were as follows: Text messaging with the experimenter (text/other-paced), reading Facebook posts (text/ self-paced), exchanging photos with the experimenter via Snapchat (image, experimenter -paced), and viewing updates on Instagram (image, experimenter -paced). Drivers also performed a driving only baseline. Brake reaction times (BRTs) were significantly greater in the text-based conditions (Mean = 1.16 s) as compared to both the image-based conditions (Mean = 0.92 s) and the baseline (0.88 s). There was no significant difference between BRTs in the image-based and baseline conditions and there was no significant effect of task-pacing. Similar results were obtained for Time Headway variability. These results are consistent with the picture superiority effect found in memory research and suggest that image-based interfaces could provide safer ways to "stay connected" while driving than text-based interfaces.

Background

Although we still call them "smart phones," the devices most people carry today serve as a conglomerate of technological devices including a phone, camera, video camera, GPS, computer and entertainment system with over 1 million applications (app's) available for download. Having such power in the palm of our hand creates a potentially major source of distraction when we are commuting and indeed it is well documented that the use of smart phones can be a cause of accidents for pedestrians (e.g., Hatfield & Murphy, 2007) cyclists (e.g., Ahlstrom & Kircher, Thoslund & Adell, 2015), and, the interest of the present study, drivers (reviewed in Caird et al., 2008; Caird et al., 2014).

To date, the vast majority of studies on the effects of smart phone use in driving have focused on two device functions: talking on the phone and texting/instant messaging. Research on cell phone use has consistently demonstrated that conversations while driving significantly increase a driver's reaction time (RT) to events and stimuli—a meta-analysis of 33 studies conducted by Caird and colleagues found a mean increase in RT of .25 s (Caird et al., 2008). As the authors acknowledge, this is likely an underestimate of the true effect because in most experiments the attentional demands are unlike those in real driving e.g., drivers are abnormally vigilant to the driving task because they are being observed (Ho et al., 2014). A key finding of these studies is that the increase in RT is similar for handheld and hands-free phones. This indicates that the detrimental effects of talking on a cell phone while driving are due to a reduction in the attentional and/or working memory resources devoted to driving rather than the commonly held belief that the impairments are solely due to the physical demands of

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holding the phone and taking one's eyes of the road to dial/receive a call. It should be noted, however, recent naturalistic driving studies have provided data inconsistent with these findings i.e., no significant increase in the likelihood of an accident when using a hands-free cell phone while driving (e.g., Fitch, Soccolich, Guo, McClafferty, Fang & Olson, 2013). Although some studies have reported other (perhaps compensatory) effects talking on a cell phone while driving on driver behavior including increased time headway (TH), decreased speed and poorer lateral control, these effects have not been found consistently (Caird et al., 2014).

Turning to texting, studies have reported similar (and often greater) detrimental effects on driving performance. In a meta-analysis of 28 studies conducted by Caird and colleagues (Caird et al., 2014), it was found that texting while driving produces significantly longer brake RTs (BRT), increased collisions, as well as adversely affecting lane position, speed and headway regulation. These effects were found both when the driver was typing and reading text messages. A similar pattern of performance degradation was also found regardless of what phone interface was used to text message e.g., participants using either a touch-screen interface (lacking tactile feedback) or a hard numeric keypad interface (Young, Rudin-Brown, Patten, Cici, & Lenne, 2014). Additionally, although slightly less detrimental to overall driving performance, He et al. recently reported that even text messaging via speech-based interfaces negatively impacted driving performance in simulator (He et al., 2014)

In addition to the texting and talking studies, Kujala and colleagues have investigated the effects of using a music player and a navigation device on a smart phone during driving (Kujala, 2013; Kujala & Saarilumo, 2011). Both of these tasks were found

to significantly impair driving performance in a simulator (e.g., increases the number of lane excursions) with the effect magnitude depending on the design of the interface (e.g., kinetic vs. button scrolling, grid vs list menu).

As discussed above, smart devices now have many other uses including the main interest of the present study: social networking (e.g., Facebook, Twitter, etc). To date, we have been only able to find one study that has specifically focused on the effect of social networking on driving other than solely texting or instant messaging. Basacik et al. investigated the effect of Facebook use on driving performance in a simulator (Basacik et al., 2012). In this study, participants were asked to send and receive messages through Facebook's instant messaging system and update their status. Relative to an only driving control condition, Facebook use resulted in an significant increase in the RT to target stimuli (by 0.4 s on average), increase in the number of lane departures, increased variability of TH, and increased amount of time with eyes off the road. Similar effects were observed for both instant messaging and status updating.

The limited amount of research on the effects of social networking on driving represents an important gap in the literature for two reasons. First, the frequency of this behavior is continuing to increase particularly in younger drivers. A State Farm survey conducted in 2014 (State Farm, 2015) reported that between the years 2009–2014 the number of drivers reading social media networks while driving increased from 21 to 41% for the ages 18 to 29 and increased from 9 to 20% across drivers of all ages. Over the same time period, talking on a hand-held phone while driving has decreased. The second important issue is that modern social networking apps include a variety of different methods of interaction that go beyond reading text on a screen and writing text messages.

These include exchanging photos (e.g., Snapchat, Instagram) and videos (e.g., YouTube, Vine) which have been shown to have different memory and attentional demands than text (e.g., Weldon, Roediger, & Challis, 1989). For example, there is a well-documented "picture superiority effect" in that memory for images is better than memory for text Paivio & Csapo, 1973). Finally, unlike the cell phone use and texting tasks used in most previous driving studies which are typically initiated by someone else, many social networking apps can be either self or other paced (e.g., Facebook). Previous research has shown that for self-paced secondary tasks drivers may adapt their driving behaviors and engage in secondary tasks when a situation is less demanding such as when they are stopped at a red light or before entering "danger zones" (Metz, Landau, & Just, 2014; Liang, Horrey & Hoffman, 2014) however these findings have not be entirely consistent and more research is needed to determine the differences between self and other-paced secondary tasks in driving. For these reasons the effects of social networking on driving may not be directly predictable from the research on cell phone use and texting described above.

The aim of the present study was to compare the effects of four different smart phone tasks on driving performance. In particular, we were interested in two factors: interaction medium (text vs image) and interaction type (self-paced vs experimenter-paced). To achieve this end, drivers were asked to perform four different smart phone tasks (in separate blocks) while also performing a car-following task in a driving simulator: Text messaging with the experimenter (text/experimenter-paced), reading Facebook posts (text/self-paced), exchanging photos with the experimenter via Snapchat (image, experimenter-paced), and viewing updates on Instagram (image, self-paced). As

described below, these tasks were designed so that they required a comparable amount of manual interaction and off-road glances. Drivers also performed a baseline driving condition and their performance on the secondary tasks was assessed via post-driving recognition tests. The experiment was designed to test the following predictions:

1. Driving performance would be impaired (e.g., significantly higher BRTs, larger variance in TH) in all four smart phone conditions in comparison to just driving

2. Impairments in driving performance would be significantly greater for the text-based tasks (texting and Facebook) as compared to the image based tasks (Snapchat and Instagram) due to the higher processing demands required for the former (Paivo & Csapo, 1973).

3. Impairments in driving performance would be significantly less for the self-paced tasks (Facebook and Instagram) as compared to the experimenter-paced tasks (texting, Snapchat) because, as found in previous studies, drivers would adapt their behavior to perform the self-paced tasks in less dangerous intervals

Method

Participants

Eighteen undergraduates from Arizona State University participated for partial fulfillment of an introductory psychology research requirement. All were native English speakers with normal or corrected-to-normal vision with a valid driver's license, were right-handed and were smart phone users. Participants ranged in age from 18–22 years

($M = 20.4$). All participants gave informed written consent and the experiment was given ethics approval by the Arizona State University Institutional Review Board (IRB).

Apparatus

The DS-600c Advanced Research Simulator by DriveSafety™ was used. As shown in *Figure 1,* this simulator was comprised of a 300 deg wraparound display, a full-width automobile cab (a Ford Focus) and a motion platform. Tactile and proprioceptive feedback cues were provided via dynamic torque feedback from the steering wheel and vibration transducers mounted under the driver's seat. The motion platform provided coordinated inertial cues for the onset of longitudinal acceleration and deceleration. The data recording rate was 60 Hz. During the drive, the participant's face and right hand (i.e., the one used to hold their phone) were video recorded using a Logitech C920 Webcam.

Figure 1- The driving simulator

Procedure

Car following task

The car following task was identical to that used in several previous studies (e.g.,

Scott & Gray, 2008; Mohebbi et al., 2009). 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 2.0 s time headway (TH) with the lead car.

If the drivers followed too far behind the lead car, the words "Speed Up!" would appear

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 5-min

practice drives (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 traveled 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 msec and lead vehicle disappeared from the screen.

Each driver completed 5 driving tracks corresponding to the four smart phone tasks plus the baseline driving condition. Each track had 10 unpredictable full stops of the lead car, and required roughly 6–7 minutes to complete. The location of the stops was randomly varied across tracks. Similar to our previous studies (e.g., Scott & Gray, 2008) drivers always performed the baseline condition first. The order of the 4 smart phone conditions was partially counterbalanced across participants. In particular, we ensured that each of the 4 tasks occurred first and last for an equal number of participants. Participants rested for 5 min between conditions to minimize simulator sickness and fatigue.

Smart phone tasks

After the practice and baseline driving condition participants were next given instructions about the four smart phone tasks. For all tasks, participants used their own smart phone and were informed that they would be given a memory test about the content of the task after the driving was complete. The tasks were designed to produce comparable levels of manual interaction with the phone and off-road glances and these variables were analyzed as described below. The four tasks were as follows.

Texting: In this condition, participants were told to imagine that they were 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 the make, model and year of your vehicle, how long have you owned it?) to which the participant was required to write a text response as they typically would respond. Participants were sent a text once per minute.

Facebook: In this condition, participants were required to scroll through and read the updates from a Facebook account made up by experimenters. All of the updates were text only and included no images. Examples were: "A day without sunshine is like, well, night" and "Whatever you are, be a good one." There were a total of 100 possible updates.

Instagram: In this condition, participants were required to scroll through and view the updates on an Instagram account posted by the experimenters. All of the updates were images with no text and there was 120 in total.

Snapchat: In this condition, participants were required to view an image sent by the experimenter and then choose an image from the photo album on their phone

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that matched in some way (e.g., sending a picture of a dog in response to being sent a picture of a dog). Prior to the beginning of the experiment, participants were sent 12 images by the experimenter to save on their phone. Participants were sent an image once every 30 sec.

After each condition, participants completed the NASA-TLX workload questionnaire as well as a recognition test. The recognition tests involved 10 images (for the Snapchat and Instagram conditions) or 10 written statements (for the Facebook and Texting conditions) in which only 5 items were actually used in the experiment and 5 were not. After completing the 5 tracks participants filled out a demographics sheet, were debriefed and were given credit for their participation.

Data Analysis

To assess driving performance two dependent variables that have been shown to be sensitive to distraction in previous studies, BRT and TH variability were used. To compare the visual and manual demands of the smart phone tasks we calculated total on-phone glance time and total time in which the participant's thumb was in contact with their phone for each condition. These data were analyzed using separate One-Way Repeated Measures ANOVAs with task condition (baseline, texting, Facebook, Instagram and Snapchat) as the factor. Planned comparisons were used to test hypotheses (ii) and (iii) listed above. One-Way Repeated Measures ANOVAs were also performed for the NASA-TLX and the recognition test data. For all results reported, statistical significance is set at $p<.05$. Effect sizes were calculated using partial eta squared (η_p^2) for ANOVAs and Cohen's *d* for *t*-tests for all significant findings.

Results

Brake Reaction Times

Brake Reaction Times (BRT) Figure 2 shows the mean BRTs for the five different driving conditions. The one-way ANOVA performance on these data revealed a significant effect of condition, $F(4, 68) = 5.93$, $p<.001$, $\eta_p^2 = .26$. The first planned contrast indicated that the combined BRT for the text-based tasks (texting and Facebook, Mean = 1.16 s) was significantly larger than the combined BRT for the image based tasks (Snapchat and Instagram, Mean = .92 s), $t(17) = 3.47$, $p = .001$, $d = 0.75$. The second planned contrast revealed that the combined BRT for the self-paced tasks (Facebook and Instagram, Mean = 1.04) was not significantly different that the combined mean for the experimenter-paced tasks (texting, Snapchat, Mean = 1.04), p>.9. Finally, post-hoc t-tests (with Bonferroni correction, p = 0.0125) were used to compare each of the BRT in each of the phones conditions with baseline driving. These tests revealed that, in comparison to the baseline condition (Mean = 0.88 s), the mean BRT was significantly higher in the Facebook (Mean = 1.18 s, t(17) = 3.30, p = 0.004, d = 1.2) and texting (Mean = 1.14 s, t(17) = 3.40, p = 0.003, d = 1.15) conditions. The mean BRTs were not significantly different from the baseline in either the Instagram (Mean = 0.89 s) or Snapchat (Mean = 0.95 s), p's both >0.25, d's both <0.25. Finally, there was no significant effect of condition order on BRT, p>0.25.
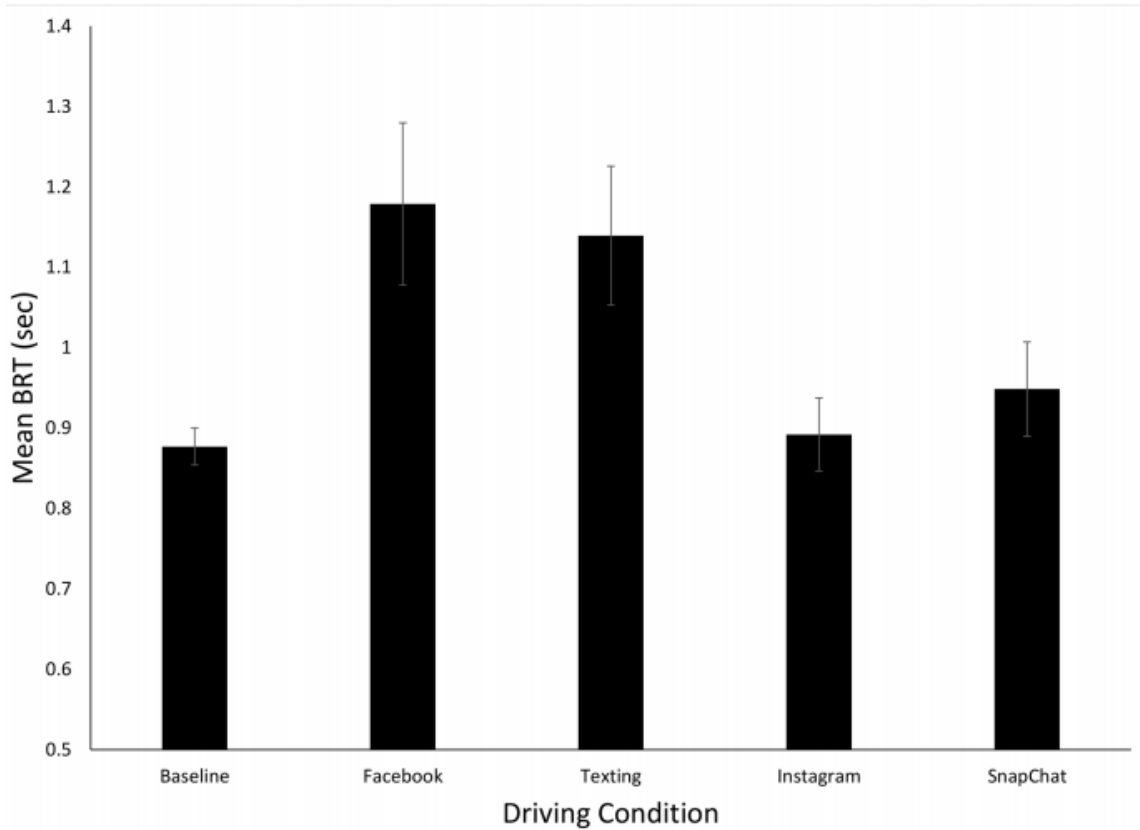
Figure 2- Mean brake reaction times (BRT) for the five difference driving conditions, Error bars are standard errors.

Time Headway

Time Headway (TH) variability Figure 3 shows the mean TH variability for the five different driving conditions. The one-way ANOVA performance on these data revealed a significant effect of condition, $F(4, 68) = 5.02$, $p<.001$, $\eta_p^2 = .23$. The first planned contrast indicated that the combined TH variability for the text-based tasks (texting and Facebook, Mean = .26) was significantly larger than the combined TH variability for the image based tasks (Snapchat and Instagram, Mean = .24), $t(85) = 3.2$, $p = .002$, $d = 0.8$. The second planned contrast revealed that the combined TH variability for the self-paced tasks (Facebook and Instagram, Mean = .24) was not significantly different that the combined mean for the experimenter-paced tasks (texting, Snapchat,

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Mean = .24), p>.9. The post-hoc tests revealed that, in comparison to the baseline

condition (Mean = .23), the TH variability was significantly higher in the Facebook

(Mean = .26, $t(17) = 2.97$, $p = 0.008$, $d = .71$) and texting (Mean = .26, $t(17) = 3.02$, $p = 0.007$, $d = .74$) conditions. The mean TH variability was not significantly different from

the baseline in either the Instagram (Mean = .23) or Snapchat (Mean = .24), p's both

>0.4, d's both <0.2. Finally, there was no significant effect of condition order on TH
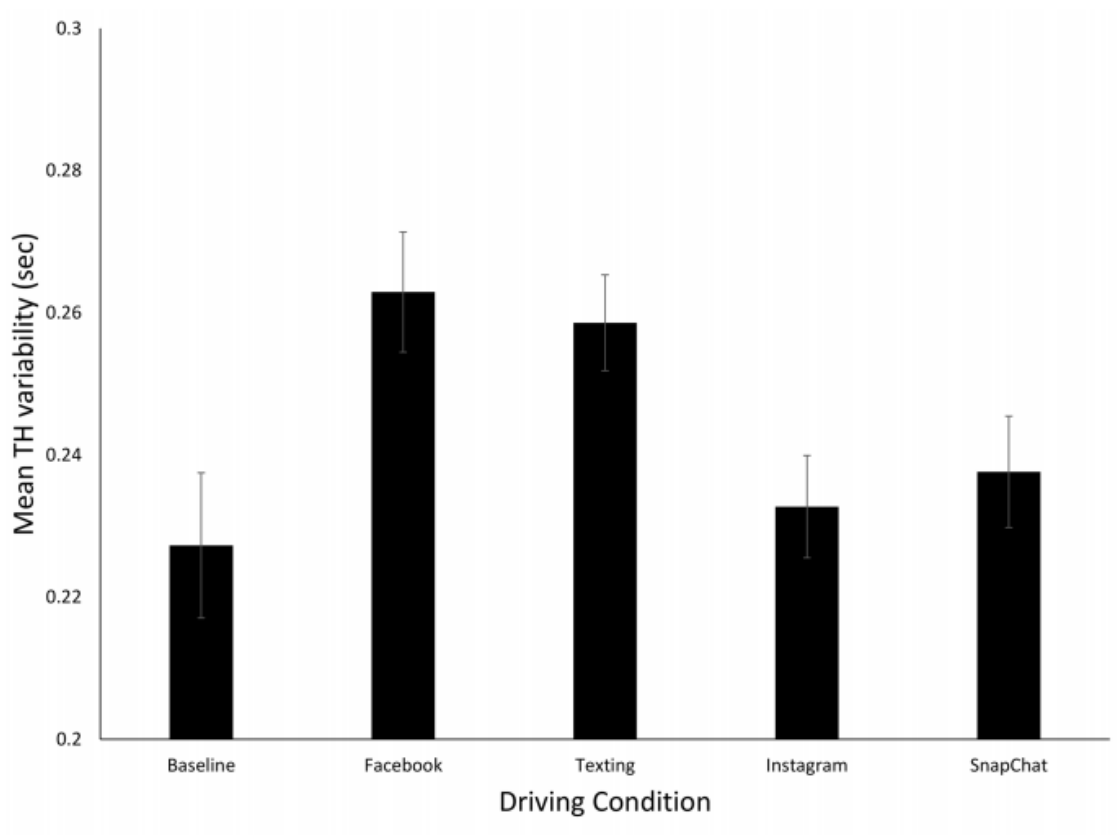
Variability, p>0.4.

Figure 3- Mean time headway variability (TH) for the five difference driving conditions.

Error bars are standard errors.

Gaze and Manual Interaction Behavior

The mean total on-phone glance times were 135.9 (SD = 26.0), 130.9 (SD = 30.1), 121.7 (SD = 27.2), and 146.4 (SD = 28.0) sec for the Facebook, texting, Instagram and SnapChat conditions respectively. The one-way ANOVA performance on these data revealed a non-significant effect of condition, $p>0.1$, $\eta_p^2 = .08$. The mean total thumb-phone contact times were 58.9 (SD = 10.3), 62.0 (SD = 16.7), 57.8 (SD = 19.3), and 54.2 (SD = 11.5) sec for the Facebook, texting, Instagram and SnapChat conditions respectively. The one-way ANOVA performance on these data revealed a non-significant effect of condition, $p>0.25$, $\eta_p^2 = .07$

Questionnaire Data

Table 2 shows the means for mental, physical and temporal demand, as well as task performance, required effort and overall frustration dimensions of the NASA-TLX questionnaire. There was a significant effect of task condition on perceived physical demand [$F(4, 68) = 5.89$, $p = <0.001$, $\eta_p^2 = .26$] and perceived mental demand [$F(4, 68) = 3.06$, $p = 0.022$, $\eta_p^2 = .15$]. As can be seen in *Table 3*, the baseline condition was rated as easier than all of the other four conditions. There was no significant effect of task condition for any of the other NASA-TLX dimensions.

A signal detection analysis was completed for each participant's four recognition tests and d-prime (d') values were calculated. As can be seen in Table 3, the means for all participants in each of the four task conditions are similar. A one-way ANOVA performed on the mean d' values revealed a non-significant effect of condition, $p>0.05$. This non-significant effect implies that the tradeoff between the driving and phone tasks was similar for all conditions.

NASA TLX MEASURES						
Condition	Mental Demand	Physical Demand	Temporal Demand	Perform.	Effort	Frustration
Baseline	9.06	4.11	8.83	10.50	10.22	7.61
Facebook	12.72	7.50	10.28	11.28	11.22	9.67
Texting	12.28	8.61	10.28	10.33	11.11	7.78
Instagram	11.33	8.39	10.00	10.50	10.56	8.17
Snapchat	11.24	8.06	9.41	9.00	9.41	8.24

Table 2 – Mean task-load response ratings captured from the NASA-TLX form. All responses are based on a 1-21 increment scaled with 1 being very low and 21 being very high.

Recognition Tests Signal Detection Measures	
Condition	d'
Facebook	3.49
Texting	4.83
Instagram	3.57
Snapchat	3.09

Table 3 – Mean d'(dprime scores) for each of the 4 recognition task conditions.

Discussion

Previous research on smart phone use while driving has primarily focused on phone calls and texting. Drivers are now increasingly using their phone for other activities during driving, in particular social media (State Farm, 2015) which have different cognitive demands. The aim of the current experiment was to investigate the effect of four different smart phone tasks on driving performance. In particular, we were interested in two factors: interaction medium (text vs image) and interaction type (self-paced vs other-paced).

Given the consistent negative effects of phone use on driving performance that have been found in previous research (reviewed Caird et al., 2008; Carid et al., 2014) our

first hypothesis was that BRTs and TH variability would be significantly elevated in all four smart phone conditions as compared to the baseline driving condition. This was not the case as significant effects on driving performance were only found for the two text-based conditions (Facebook and texting). The significant increase in BRT and TH variability for the text-based conditions is consistent with previous research which has shown both reading and entering text on a phone can impair driving performance Caird et al., 2014). The lack of significant effects for the image-based conditions (and the significant difference between the image-based and text-based conditions found for both BRT and TH variability, which was consistent with our second hypothesis) suggests that interacting with image-based smart phone app's has different effects on driving performance than text.

Consistent with this idea, previous research has shown that the processing of images has different memory and attentional demands in comparison to text, commonly called the picture superiority effect (Paivio, & Csapo, 1973). This is evidenced by the consistent finding that memory for pictures (e.g., a photo of a car) is better than memory for words (e.g., the word "car") even when the recall task involves written responses. According to dual coding theory, this effect is due to differences in encoding: pictures are encoded twice (first in a sensory based, visual code then in a symbolic, verbal code) while words are only coded once in a verbal code (Paivio, & Csapo, 1973). These dual codes are thought to be independent and additive, thus, the increasing the likelihood it will be accessed from memory. In the image-based condition in the present study this would have made it easier for participants to remember the images they saw while

scrolling in Instagram and the images they have saved in their photo album, thus reducing the demands of the task consistent with this idea.

Contrary to our third hypothesis, there was no significant effect of pacing of the phone task (self vs other) on driving performance. The rationale behind this prediction was previous research which has shown that when drivers engage in self-paced tasks they are more likely to adapt their driving behaviors to engage in the secondary task when conditions were deemed as more "safe," such as when stopped at a red light or before entering an attention demanding situation Ahlstrom et al., 2015; Metz et al., 2014; Liang et al., 2014). We would argue that the most likely reason for the lack a pacing effect in the present study was the nature of the car-followed task used in our study. The task was a highly dynamic, continuous control task in which there were no clear break periods (e.g., stop lights or stretches of road with no traffic) which the driver could use for the phone tasks. For the entire duration of the trial participants were required to maintain a 2 sec TH with vehicle undergoing regular changes in speed and fairly frequent sudden stops. Therefore, there was very limited opportunity for adaptation of driving behavior. It will be important for future research to investigate whether similar effects occur when self-paced adaption is more feasible.

The present study used the task of car following, a driving behavior that has been modeled in several previous studies, therefore, it is interesting to consider how such models might be used to understand driver distraction in this situation. First, it has been proposed in recent models that car following behavior depends on a driver's memory for the speed and position at a previous time period (e.g., Yu & Shi, 2015; Yu & Shi, 2015; Tang, Huang, Zhao & Xu, 2009). Since it well know that memory is strongly linked to

attention (review in (Fougine, 2008)), it is likely that distraction from using a smart

phone (which takes a driver's attention away from the road) will alter this specific

parameter of the model. Second, it has been shown that traffic forecasting information

providing by intelligent transportation systems can have a direct effect on car following

behavior (Tang, Li & Huang, 2010), therefore, it would be interesting to investigate

whether drivers might use such information to mitigate the effects of distraction (e.g., by

deciding when to engage in smart phone tasks). Finally, since most car following models

used parameters such as time headway, speed and reaction time (e.g., Jiang, Wu & Zhu,

2001) that were shown to be influenced by distraction in the present study, it will be

important for future research to attempt to explain and predict the effects of distraction on

car following by directly applying such models.

The findings of the present experiment were limited by certain constraints

imposed through the simulation paradigm (Ho et al., 2014) First, the drivers in the

present experiment were fully expecting the lead car to stop suddenly, so driver responses

recorded in this simulation were likely faster than can be expected in a real driving

situation. However, it is reasonable to expect that the relative differences in BRT between

the different conditions would be the same in real driving. Nonetheless, this needs to be

tested empirically. Second, although we attempt to match the smart phone tasks in terms

of demands, it is possible that the differences between conditions were not solely due to

the differences in interaction medium and pace between conditions. Future research is

needed in which warnings occur at a much lower frequency.

On a practical level, the present findings suggest that image-based interfaces may

provide a relatively safer ways for people to "stay connected" (e.g., interact with social

media, instant message friends, etc.) while driving as compared to text-based interfaces–

a function that drivers increasingly want in their vehicle (State Farm, 2015).. In the

present study, viewing image updates and exchanging images with another person on a

smart phone did not have any significant effects on driving performance. Since an

auditory analog of the picture superiority effect has also been found (e.g., a ringing sound

is remembered better than the word "ringing", (Crutcher, & Beer, 2011), it will be

interesting for future research to investigate whether earcons (Blattner, Sumikawa &

Greenberg, 1989) have a similar advantage over talking over a phone in terms of driver

distraction.

References

Ahlstrom, C., Kircher, K., Thorslund, B., & Adell, E. (2016). Bicyclists' visual strategies when conducting self-paced vs. system-paced smartphone tasks in traffic. *Transportation research part F: traffic psychology and behaviour*, *41*, 204-216.

Basacik, D., Reed, N., & Robbins, R. (2012). *Smartphone use while driving: a simulator study* (No. PPR592)

Blattner, M. M., Sumikawa, D. A., & Greenberg, R. M. (1989). Earcons and icons: Their structure and common design principles. *Human–Computer Interaction*, *4*(1), 11-44.

Caird, J. K., Johnston, K. A., Willness, C. R., Asbridge, M., & Steel, P. (2014). A meta-analysis of the effects of texting on driving. *Accident; Analysis and Prevention, 71*, 311-318. doi:10.1016/j.aap.2014.06.005

Caird, J. K., Willness, C. R., Steel, P., & Scialfa, C. (2008). A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis & Prevention*, *40*(4), 1282-1293.

Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of verbal learning and verbal behavior*, *11*(6), 671-684.

Distracted Driving. (2015, January 5). Retrieved April 28, 2015, from https://www.aaafoundation.org/distracteddriving?gclid=CK3QqYT3qsUCFUuTfg odD7sA3g

Crutcher, R. J., & Beer, J. M. (2011). An auditory analog of the picture superiority effect. *Memory & cognition*, *39*(1), 63-74.

Distracted Driving Facts & Stats. (2015, January 5). Retrieved April 28, 2015, from https://www.childrenshospital.vanderbilt.org/services.php?mid=10638

Drews, F. A., Yazdani, H., Godfrey, C. N., Cooper, J. M., & Strayer, D. L. (2009). Text messaging during simulated driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 51*(5), 62-762. doi:10.1177/0018720809353319

Fitch, G. M., Soccolich, S. A., Guo, F., McClafferty, J., Fang, Y., Olson, R. L., ... & Dingus, T. A. (2013). *The impact of hand-held and hands-free cell phone use on driving performance and safety-critical event risk* (No. DOT HS 811 757).

Fougine D. (2008). The relationship between attention and working memory. In
Johansen, N. B. (Ed.). (2008). *New research on short-term
memory*. Nova Science Pub Incorporated.

Gray, R. (2011). Looming auditory collision warnings for driving. *Human Factors: The
Journal of the Human Factors and Ergonomics Society*, *53*(1), 63-74

Hatfield, J., & Murphy, S. (2007). The effects of mobile phone use on pedestrian crossing
behaviour at signalised and unsignalised intersections. *Accident analysis &
prevention*, *39*(1), 197-205.

He, J., Chaparro, A., Nguyen, B., Burge, R. J., Crandall, J., Chaparro, B., ... & Cao, S.
(2014). Texting while driving: Is speech-based text entry less risky than handheld
text entry?. *Accident Analysis & Prevention*, *72*, 287-295.

Ho, C., Gray, R., & Spence, C. (2014). To what extent do the findings of laboratory-
based spatial attention research apply to the real-world setting of driving? *IEEE
Transactions on Human-Machine Systems, 44*, 524-530

Hosking, S. G., Young, K. L., & Regan, M. A. (2009). The effects of text messaging on
young drivers. *Human Factors: The Journal of the Human Factors and
Ergonomics Society, 51*(4), 582-582. doi:10.1177/0018720809341575

Jiang, R., Wu, Q., & Zhu, Z. (2001). Full velocity difference model for a car-following
theory. *Physical Review E*, *64*(1), 017101.

Kujala T. (2013). Browsing the information highway while driving—Three in-vehicle
touch screen scrolling methods and driver distraction. Personal and Ubiquitous
Computing, 17, 815–823. 10.

Kujala T, Saariluoma P. (2011). Effects of menu structure and touch screen scrolling
method on the variability of in-vehicle glance durations during in-vehicle visual

Lee, J. (2014). *Integrating the saliency map with distract-r to assess driver distraction of
vehicle displays* (Doctoral dissertation, THE UNIVERSITY OF WISCONSIN-
MADISON).

Liang, Y., Horrey, W. J., & Hoffman, J. D. (2014). Reading Text While Driving
Understanding Drivers' Strategic and Tactical Adaptation to Distraction. *Human
Factors: The Journal of the Human Factors and Ergonomics Society*,
0018720814542974.Paivio A, Csapo K (1973)

Metz, B., Landau, A., & Just, M. (2014). Frequency of secondary tasks in driving–
Results from naturalistic driving data. *Safety science*, *68*, 195-203.

Mohebbi, R., Gray, R., & Tan, H. Z. (2009). Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone. *Human Factors*, *51*(1), 102-110.

Saiprasert, C., Supakwong, S., Sangjun, W., & Thajchayapong, S. (2014). Effects of smartphone usage on driver safety level performance in urban road conditions. 1-6. doi:10.1109/ECTICon.2014.6839778

Salvucci, D. D., Zuber, M., Beregovaia, E., & Markley, D. (2005, April). Distract-R: Rapid prototyping and evaluation of in-vehicle interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 581-589). ACM.

Scott, J. J., & Gray, R. (2008). A comparison of tactile, visual, and auditory warnings for rear-end collision prevention in simulated driving. *Human factors*, *50*(2), 264-275.

Six Annual State Farm Distracted Driving Survey (2014). Available http://www.multivu.com/players/English/7292854-state-farm-distracted-driving-survey cellphone-use/

Tang, T. Q., Huang, H. J., Zhao, S. G., & Xu, G. (2009). An extended OV model with consideration of driver's memory. *International Journal of Modern Physics B*, *23*(05), 743-752.

Tang, T. Q., Li, C. Y., & Huang, H. J. (2010). A new car-following model with the consideration of the driver's forecast effect. *Physics Letters A*, *374*(38), 3951-3956.

Weldon, M. S., Roediger, H. L., & Challis, B. H. (1989). The properties of retrieval cues constrain the picture superiority effect. *Memory & Cognition*, *17*(1), 95-105.

Young, K. L., Rudin-Brown, C. M., Patten, C., Ceci, R., & Lenné, M. G. (2014). Effects of phone type on driving and eye glance behaviour while text-messaging. *Safety Science, 68*, 47-54. doi:10.1016/j.ssci.2014.02.018

Yu, S., & Shi, Z. (2015). An extended car-following model considering vehicular gap fluctuation. *Measurement*, *70*, 137-147.

Yu, S., & Shi, Z. (2015). An improved car-following model considering headway changes with memory. *Physica A: Statistical Mechanics and its Applications*, *421*, 1-14.

CHAPTER 3

EXPERIMENT TWO-A Comparison of Different Smart Phone Based

Applications for Mitigating Driver Distraction

Background

Distraction from smart phones while driving is an ever increasing problem in our society. According to a recent ATT&T study, it was found that 70% of drivers engage in smart phone activities such as texting (61%), emailing (33%) and even social networking, mainly checking Facebook (27%) while driving (ATT&T, 2015). Previous research has demonstrated negative effects produced when drivers talk on a phone while driving (Caird et al., 2008), text on a phone while driving (Caird et al., 2014) and more recently when they engage in social media applications (app's) on their smart phone (i.e., Facebook and Instagram) while driving (Basacik, Reed and Robbins, 2012; McNabb & Gray, 2016, *Experiment 1*). These effects include delayed brake reaction time (RT) to collision events and impaired lane position and headway regulation. Depending on the nature of the task being performed, smart phone use can produce manual, visual and/or cognitive distraction (Strayer, 2015).

In response to this problem, several smart phone app's have recently been developed which attempt to regulate a driver's use of their smart phone in some way with a particularly focus on texting (e.g., Drive Now Text Later, DriveSafe Mode, Live2Txt). In addition, it has been suggested that a special "driving mode" (similar to the existing "airplane mode") be a built-in feature of all phones (Simons & Chabris, 2015). These interventions typically run in the background by linking to the driver's GPS system and automatically activating when a threshold speed (e.g. 10 mph) is reached. When the

threshold is reached, incoming calls and texts are blocked and the sender is typically sent a message that the driver is unable to respond. When the driving speed goes below the threshold (e.g., if the vehicle is stopped at a red light), the messages are allowed to come through and the driver can then check them. Although well intentioned, there are several important limitations with these app's. First, it seems unlikely that the large proportion of drivers that want to use their phone during driving (ATT&T, 2015), will voluntarily use an app that will prevent this. Consistent with this idea, it has been shown that even when drivers experience the benefits of driver-related smart phone applications as research participants, they stop using the app almost immediately after the study is concluded (Musicant & Lotan, 2016, Botzer, Musicant & Perry, 2017). Drivers have identified several issues related to the reluctance to use these apps including potential draining of the phone battery, use of their data allowance, and dislike of being monitored and restricted. Second, these types of app's have the potential to drain the user's phone battery and/or use of their data allowance. Finally, and most importantly, the design of these app's raise some other possible human factors issues.

First, even when the message blocking in these app's is activated it is still likely that the driver will be alerted that they have received a message. For example, visual notifications (e.g., from an iPhone's notification center) are not fully disabled in most of these app's and some app's still allow auditory and vibration notifications. It has recently been shown that receiving a message notification can be distracting and result in impaired performance on an attentional-demanding task, even when participants did not directly interact with their smart phone during the task (Stothart, Mitchum & Yehnert, 2015). The authors proposed that notifications can prompt task-irrelevant thoughts and mind

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wandering which are also known to impair driving performance (Yanko & Spalek, 2013). It is possible that this mind wandering will result in more sustained distraction as compared to if the driver were just allowed to check the message in the first place.

A second potential problem could arise when a driver's speed drops below the threshold level and messages are allowed through. If they have been driving for a long time and/or are highly active on social media it is possible that they could be inundated with several messages. If they are checking these at a red light these could in turn lead to slower reaction time to the light changing green and/or impaired awareness of the traffic environment at the intersection.

The goal of the present study was to compare different smart phone mitigation methods in a driving simulator. In an attempt to re-create the natural desire drivers have to check their own personal messages, participants were asked to perform a riddle task while driving. Specifically, they received texts from the experimenter which were each clues to a riddle that had to be solved at the end of the drive. The five conditions were as follows:

Baseline – participants drove around the simulated environment without their smart phone. They were asked to make sure their phone was on silent and not to bring it in the vehicle with them.

Airplane Mode – participants drove with their phone sitting face down on the passenger seat and set in airplane mode (i.e., no messages or notifications). They were told that they would be receiving messages to the riddle that could be checked once the drive was completed.

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On Mode – participants drove with their phone as the normally do while driving and fully activated. They were told that they could check the incoming text messages whenever they wished.

Notifications Only Mode - participants drove with their phone face down on the passenger seat and fully activated. However, they were instructed not to check their messages until after the drive was complete.

Check at Stop Mode - participants drove with their phone face down on the passenger seat and fully activated. However, they were instructed to only check their messages when they were stopped (e.g., at a red light). The experiment was designed to test the following predictions:

(i)   Driving performance would be impaired (e.g., significantly higher speeds and lane position variability) in On, Notifications Only and Check at Stop modes relative to the other conditions due to mind wandering,

(ii)   Impairments in driving performance would be significantly greater for conditions in which drivers were physically allowed to check messages while driving (On and Red Light) as compared when they could not (Airplane and Notifications Only) due to the added visual and manual distraction and

(iii)   Driving performance in stopping situations would be impaired (i.e., longer wait times and slower reaction times) in the Check at Stop condition.

Methods

Participants

Fifteen undergraduates (mean age=20.1) from Arizona State University participated for partial fulfillment of an introductory psychology research requirement. All were native English speakers with normal or corrected-to-normal vision with a valid driver's license and were smart phone users.

Apparatus

The same apparatus was used as in Experiment 1, (*Chapter 2*).

Procedure

Driving Task

In all conditions, drivers were asked to drive in a simulated city environment and were instructed to drive as they normally would while following auditory turn instructions from a navigation system. They were further instructed to obey the posted speed limit (30 mph) at all times. Intermittent opposing roadway traffic was included to more closely simulate real-world driving conditions. Each drive lasted roughly 7 minutes.

Drivers were given a 5-min practice to become familiar with the driving simulator before the experimental conditions began. The order of conditions was partially counter-balanced across drivers.

Riddle Task

Drivers were instructed that in the experimental conditions they would be asked to solve a riddle at the end of each drive. They were further instructed that they would be receiving the clues to the riddle via text messages sent by the experimenter to their smart phone which they may or may not be able to check (and begin thinking about the

solution) while driving, depending on the condition. After they had finished the drive and put the vehicle in park, they had 1 minute to solve the riddle. For each riddle they answered correctly they were entered into a drawing to win an iPad.

Riddles were chosen from the MindTrap™ board game. Each riddle had 4 parts that were delivered in 4 separate text messages. An example of one the riddles use was: Text 1: A taxi driver was called to take a group of passengers to the train station. Text 2: The train station is normally an hour away but with traffic being extra heavy it took a full hour and a half. Text 3: On the return trip the traffic was still as heavy, Text4: And yet it took only 90 minutes. Why? Answer: Because 1.5 hours and 90 minutes are the same.

Data Analysis

The mean values for the following driving performance variables were analyzed: Speed, Lane Position Variability, Reaction Time to lights changing green and Lane Position Variability after light change when stopped at pedestrian crosswalks. For all results reported, statistical significance was set at *p<.05*. Effect sizes were calculated using partial eta squared (η_p^2) for ANOVAs and Cohen's *d* for *t*-tests for all significant findings.

Results

Mean Speed

Figure 5 shows the mean driving speed for the five different conditions. The Repeated Measures ANOVA performed on these data revealed a significant effect of condition, $F(4,56) = 5.23$, $p=.001$, $\eta_p^2 =.27$. Follow up pairwise comparisons demonstrated that all four experimental conditions had a significantly faster mean Speed

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as compared to the baseline condition (M=12.1m/s), Airplane Mode ($M = 13.7$m/s, $t(14)$

= -3.20, p=.006, d=-1.21), On Mode ($M = 13.8$m/s, $t(14)$ =-2.19, p=.046, d=-.93),

Notifications Only Mode ($M = 14.8$m/s, $t(14) = -4.86$, p=.019, d=-1.13) and Stop Check

Mode ($M = 14.2$ m/s, $t(14) = -3.04$, p=.009, d=-1.19).
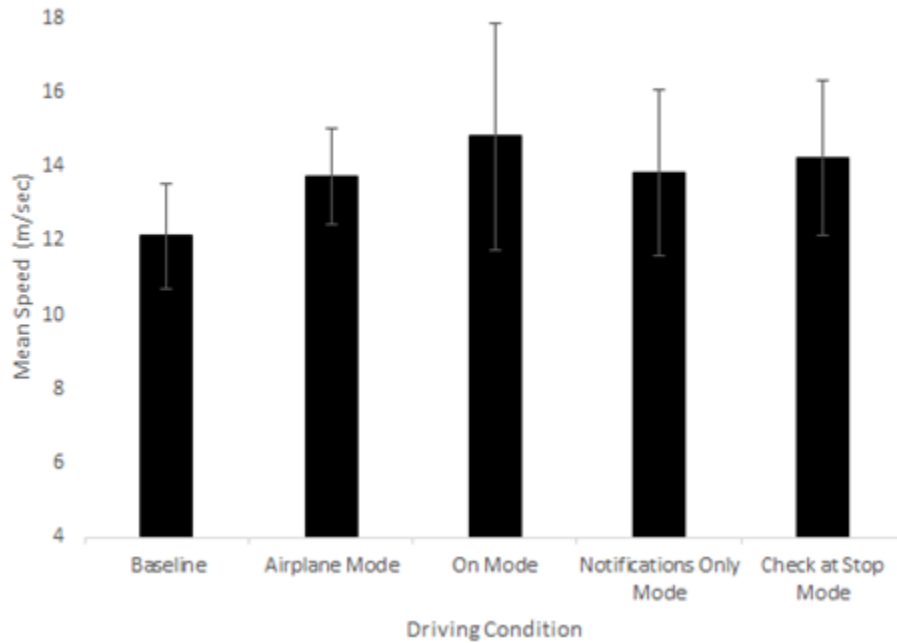
Figure 4. Mean Speed across the five different experimental conditions. Error bars are

standard errors.

Mean Lane Position Variability

Figure 6 shows the mean Lane Position Variability for the five different driving

conditions. The Repeated Measures ANOVA performed on these data revealed a

significant effect of condition, $F(4,56) = 5.05$, p=.002, η_p^2 =.27. Follow up pairwise

comparisons demonstrated that three of the four experimental conditions had significantly

greater mean Lane Position variability as compared to the baseline condition (M=-.13),

On Mode (*M* =-.*33*, *t*(14) = 3.89, *p*=.002, *d*=-.86*),* Notifications Only Mode (*M* =-.*38*,

t(14) = 3.07, *p*=.008, *d*=-.81*)* and Stop Check Mode (*M* = -.37, *t*(14) = 5.07, *p*=.000, *d*=-

1.06*)* were significant while Airplane Mode was approaching significance (*M* = -.25,

t(14) = 1.80, *p*=.094, *d*=-.47*),*
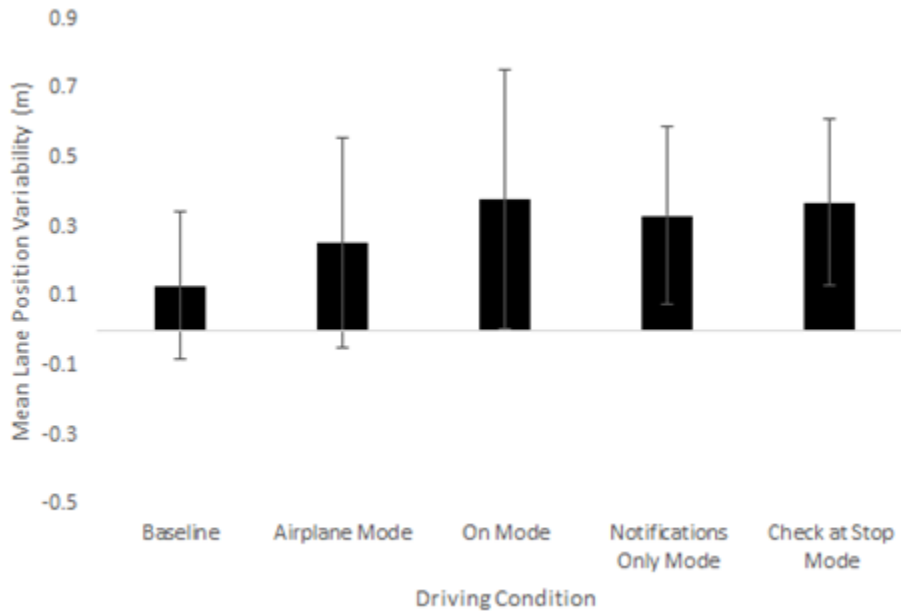
Figure 5. Mean Lane Position Variability across the five different experimental

conditions. Error bars are standard errors.

Red Light & Pedestrian Delays

Figure 7 shows the mean Reaction Time (i.e., accelerator response) after the

signal light turned to green for the different driving conditions.

The Repeated Measures ANOVA performed on these data revealed a significant

effect of condition, $F(3,56) = 19.71$, $p=.000$, $\eta_p^2 =.59$. Follow up pairwise comparisons

demonstrated that as compared to the baseline condition (*M* = 2.03 s) only drivers in the

Stop Check Mode had significantly longer Reaction Times to the green light change (*M* =

3.63 s, *t*(14) = -7.12, *p*=.000, *d*=-2.23) than all other conditions, Airplane Mode (*M* =

2.07 s, $t(14) = -.317$, $p=.76$), Ignore Mode ($M =1.98$s, $t(14) = .213$, $p=.84$) and

Notifications Only Mode ($M =1.7$s, $t(14) = 1.18$, $p=.29$).

Drivers mean wait times at pedestrian cross walks were also analyzed for each of

the experimental conditions. The Repeated Measures ANOVA performed on these data

revealed a significant effect of condition, $F(3,42) = 4.96$, $p=.005$, $\eta_p^2 =.26$. Similar to the

red light Reaction Times, follow up pairwise comparisons demonstrated that drivers in

the Stop Check Mode average Time waited on average ($M = 18.1$s) significantly longer

than each of the other three conditions, Airplane Mode ($M = 9.9$s, $t(14) = 2.45$, $p=.028$,

$d=.53$), Ignore Mode ($M = 4.06$s, $t(14) = 3.33$, $p=.005$, $d=.98$) and Notifications Only

Mode ($M =7.0$s, $t(14) = 2.07$, $p=.058$, $d=.75$).
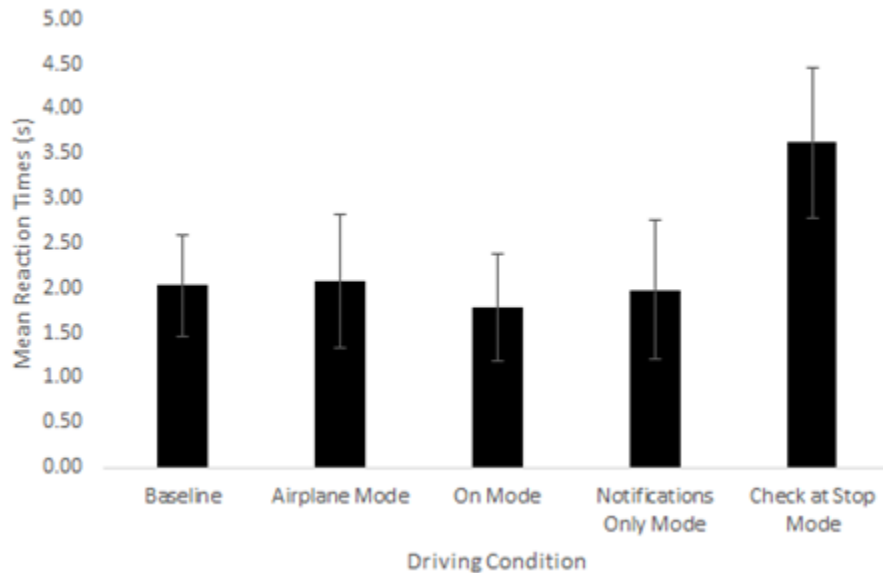
Figure 6. Mean Reaction Time to green light changes across the five different

experimental conditions. Error bars are standard errors.

Lastly, we also examined drivers' behavior for the 10 sec period immediately

after the light turned to green for all five conditions, as shown in Figure 8. Repeated

Measures ANOVAs results show that while the average speeds in the conditions were not significantly different from each other $F(4,56) = 1.69$, $p=.165$, $\eta_p^2 =.49$, average Lane Position Variability was significantly different $F(4,56) = 3.41$, $p=.015$, $\eta_p^2 =.20$. In particular pairwise comparisons revealed that drivers only in the On and Stop Check Mode conditions had significantly higher Lane Position Variability in 10 sec period as compared to the baseline condition. $(M = -.30, t(14) =2.63, p=.02, d=-.89)$ and $(M=-.22, t(14) = 2.59, p=.021, d=-.70)$, respectively.
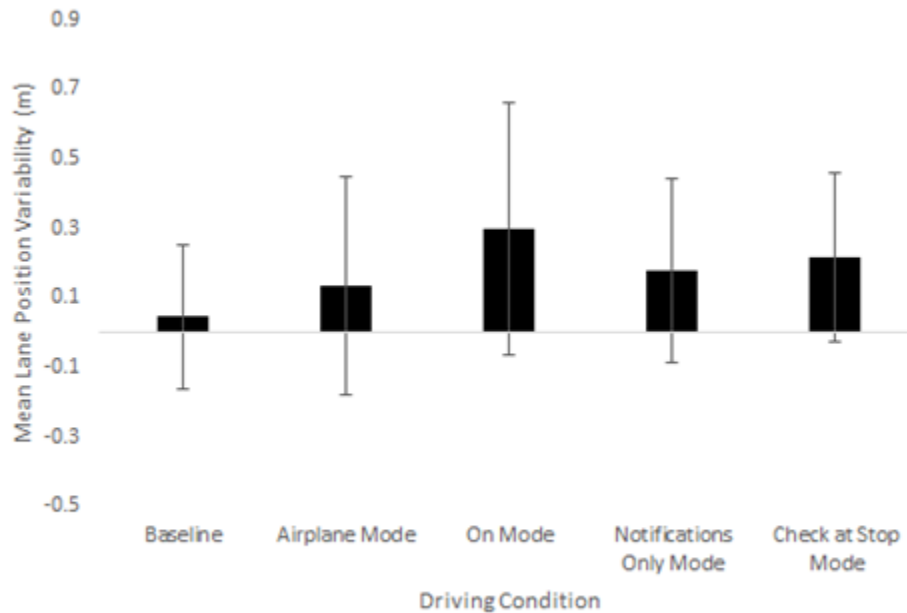
Figure 7. Mean Lane Position Variability across the five different experimental conditions after green light. Error bars are standard errors.

Discussion

Simply put, people want to use their smart phones to stay connected while on the move. For example, in a 2014 survey conducted by State Farm found that in the past 5

years the number of people aged 18-29 that use social media while driving doubled from 21 to 42% (State Farm, 2014). This is, however, worsening one of the single biggest human factor problems in society today: driver distraction (Strayer, 2015). How can we satisfy the conflicting forces of connectivity-on-the-go and safe mobility?

An approach that has become popular in more recent years is the development of smart phone app's which somehow alter the way in which information is delivered to the driver (i.e., silencing or blocking an incoming message). Unfortunately, these types of app's have potential to introduce safety problems of their own. For instance, if the driver places their smart phone within viewing distance, the incoming messages may still be visually displayed on the screen (i.e., the notifications bar of an iPhone) and additionally some app's may not completely silence the incoming alert sound. Most concerning is how the speed threshold operates. For example, when a driver is stopped at red lights or slowed down due to traffic the app interprets the driver as having stopped. This could potentially causing the phone to be inundated with messages although they are still behind the wheel. This could result in delayed reactions/impaired situation awareness when a driver at a routine stop attempts to read a large number of messages during various traffic stops. Lastly, these app's may exacerbate off-task, mind wandering thoughts when drivers feel restricted and inhibited from receiving messages as well as contribute to distracted driving. The goal of the present study was to evaluate these specific issues associated with safe driving app's.

Unexpectedly, in the present study, driving performance was significantly (and negatively) affected in all conditions for which drivers had their phone in the car, regardless of the mode. In particular, both driving speed and lane position variability

were significantly higher as compared to the baseline condition in which the driver did not have their phone. We would argue that most likely explanation for this effect is that drivers in the present study engaged in off-task thoughts about potential messages. For instance, the observed negative effects in the Airplane, Notifications Only and Check at Stop modes were most likely due to the cognitive resources taken up by off-task thoughts about what messages they would be receiving i.e., participants knew that were receiving message relevant to the riddle task but were not allowed to check them. These findings are consistent with a recent study showing that the cognitive distraction imposed by a simple alert, not the physical interaction with the smart phone can influence performance on a sustained attention task (Yanko & Spalek, 2013; Stothart et al., 2015). For the On mode, it is likely that negative effects observed were due to both the visual and manual distraction produced by the driver physically interacting with their phone while driving, consistent with previous research on texting and driving (Caird et al., 2014).

As predicted, allowing drivers to check stored messages at traffic stops produced negative effects on driving performance. Specifically, driver's reaction times to green lights and wait times at crossings were significantly longer for the Check at Stop mode than all other conditions. Furthermore, after participants finished checking their messages and began driving the overall average Speeds for each condition remained consistent whereas lane position variability was negatively impacted. Only the Check at Stop mode and On mode lane position variability were significantly different from the Baseline mode reflecting that restricted drivers receiving messages at the stop light suffer the same performance decrements drivers that have no imposed phone restrictions. These findings are consistent with previous research that engaging with a smart phone, even if only at

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stop lights may contribute to inattentional blindness or in more extreme cases a loss of situational awareness as demonstrated by delays in reaction times to relevant traffic situations (Caird et al., 2014).

In summary, the present study provides evidence that the presence of a smart phone in a driver's vehicle, regardless of a driver's physical interaction with the device, can be distracting, enough so, as to negatively impact a drivers driving performance (i.e., Speed, Lane Position Variability, RT's). Surprisingly, even the expectancy of receiving an important message, without an auditory notification seems to create enough cognitive distraction through mind-wandering to impact a driver's performance. Paradoxically, when drivers are restricted to only looking at their incoming messages at red lights or crossings they may become so overly absorbed with their phones they actually suffer the same or worse performance decrements as an unrestricted driver. In sum, app's which restrict incoming messages in some manner do not seem to an effective method for mitigating driver distraction problems

CHAPTER 4

Experiment Three- Informative Warnings at the Source of Distraction

Background

Driver distraction has contributed to accidents on the roadways since the introduction of vehicles (Graham-Little, 1934). Over time, as technology has progressed, distractions from smart phones have become one of the biggest concerns regarding driver safety. While drivers are not likely to admit that they use their smart phone while driving, it was revealed that a majority of drivers have confidence in their own abilities to use their phone while driving although ironically they fear other driver's capabilities relative to their own (Sanbonmatsu, Strayer, Behrends, Ward & Watson, 2016). Furthermore, as shown in Experiment 2, when a driver's smart phone is put away, there can still be cognitive mind-wandering disturbances that hinder driving performance, as driver's may experience a phenomenon known as a Fear of Missing Out (FoMO) (Przybylski, Murayama, DeHaan & Gladwell, 2013). Driver's experiencing FoMO while driving may be preoccupied by various thoughts about what they could be missing out on such as the most recent social updates, current events or work related activities (Mason, Norton, Van Horn, Wegner & Macrae, 2007; Stohart, et al., 2015). From the observed increase in dependency and emotional attachment to smart devices it remains unlikely that drivers, even while driving, will disconnect from their devices.

Due to the driver always being connected, it becomes crucial to find new methods to warn a distracted driver. With the expectations that future technology will allow a smart phone to have the ability to collect, interpret and display data about the driver's behavior, the driver's vehicle as well as pertinent information about nearby vehicles on

the roadway, the goal of this study was to investigate whether a warning given on or near the location of the smart phone as well as conveying apparent motion can improve reaction times to a critical event. In order to achieve this goal, we investigated a novel approach of using a driver's smart phone, the main cause of distraction within a vehicle, as the source of the warning to the driver.

Driver distraction typically has been understood in terms of competing or limited attentional *resources.* More recent, an emerging theoretical perspective from Lee (2014) considers the attentional *dynamics* of distraction as the ability to "manage interruptions." Specifically, within this conceptual interruption model there are four stages known as, *detection, interpretation, shifting of attention* and then *resumption* of the task. For our study in particular, the focus was on the first three stages of Lee's (2014) model. Primarily, this study focused on how to introduce a warning that is detectable under distraction. Secondly, this study was aimed to reveal if the warning signal could be easily interpreted by attempting to convey movement in the warning signal to match the real world situation. Lastly, this study investigated if the warning signal could potentially shift a driver's attention from their smart phone to the roadway.

In terms of the first stage, numerous warning studies have been conducted with respect to a driver successfully detecting a collision warning while driving (Ho, Reed & Spence, 2006: Spence & Ho, 2008). Reaction time benefits have been observed with auditory, visual, tactile and multisensory warnings (Lee et al., 2002). While auditory and tactile warning modalities have shown the most success, various factors such as loud noises in the vehicle (Edworthy, 1994) talking on the phone (Mohebbi et al., 2009) or even a bumpy road (Spence & Ho, 2008) may reduce their detectability.

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Additionally, fewer studies have determined if a driver can detect these same types of warnings while engaged with their smart phone for uses other than talking (i.e., checking Facebook). Ahtamad et al., *(under review)* recently investigated the effect of a task relying primarily on the sense of touch (texting with a smart phone) on tactile warning effectiveness. Results revealed that texting on the smart phone while receiving a tactile warning on the opposite hand/arm rendered the tactile warnings ineffective (i.e., no reduction in BRT relative to a no warning condition). In order for a driver to successfully detect a warning, it may be necessary that the warning is emitted from or near the smart phone, the area of attentional focus, due to the required interaction with a smart phone (i.e., holding the phone with one hand and eye fixation at the screen).

Secondly, the interpretation of the interruption to improve a driver's reaction to a critical event is vital. Traditional warning studies have been conducted in driving research that focus on understanding the timing implications of the warning (Lee et al., 2002; Spence & Squire, 2003; Straughn et al., 2009), and the optimal location of the warning (Ho & Spence, 2008). More recently, warning studies have begun to investigate what information might be conveyed or interpreted in the warning signal to increase a driver's overall situation awareness (SA) of a critical event (Gray, 2011; Ho, Gray & Spence, 2014). Auditory looming warnings and vibrotactile apparent motion signals have been shown to successfully convey urgency when the warning signal parallels the incoming information about the closing velocity (CV) with the lead car or when the warning simulates apparent movement that is presented as moving towards the driver's head or torso (Gray, 2011; Meng, Gray, Ho, Ahtamad & Spence, 2015). In order for the driver to effectively interpret an interruption from the warning signal it is worthwhile to

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investigate if the warning from a smart phone could convey pertinent information to the driver before any head or eye movement is necessary.

Lastly, re-orienting a driver or shifting a driver's attention from their smart phone may prove more difficult than expected. One prominent aspect of the interruption perspective is task preservation (Zeigarnik, 1938), where a driver fails to interrupt their interaction with a task (i.e., smart phone) and return their attention to the road or warning system due to their fixation with completing a goal on the smart phone. Unfortunately, smart phones have the ability absorb the user in a multitude of ways with unlimited goals that can cause the user to lose track of both time and their surroundings (Wickens, Martin-Emerson, Larish, 1993). An alert given at the location of the driver's smart phone may successfully interrupt the driver, consequently shifting their attentional focus to the forward position of the roadway. Conversely, an alert given at their smart phone may cause a driver to be unnecessarily oriented to the smart phone longer (i.e., processing the sound or vibration coming from the device) (Posner, 1980). Due to these unknown implications on warnings involving smart phone distraction, it is valuable to investigate if the apparent motion could be used to successfully re-orient the driver to the forward facing direction.

Aforementioned, simulating apparent motion as moving towards the driver has resulted as an effective method for alerting drivers (Ho, Spence & Gray, 2013; Meng et al., 2015). In the case of a warning a distracted driver, little is known if the towards motion will remain the more effective option. In line with previous research, the apparent motion simulating movement towards a driver may allow the driver to successfully process and react to the warning information prior to looking forward at the roadway.

Conversely, the reverse result may occur. When a distracted driver is presented an apparent motion warning appearing to move towards them, because the initial sound or vibration is presented outside a driver's area of attention or focus (i.e., a speaker on the dash, or vibration to their non-dominant hand) a driver to be less inclined to break their attentional focus with their smart phone. Although counter to previous research on apparent motion, simulated motion away from a driver that is distracted may be as or more efficient in improving a driver's reaction time. For example, when a driver is looking away from the road, down at their smart phone, motion that appears to have initiated from their device may be more successful in breaking a driver's attentional focus with their smart phone. Furthermore, the secondary sound or vibration simulating the "away" motion (i.e., a speaker on the dash, or vibration to their non-dominant hand) could potentially create a faster and accurate orientation of the driver's attention to the forward facing position and towards the location of the critical event.

Current Study

A literature review revealed that no study to date has used the smart phone as the source for the warning. In the current study both the auditory and tactile warnings that conveyed direction were presented on or near the source of the driver's smart phone (i.e., via a speaker that produced a tone next to the hand they held their smart phone with or a vibration given to the wrist of the hand that held their smart phone). Drivers were asked to perform a car-following task while simultaneously using their smart phone to watch a video. The driving simulator would trigger an auditory or tactile warning when a driver's time to collision (TTC) and the lead car approached less than 3 seconds. Additionally, for both the auditory and tactile warning conditions participants were given sound or

vibrations that appeared to be moving either towards the driver, away from the driver, or presented in a non-informative, static manner at the smart phone location only. This experiment was designed to test the following predictions.

(i)   Driving performance to a potential rear-end collision will be improved (faster brake reaction times (BRT's) in conditions with warnings relative to the non-warning baseline condition.

(ii)   The benefits of the tactile warnings (i.e., changes in BRT relative to the non-warning condition) will be significantly greater than for the auditory warning due to the notion that the secondary task had an auditory component (listening to video) and no tactile component.

(iii)   If interpretation of the warning (i.e., signalling an approaching object) is more beneficial to the driver, then warnings that simulate motion towards the driver will be significantly faster (i.e., changes in BRT relative to the no warning baseline) versus the away and static movement conditions. If re-orienting of the warning is more beneficial to the driver, then warnings that simulate motion away from the driver will be significantly faster (i.e., changes in BRT relative to the no warning baseline) versus the toward and static movement conditions.

Method

Participants

Fifteen undergraduates (mean age= 20.13) from Arizona State University participated for partial fulfillment of an introductory psychology and human systems engineering research requirement. All participants had corrected-to-normal vision, held a valid driver's license, were right-handed and owned a smart phone.

Apparatus

Simulator

The same apparatus was used as in Experiment 1, (*Chapter 2*).

Procedure

Car following task

The same car-following task as Experiment 1 was used. Each driver completed 7 driving tracks corresponding to the 6 smart phone warning conditions tasks plus the 1 non-warning baseline condition. Each track had 10 unpredictable full stops of the lead car, and required about 6–7 minutes to complete. The locations of the stops were randomly varied across tracks. The 7 smart phone warning conditions order were counterbalanced across participants, such that each participant participated in one of three block randomization presentation orders (tactile, non-warning, auditory: auditory, tactile, non-warning: and non-warning, tactile, auditory). Additionally, within each of the conditions the order of warning trials (towards, away or static) was partially counterbalanced such that each participant was given one of three blocked orders

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(towards, away, static; away, towards, static; static, towards, away). Each participant was given a 3-minute practice trial to get acquainted with the simulator. Participants were able to rest as long as needed between conditions to minimize simulator sickness and fatigue.

Driving Conditions

Drivers were instructed that in all the experimental conditions they would be driving around a track while watching a YouTube science video of their choice and simultaneously receiving warnings, either auditory or tactile. Drivers were informed they would be given a quiz about the video at the end of the drive, so they needed to try to maintain an appropriate balance of their attention, as best as they could, between driving the vehicle and watching the video. Drivers were asked to hold their smart phone in their right hand, in a comfortable position that was lower than the center of the steering wheel while keeping their left hand on the steering wheel at all times.

The warning types drivers received were either auditory or tactile and given in either a static, toward or away motion. The warnings were only triggered when the drivers TTC with the lead car reached the threshold of 3 seconds or less and repeated every second until the driver's TTC was greater than 3 seconds.

> **Auditory Static**: A 250-hz tone was given for a total of 700msec on the right speaker that was placed near the driver's smart phone.
>
> **Auditory Away***: A 250-hz tone was given for a total of 300msec to the right speaker (near driver's right hand) followed by 100msec of silence and then a 250-hz tone presented to the left speaker (left side of dash) for a total of 300msec.

Auditory Toward: A 250-hz tone was given for a total of 300msec to the left

speaker (near dash) followed by 100msec of silence and then a 250-hz tone

presented to the right speaker (near driver's right hand) for a total of 300msec.

Tactile Static: A 250-hz tone was given for a total of 700msec via a tactor that

was velcroed onto the participant's right wrist.

Tactile Away: A 250-hz tone was given for a total of 300msec via a tactor that

was velcroed onto the participant's right wrist, followed by 100msec pause, and

then another 250-hz tone that was presented for 300msec to the left wrist.

Auditory Toward: A 250-hz tone was given for a total of 300msec via a tactor

that was velcroed onto the participants left wrist, followed by 100msec pause and

then another 250-hz tone that was presented for 300msec to the right wrist.

Data Analysis

To assess driving performance two dependent variables that have been shown to

be sensitive to distraction in previous studies, BRT and TH variability were used. These

data were analyzed using a Repeated Measures ANOVAs with warning modality

(auditory or tactile) and direction (static, towards, away) as the two factors. Planned

comparisons (using pairwise t-tests) between each warning type and the no warning

condition were used to test hypotheses (i) listed above. For all results reported, statistical

significance is set at *p<.05*. Effect sizes were calculated using partial eta squared (η_p^2) for

ANOVAs and Cohen's *d* for *t*-tests for all significant findings.

Results

Brake Reaction Times

Figure *9* shows the mean BRTs for the seven different driving conditions. The repeated measures ANOVA performed on these data revealed a significant main effect of modality, $F(1,28) = 9.03$, $p<.009$, $\eta_p^2 = .39$, such that the BRT for the auditory warnings (Mean = .60 s) was significantly faster than the BRT for the tactile warnings (Mean = .73 s). Contrary to our predictions, the main effect for direction and the modality by direction interaction were not significant, $F(1,28) = .46$, $p=.64$, $\eta_p^2 = .31$ *and* $F(1,28) = .03$, $p=.97$, $\eta_p^2 = .00$, *respectively.*

Follow-up paired samples t-tests, comparing the non-warning baseline condition (Mean = 0.82 s) to each of the six experimental conditions, were run. Results demonstrated that each of the mean auditory conditions BRT's were significantly faster than no warning, auditory away (Mean = 0.61 s, $t(14) = -3.28$, $p = 0.005$, $d=.82$) auditory towards (Mean = 0.58 s, $t(14) = -8.14$, $p = 0.000$, $d=1.11$) and auditory static (Mean = .60 s, $t(14) = -4.26$, $p = 0.001$, $d=.93$) conditions. Additionally, for the tactile conditions it was revealed that only the tactile towards condition BRT's were significantly faster than the non-warning condition (Mean = .70 s, $t(14) = -2.78$, $p = 0.015$, $d=.55$) while the tactile away (Mean = 0.74 s) and tactile static (Mean = 0.75 s) were not significantly different from the non-warning condition *p's* all >0.005.

Figure 8- Mean brake reaction times (BRT) for the seven different driving conditions.

Error bars are standard errors.

Additional Analyses

One condition that was not run in the present study was a static warning presented on the dashboard. This is an important omission because it is possible that all of the warnings used in the present experiment, (Experiment 3) were equally effective because they all included a sound or vibration that occurred near the phone. To address this issue, data from a similar study, that included the static-dashboard condition, was compared to the present results. Figure 10 shows the mean BRTs for these three different driving conditions. The first condition was the supplemental data from the similar study, in which the warning was presented at the dashboard location only. The second condition was from the present study, Experiment 3, and was the auditory static warning given in the location of the driver's hand. The third condition, also from Experiment 3, was the tactile

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static warning given to at the location of the driver's hand. Independent samples t-tests were used to compare the auditory static at dash condition to each of the two static at hand (tactile and auditory) conditions. It was revealed that the static tactile at hand condition BRT's (Mean = 0.75 s) and the static auditory at hand condition BRT's (Mean = 0.60 s) were both significantly faster than the static auditory at dash condition BRT's (Mean = 0.93 s), $t(28) = -2.30$ p = 0.029, $d=.82$) and $t(28) = --4.23$ p = 0.000, $d=1.56$), respectively.
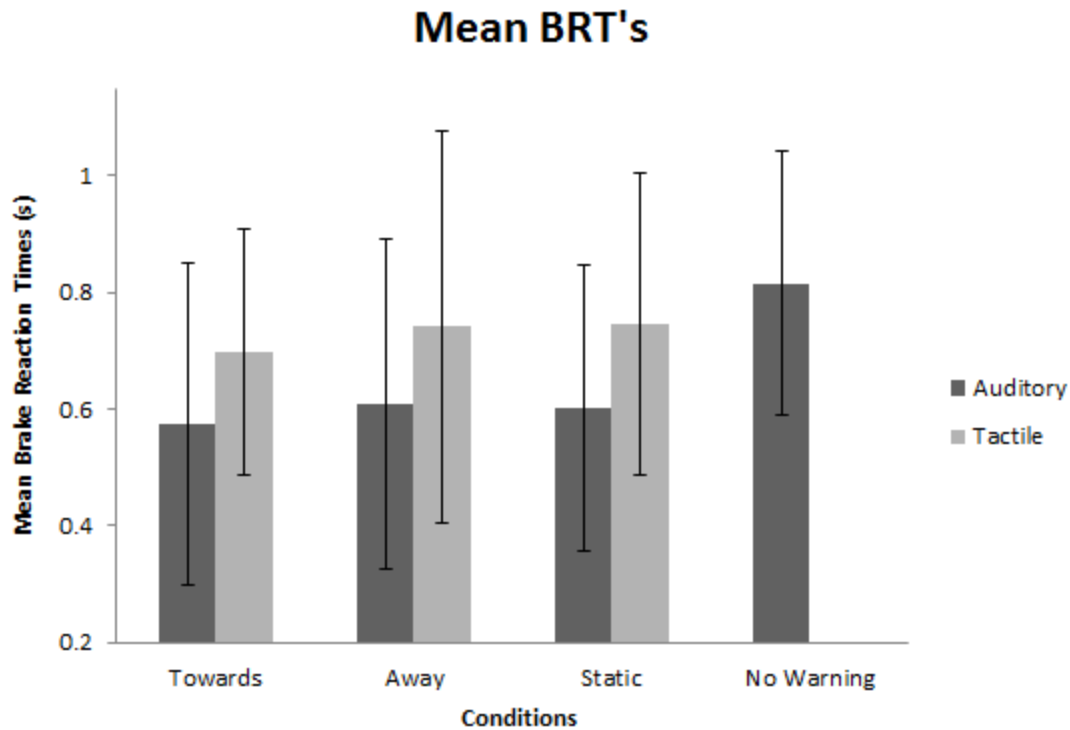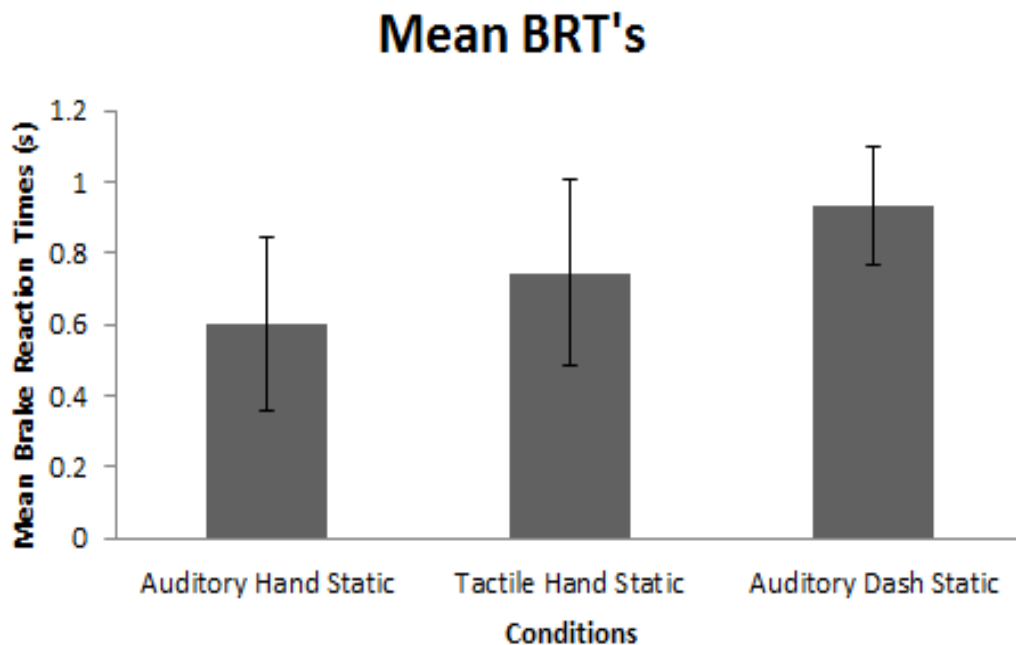
Mean BRT's

Figure 9- Mean brake reaction times (BRT) for the three different driving conditions. Error bars are standard errors.

Discussion

Previous research on warning drivers have found both auditory looming and apparent motion tactile modalities can be used to improve driver's reaction times to critical events (Gray, 2011; Ho et al., 2014). Interestingly, these same warnings have been shown to be nearly rendered ineffective when drivers are simultaneously distracted by their smart phone (Athamad et al., *under review*). In an applied setting, a driver's increased dependency with their smart phone, combined with the potential for a driver to experience FoMo, sets the stage for a driver's inability to disconnect both physically and cognitively while driving (as observed in Experiment 2). For this reason, the overarching aim of this study was to explore practical ways to warn a distracted driver, specifically, by implementing the warning near the location of their smart phone. In particular, we were interested in two factors for the warning: modality (auditory vs tactile) and direction of apparent motion (towards vs away vs static).

Given that overall warning studies tend to show warnings improve driver's reaction times to a critical event (Ho et al., 2013), our first hypothesis was that the BRT's would be significantly faster when drivers were given a warning as compared to the non-warning condition. Interestingly, the findings support our first hypothesis for the BRT's, all conditions involving the auditory warning decreased a driver's BRT as compared to the non-warning condition, consistent with previous research on auditory looming warnings (Gray, 2011). For the tactile apparent motion warning conditions, results found that only the tactile warning presented as moving towards the driver had the ability to improve a driver's BRT as compared to non-warning conditions. These findings are partially consistent with both previous research findings that tactile warnings can be

rendered ineffective when given to a distracted driver (Ahtamad et al., *under review*) and

research findings that the most effective apparent tactile motion warning is when the

motion is presented as moving towards the driver (Ho et al., 2014).

In line with the notion that the secondary task was highly demanding, both with

respect to the visual and auditory processing, the second hypothesis was that the tactile

warnings would significantly reduce BRT's as compared to the auditory warnings. This

hypothesis was based on the premise that the tactile warnings would not be directly

competing for a driver's attention with the visual and auditory modalities thus allowing a

driver to more quickly process the tactile warning information. Surprisingly, the results

suggest the opposite effect for the driver's BRT's. The BRT data revealed that the

auditory warnings actually improved reaction times to the critical event as compared to

the tactile warnings. Upon further consideration, this observed benefit may have been

more pronounced in this study due to again, the nature of the secondary task. Although

the auditory warnings were competing for the driver's attention with the secondary task,

the secondary task of listening and watching a video was, in essence, more passive as

compared to past studies requiring driver's to *actively* engage in conversations with a

passenger or on talk on their cell phone (Mohebbi et al., 2009). The passive interaction

drivers maintained with watching a video displayed on their smart phone while driving,

albeit a common use of the smart phone, may have allowed drivers to become more

receptive to an auditory signal as they were enhancing their auditory channel required by

listening to the video. In turn, this auditory receptiveness may have contributed to a

driver's ability to react more quickly to the auditory warning as compared to the tactile

warning.

Furthermore, and contrary to our third hypothesis, there was no benefit of direction on BRT when simulated as moving toward the driver as compared to when the motion was simulated as moving away or those that were static. The rationale for this hypothesis was with past research success from presenting informative warnings, that either increase in sound and intensity as a driver approaches a lead car or tactile vibrations that move towards a driver's head (e.g., Gray, 2011). Additionally, from studies that demonstrate motion simulated as moving away from the driver may potentially aid in reorienting their attention to the collision event (Gray & Tan, 2002). Further investigation on the effectiveness of the warning location was considered. For the static conditions, follow-up analysis combined this experiment with data from a previous static auditory warning experiment. Results revealed that BRT's were significantly faster when the static auditory or tactile warnings were given near the participant's hand holding the smart phone as compared to an auditory warning presented at the dash only. These findings support the notion that giving an initial warning near the location of the smart phone is more likely to break the driver's attentional focus with their smart phone rather as opposed to orienting them to the smart phone longer. Future research to investigate if auditory information can convey informative information or re-orient a driver by using 3D looming audio or a secondary auditory sound presented in the direction of the critical event is worth exploring.

There is a large body of literature discussing the various ways that can successfully warn a driver, although most are without consideration of warning a driver that is distracted by their smart phone. Overall, these data are in line with the previous findings that distracted drivers given a tactile warning while simultaneously distracted by

their smart phone had the equivalent reaction times as not warning a driver in the first place (Ahthamad et al., *under review*). Notably, results of this study did reveal that the auditory modality can be used to improve a driver's BRT although apparent motion information was unable to provide any benefit. From Lee's (2014) perspective of a driver being able to "manage interruptions" these results demonstrate the driver was able to *detect* the auditory warning more so than the tactile warnings although they were unable to accurately *interpret* the directional information provided in the warning. One potential reason for the interpretation discrepancy may be attributed to our warning presentation methodology. Unlike typical warning studies, where the warning presentation is given at the dash, our warnings were presented near a speaker at the driver's smart phone. Again, the rationale for this warning presentation method was that due to more applied real world driving conditions in which a driver is being distracted by their smart phone, this location may increase potential to improve a driver's reaction time to the critical event.

Future research is necessary to explore how information to a driver can be best conveyed for a driver to both quickly interpret and most effectively *shift their attention* to the roadway. As technology increases and has the capability to keep drivers connected at all times there become more challenges in convincing drivers to disconnect. From the perspective that drivers ARE engaging with their smart phone while driving, the goal of this study was an exploratory investigation on novel methods to warn a distracted driver. Warnings were presented to a distracted driver from sounds or vibrations that were given near the source of the distraction, their smart phone, in hopes to reveal a potential solution of using a driver's smart phone as a source of the warning to convey event information. While warning a distracted driver proves to be challenging, hopefully more

applied studies such as these may shed light on alternative, novel and beneficial methods

for alerting a distracted driver.

CHAPTER 5

EXPERIMENT 4- Take-Over Request Signals while Operating an Autonomous

Vehicle

Background

Autonomous vehicles pose a solution to issues associated with distracted driving although inadvertently the autonomous vehicles may create unforeseen issues with a driver's ability to maintain proper situation awareness (SA). Naturally, a driver of an autonomous vehicle will inherit a more passive supervisory control role that requires a driver to monitor the system and only intervene with the system when necessary or urgent (Endsley & Kaber, 1999; Lee & See, 2004). A supervisory control role can lead drivers to boredom and fatigue due to low cognitive workload required to operate the vehicle (Parasuraman & Riley, 1997), thus leading to an increase in a driver's engagement with other tasks (i.e., smart phone tasks). A driver's engagement with tasks, other than the main task of driving, consequently may decrease a driver's overall SA (Endsley, 1995; Ma & Kaber, 2005). In general, a reduction of a driver's SA while monitoring an autonomous vehicle may not pose an absolute risk but in an unexpected critical situation, the driver being "out-of-the-loop" (OOTL) may have detrimental or even deadly consequences.

Situation awareness (SA), as defined by Endsley (1995), is the "perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." For drivers to achieve proper SA they need to be able to recognize and process relevant information in their driving environment, such as their location in relationship to other vehicles, to accurately

respond to a critical situation. Moreover, SA has been extensively studied in the driving domain. Results of these studies have found that engaging in distracting secondary tasks, such as cell phone use, can reduce a driver's overall SA thus leading to drivers missing warning signs as well as an overall decrease in driving performance (Strayer & Johnston, 2001; Kass, Cole & Stanny, 2007). Additionally, drivers engaged in secondary tasks (e.g., watching a video on their smart phone) while monitoring fully automated systems tend to react slower and more inappropriately respond to critical events, thus increasing their risk for potential collisions (Merat & Jamson, 2014). For these reasons, drivers of autonomous vehicles are encouraged to increase SA during driving by remaining "in-the-loop" both physically (e.g., hands on the steering wheel) and cognitively (i.e., looking forward at the roadway to process the situation) though the evidence suggests the latter is far more imperative (Louw, Merat, Jamson, 2015; Zeeb,et al., 2015).

OOTL automated driving studies have focused on understanding what level of a drivers SA is required for a driver to more accurately regain control of the vehicle during a take-over request (TOR) situation (Louw, et al., 2014). A TOR is a situation in which the automated system has been deactivated (e.g. due to sensor loss) and the driver needs to initiate steering and braking control (Gold, Dambock, Lorenz & Bengler, 2013). Overall findings reveal challenges in assessing drivers SA levels in this situation as a drivers eyes being forward towards the roadway are not always an accurate assessment of SA and even more so if the driver is engaged in other cognitive tasks (Radlmayr, Gold, Lorenz, Faird & Bengler, 2014). Moreover, when distracted drivers are redirected quickly to the forward direction of the roadway they are not as always able to cognitively process the situation in a timely manner, resulting in more brake responses rather than accurate

maneuvers to the critical event (Gold et al., 2014). Due to the ambiguity of SA, indirect measures of SA have been developed that analyze not just the reaction times and response types to critical situations, but evaluate the driver's glance behaviors towards latent hazards on simulated driving roadways (Gibson, Lee, Venkatraman, Price, Lewis, Montgomery & Mutlu, 2016). While these measures give some insight to the driver's overall level of SA at the TOR, methods for enhancing a driver's SA, especially through a warning given in conjunct or prior to the TOR becomes imperative.

Various studies have attempted to design and analyze different methods of enhancing a drivers SA at the time of take-over through the use of warnings. Auditory warnings have been shown to not only be able to orient a driver to the roadway but orient a driver to the specific location of a critical event. Specifically, Straughn et al., (2009) had participants drive along a three lane simulated highway where pedestrians randomly walked from the sidewalk to one side of the road. Findings revealed that drivers SA could be successfully improved by orienting a driver to either the danger or safe lane of travel depending on the timing of the auditory warning. Similarly, although to a lesser extent, improving SA at the TOR for a distracted driver in the realm of automated driving has been attempted. Lorenz, Kerschblaum and Schumann (2014) designed a novel augmented reality overlay on an autonomous driving simulation that either illuminated the roadway as green or red. The red color was indicative of the accident location and the green color was indicative of the safe location. They found that participants were influenced by these colors, not in their reaction take-over times but in the appropriateness of their decision making. Similarly, Beller, Heesen & Vollrath (2013) implemented an uncertainty symbol on the dash that was presented to

drivers when the automation was "uncertain" in conjunction with varying the reliability of the automation system. With regard to SA, it was found that in the uncertain conditions in which the drivers were given the uncertainty symbol, drivers increased their overall SA by decreasing their engagement (e.g., performance) with the secondary task.

As automated driving becomes more mainstream it becomes necessary to investigate the most effective way enhance a drivers SA while simultaneously directing their attention back to the roadway (i.e., the "loop") as quickly as possible. One potential solution to this problem would be to develop a warning system on the smart phone (or other infotainment device that a driver might use while the automation is engaged) that is effective enough to both alert a driver of a critical event (as shown in Experiment 3) but additionally, to provide enough SA information about the critical event to the driver that they can quickly assess the situation and appropriately react.

The aim of the current study was to compare different types of auditory warnings designed to signal a take-over event in an automated driving scenario. To test this, drivers were asked to take-over control from the automated vehicle in response to obstacles on the roadway which required them to steer to the left or right around the obstacle or bring the vehicle to a stop in front of it. We were primarily interested in two questions. First, similar to the results of our Experiment 3, would take-over signals be more effective when presented at the location the driver was attending (i.e., their smart phone) as compared to signals presented at the location of the danger? Second, would responses to take-over requests be more effective when the signal contained apparent motion oriented towards the location of the obstacle on the roadway as compared to

non-directional signals as has been shown in manual driving conditions (e.g., Straughn, et al., 2009)? Specifically, this experiment was designed to test the following predictions.

(i)   Take-over performance will be improved (faster brake reaction and steering response times) in conditions with take-over request signals relative to the no signal baseline condition.

(ii)   Take-over performance will be significantly better for apparent motion signals as compared to signals that are static (i.e., no movement) as predicted by the observed benefits from auditory looming signals (Gray, 2011).

(iii)   Take-over performance will be significantly better for directional apparent motion signals (i.e., that are oriented towards to location of the obstacle) as compared to non-directional apparent motion signals (i.e., that are always just oriented towards the center of the road).

Method

Participants

13 undergraduates (mean age=22.4) from Arizona State University participated for partial fulfillment of an introductory psychology research requirement. All were native English speakers with normal or corrected-to-normal vision with a valid driver's license and were smart phone users.

Apparatus

The same apparatus was used as in Experiment 1, (*Chapter 2).*

Procedure

Driving Task

In the automated driving scenario, the vehicle's lateral position and speed was controlled by the simulator as the autonomous vehicle followed a lead vehicle on a straight stretch of a 3-lane road with intermittent road construction. On each drive, at a random time between 2-6 minutes, a critical event, TOR was programmed to occur. The critical events were designed so that they required the driver to make a decision about how to respond. They involved the lead car braking in response to lane closures and the control of the participant's vehicle switching from automated to manual. For some events, only two of the lanes were blocked and one was left open while for others all three lanes were closed. Drivers were instructed to steer into an open lane if there was one available or brake and come to a stop if there was not. In all conditions (described below), an auditory take-over signal was presented "early warning" given about 5 seconds prior to the control switching to back to manual. This timing is consistent with previous research that early warnings are more beneficial when the driver is signaled to the location of the danger because they assist in the driver's assessment of the situation (Straughn et al., 2009). Drivers were told that they would receive an auditory warning sound shortly before the automated vehicle switch to manual control in a critical situation. Drivers was told that task in these situation was to either: steer into an open lane (if possible) or if both lanes were blocked to brake as quickly as possible.

During each drive, participants were asked to perform a secondary task of watching a video on their smart phone. Participant's had a choice of watching one of three science video's that were presented on their phone via YouTube. Additionally, they

were asked to hold their smart phone with their right hand and at a level no higher than the steering wheel and to divide/shift their attention between the simulated roadway and phone as they felt most comfortable. They were informed they would be given a quiz about the video at the end of the experiment.

Takeover Request Signals

Four different auditory signals were compared to a no signal (NS) condition as follows:

Device to Danger (DD) – a 250-hz auditory tone was first presented from a speaker near smart phone location for a total of 300msec. After a delay of 100msec, a second auditory tone of the same frequency and duration was presented from a speaker mounted in the dashboard on the same side as the lane obstruction.

Device to Front (DF) - this warning was identical to the DD condition except that the second tone was always presented from a speaker mounted in the center of the dashboard.

Device Only (DO) - a 250-hz auditory tone was presented from a speaker near smart phone location. Note this warning was designed to have the same total duration (700msec) as the DD and DF warnings described above.

Front Only (FO) - a 250-hz auditory tone was presented from a speaker on a speaker mounted in the center of the dashboard. Note this warning was designed to have the same total duration (700msec) as the DD and DF warnings described above.

Data Analysis

Brake reaction times and steering reaction times were the dependent variables used to assess take-over performance. Note, under all conditions, drivers steering response was in the correct direction (i.e., towards the open lane) so we did not analyze steering accuracy. Furthermore, initial analyses revealed there was no significant effect of the side of the obstacle (i.e., left vs right). Therefore, steering and braking data were analyzed using separate One Way repeated measures ANOVAs with signal condition (DF, DO, FO, DD, No Signal) as the factors. Paired samples t-tests were used to test hypotheses (i, ii, & iii) listed above. For all results reported, statistical significance was set at $p<.05$. Effect sizes were calculated using partial eta squared (η_p^2) for ANOVAs and Cohen's *d* for *t*-tests.

Results

Steering Reaction Times

Figure 11 shows the mean Steering Reaction Times (SRT) for the five different driving conditions. The ANOVA performed on these data revealed a significant main effect of condition, $F(1,12) = 65.97$, $p<.000$, $\eta_p^2 = .85$. Consistent with hypothesis (i), SRT's were significantly slower in the non-warning baseline condition (Mean = 2.04 s) as compared to combined mean for all warning conditions (Mean = 1.35 s) revealed, $t(12) = -7.43$, $p < 0.000$, $d=2.03$).. Additionally, SRTs were significantly faster in conditions involving an apparent motion take-over signals (DF & DD, Combined Mean = 1.05 s) as compared to conditions with static signals (DO & FO, Combined Mean = 1.64 s), $t(25) = -12.94$, $p < 0.000$, $d=3.09$), supporting hypothesis (ii). Finally, SRT's were significantly

faster in conditions for which drivers were oriented to the danger (DD, Mean= .94s) as compared to being oriented to the front only (DF, Mean= 1.17 s), $t(12) = 7.84$, $p < 0.000$, d=2.62), supporting hypothesis (iii).

Mean SRT's

Figure 10- Mean steer reaction times (SRT) for the five different driving conditions. Error bars are standard errors.

Brake Reaction Times

A similar pattern of results was found for drivers BRT's to the critical event. Figure 12 shows the mean BRT's for the five different driving conditions. A one way repeated measures ANOVA performed on these data revealed a significant main effect of condition, $F(4,48) = 32.15$, $p<.000$, $\eta_p^2 = .73$. BRT's in the non-warning baseline condition (Mean = 1.55 s) were significantly faster than the combined mean for all

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warning conditions (Mean = 1.09 s) found that BRT's were significantly faster after a warning than when no warning was given, $t(12) = -7.26$, $p < 0.000$, $d=2.03$) , supporting our first prediction. Additionally, for the experimental conditions the independent samples t-test revealed that the conditions to which the auditory warning conveyed motion, (DF & DD, Mean = .93 s) were significantly faster as compared to static warning (DO & FO, Mean = 1.25 s), $t(25) = -6.63$, $p < 0.000$, $d=1.57$), supporting our second prediction. Lastly, the independent samples t-test revealed for only the conditions that the auditory warning conveyed orientating information, (DD and DF) BRT's were significantly faster when drivers were oriented to the danger (DD Mean= .81s) as compared to being oriented to the front only (DF Mean= 1.05 s), $t(12) = 5.05$, $p < 0.001$, $d=1.52$), supporting our third prediction.
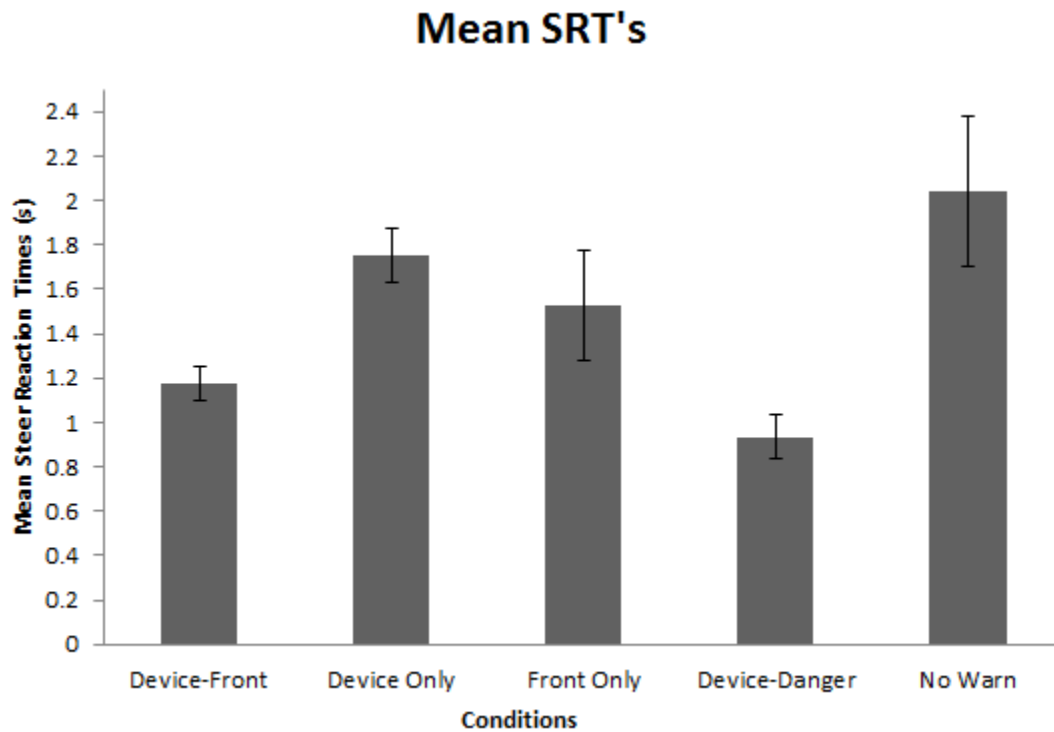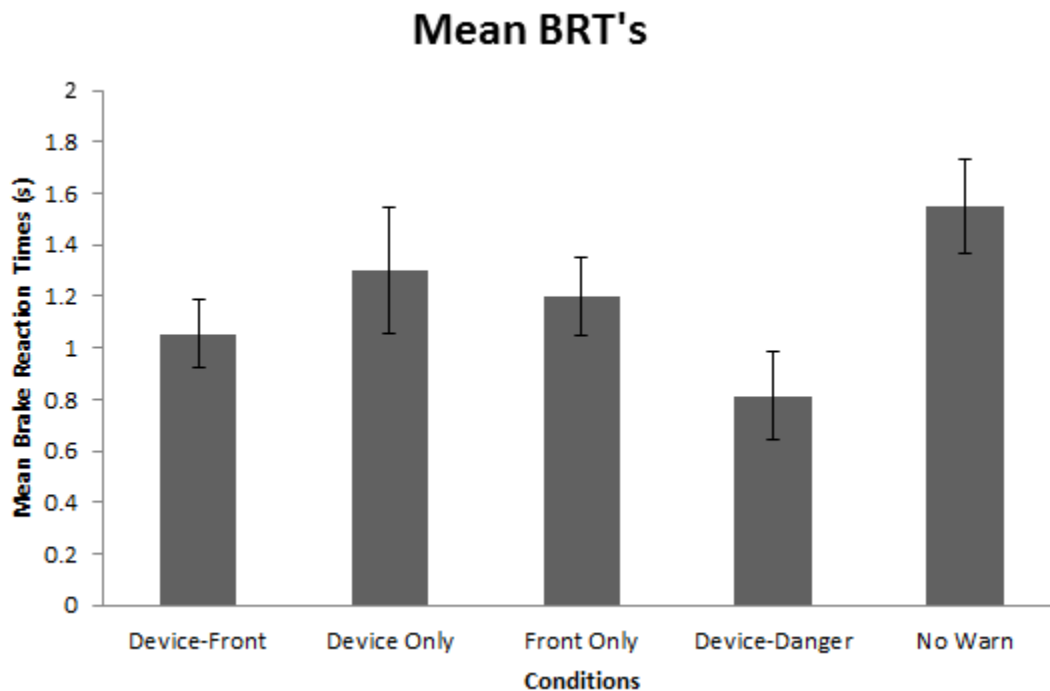

Figure 11- Mean brake reaction times (BRT) for the five different driving conditions. Error bars are standard errors.

Discussion

Recent research on distracted drivers supervising automated vehicles has started to investigate a driver's level of situation awareness (SA) at the time of request (TOR) (Ma et al., 2005; Gold et al., 2013, Louw, et al., 2014). In general, driving take-over performance when drivers are supervising an automated vehicle demonstrates that drivers tend to not fully take-over control when requested (de Waard, van der Hulst, Hoedemaeker, & Brookhuis, 1999). Additionally, it has been observed that the amount of time it takes for a driver to gain complete control of the vehicle after a TOR can be excessive. For instance, drivers can take 35-40 seconds to fully assess and appropriately respond to the situation (Merat et al., 2014). The goal of Experiment 4 was improve the responses of drivers in this critical situation by using an informative TOR signal, similar to those that have been employed for distracted manual driving. Specially, different auditory warnings, ones that conveyed motion and/or oriented the driver to the danger, were compared in terms of their ability to improve a driver's SA, by observing the drivers BRT's and SRT's to the critical event.

Given that general warning studies tend to show an improvement in BRT's to a critical event (Ho et al., 2013), our first hypothesis was that take-over performance would be improved (faster BRT's and SRT's) in conditions with take-over request signals relative to the no signal baseline condition. As expected, this hypothesis was supported for both dependent variables. Not only did the auditory warnings improve drivers BRT but also aided in a driver's ability to make a swerve decision faster (SRT) when there was a foreseen obstacle. These findings are consistent with previous research on auditory warnings (Scott & Gray, 2008; Mohebbi et al., 2009) and

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consistent with our Experiment 3 results, in which auditory warnings remained an effective modality, even when drivers were distracted by their smart phone.

Our second hypothesis, that take-over performance would be significantly better for apparent motion signals as compared to signals that are static (i.e., no movement) was also supported. This prediction was based on previous findings that warning signals that are able to convey some type of information about the critical event, such as motion, would be able to improve the reaction time and decision of the driver. These findings have been demonstrated in auditory looming signal research (Gray, 2011) as well as tactile warnings research in which the apparent that is presented as moving towards the driver's head or torso (Meng et al., 2015). Our results demonstrated that drivers that were given warnings that conveyed motion as compared to a static non-motion were effective in reducing BRT's and SRT's.

Lastly, our third hypothesis, that take-over performance would be significantly better for directional apparent motion signals (i.e., that are oriented towards the location of the obstacle) as compared to non-directional apparent motion signals (i.e., that are always just oriented towards the center of the road) was supported. This prediction was based on previous findings that attentive drivers can benefit from auditory warnings that provide SA information, specifically SA information that orient the driver to the danger (Straughn et al., 2009). Additionally, this work is congruent to previous findings such that simulating motion as moving away from the driver may potentially aid in reorienting a driver's attention to the collision event (Gray & Tan, 2002).

The pattern of BRT and SRT results in this experiment did not appear to reveal any significance or improvement when the take-over signals were presented at the

location the driver was attending (i.e., their smart phone) as compared to signals presented at the location outside their focus (i.e., the danger or dash). These results are not entirely consistent with Experiment 3's supplemental analysis, in which the location of the static auditory warning presented at the location the driver was attending (i.e., their smart phone) did make a difference. The reason for this discrepancy between experiments may be attributed to the experimental design differences, such that in the current study drivers were acting as a supervisor and not an active driver. Potential explanations for this discrepancy will be further explored and discussed in the overall general discussion. For this experiment, the significant finding was that the informative motion warnings improve BRT and SRT more so than the static non-informative warning.

There is a large body of research that attempts to warn a manual driver while simultaneously improving the driver's SA (Ho & Spence, 2005; Gray, Ho & Spence, 2014). Research on drivers being warned while supervising autonomous vehicles, are not as common. This experiment revealed similar results to previous work, such that, auditory warnings can be used to both alert an autonomous driver of the critical event, but that the warnings can convey information (Gray, 2011; Ho, Spence & Gray, 2013). Additionally, it was found that an autonomous driver can benefit from the information conveyed in the warning signal to improve their cognitive decision making when responding to the critical event. These findings suggest informative warnings that convey motion can not only orient a driver back to the main task of driving, but informative warnings that convey direction of the danger can be used to improve a drivers SA and quickly reorient them back "in-the-loop." While these results have

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potential to apply to autonomous vehicle safety, future work is necessary to improve

upon this concept

CHAPTER 6

GENERAL DISCUSSION

Distracted driving is defined as the diversion of attention away from the activities critical for safe driving and towards a competing activity (Lee, et al., 2008; Regan & Strayer, 2014). As previously discussed, due to a limited capacity of a driver's available cognitive resources, distracted driving is responsible for up to 30% of total crashes (NHTSA, 2013). Since 1995, distracted driving has been exacerbated by the development of the cell phone. Not only is the cell phone distracting when it is used for calling (Strayer & Johnston, 2001; Horrey & Wickens, 2006; Caird et al., 2008) but more recent evidence suggest that the distraction problem is further intensified with the advancement of smart phone technology (e.g., the text message, social media app's). This issue has become a growing concern for roadway officials, policymakers and automotive industry leaders leading to a variety of different attempts to mitigate driver distraction. Potential solutions have involved car assistive technologies including collision avoidance warning systems, lane departure warning systems, blind spot warning systems, and rear back-up camera warnings. Of specific interest to the current experiments was the question of how to best warn a distracted driver, an issue that has received surprisingly little research attention.

Previous research suggests that engaging in a secondary tasks while driving such as talking on the cell phone or text messaging may consequently render any warning virtually ineffective, despite the modality of the warning that is used (Mohebbi et al., 2009; Ahtamad et al., 2015). Although autonomous vehicles are able to offer a potential solution to many of the distracted driving issues, discovering methods to alert and re-

orient a driver is also important in automated driving (e.g., when the driver is required to take-over due to a control failure). The present research not only looked at the use of warnings on distracted drivers but aimed to discover the best warning implementation systems to quickly disengage a driver from specific sources of distraction, (i.e., their smart phones) and re-orient the driver's attention in the event of a critical incident. The present set of studies, across four experiments, aimed to tackle this problem from multiple angles.

Experiment 1 examined the relative degree of distraction produced by a set of commonly used smart phone tasks. In particular, we were interested in comparing app's or tasks that were primarily text- based (i.e., scrolling through Facebook, Twitter newsfeeds) with image- based (i.e., Instagram, Snapchat) apps. Additionally, we wanted to understand how task pacing (i.e., either responding at their leisure, or being required to respond to the experimenter immediately) impacted driving performance. Results revealed that text conditions created significantly longer BRT's and larger TH variability as compared to image-based conditions. Interestingly, we did not observe any significant effect of task pacing (e.g., self vs experimenter) on driving performance. These overall findings were consistent with the general finding that smart phone use is distracting and impairs driving performance. Based on the prevalence of smart phones as well as the availability of many text- based applications on the market (e.g., Facebook, Twitter, etc.) the next logical step was to investigate potential solutions to mitigate driver smart phone distraction.

Experiment 2 was concerned with mitigating driver distraction through safe driving smart phone apps. Several smart phone app's have recently been developed that

attempt to regulate a driver's use of their smart phone in some manner. We were interested in how people use and interact with these various safe driving app's and how these app's might impact a driver's driving performance. In this experiment, we simulated four different application modes, and compared them to a baseline, no phone condition. The modes varied by either allowing drivers to check their messages or not and whether or not the driver heard an audible alert of the received messages. While driving around a simulated urban environment, participants received text messages from an experimenter that were clues to a riddle. Results demonstrated that for all conditions in which drivers had their phone in the car (regardless of mode), mean driving speed and lane positive variability were significantly higher. Additionally, allowing drivers to check their messages when stopped (e.g. at a red light) produced significant delays in reaction times and higher lane position variability when driving started again, as compared to the other modes. These results are consistent with research using a simple laboratory task which has shown that when phones that are turned off or blocked they can still cause distracting task-irrelevant thoughts produced by the expectation of receiving an important message (Stothart et al., 2015). They also suggest that restricting smart phone use is not an effective method for reducing the effects of distraction on driving performance.

Unfortunately, as demonstrated in Experiment 2, even app's that help to regulate incoming information can be a source of distraction. Drivers want to stay connected as much as possible. Due to the likelihood that drivers will engage with their smart phones at some point in their drive, a potential solution for warning a distracted driver needs to be explored. This was attempted, in Experiment 3, in which both auditory and tactile

warnings were given to drivers while they were watching a movie on their smart phone. The warnings attempted to convey directional information of either moving towards or away from the driver and were compared to a no movement condition. Results revealed that only the auditory warnings produced a significant reduction in BRT's to the critical event and there was no significant effect of simulated movement direction. A follow-up analysis found that drivers benefited from a warning presented at the location of their smart phone as compared to warnings delivered from the dashboard, as is typically done in most existing collision warning systems. Overall, these results suggest that a warning given at the source of distraction (i.e., near the location of the driver's attential focus) may be the most effective method for mitigating driver distraction.

The goal of Experiment 4 was to extend the present research beyond the topic of driver distraction during manual driving to consider the related issue of take-over requests (TOR) in automated driving. Specifically, In Experiment 4, drivers were asked to take-over control from a simulated automated vehicle in response to obstacles on the roadway. Similar to Experiment 3, auditory warnings that conveyed motion information (in this case, either moving towards the location of danger of towards the center of the roadway) were used and were compared to a static warnings (delivered either on the dashboard or at the location of the smart phone). Results revealed that drivers of an autonomous vehicle benefited from the use of an informative motion warning. Specifically, an auditory warning that was first triggered at the location of the smart phone and then in the location of the danger, lead to significantly larger reductions in BRT's to a critical event as compared to all other warnings.

Experiments 1 and 2 were a starting point in understanding which smart phone tasks are the most distracting to a driver as well as investigating the effectiveness of different types of smart phone apps which restrict phone usage during driving. These two studies together demonstrated that drivers are most distracted by text-based app's (i.e., reading Facebook status updates) and even when the smart phone is turned off (i.e., using an blocking app) driving performance is still significantly impaired as compared to when their smart phone is turned off. From these findings, Experiment 3 and 4 explored new methods for warning a distracted driver. Novel to these studies was presenting warnings from the source of the distraction, using either a sound triggered at the smart phone location or presenting a vibration given on the wrist of the hand holding the smart phone. The goal was to explore the possibility of breaking the driver's attentional focus on their smart phone as well as finding the best methods to improve the driver's situation awareness by conveying direction and location information in the warning itself.

Experiment 3 and 4 found that warning a distracted driver was achievable, primarily by using auditory warnings. Interestingly, Experiment 3 found no benefit of conveying motion in the warning to the driver, while Experiment 4 did. Also, Experiment 3 found that warning a driver near their location of attentional focus (i.e., the smart phone) versus outside of their area of attentional focus (i.e., the dash) improved a driver's BRT, while Experiment 4 found no such benefit. The likely reason for this discrepancy between experiments is differences in the nature of the driving task. In Experiment 3, drivers were actively engaged in controlling the vehicle while in Experiment 4, drivers were passively supervising the vehicle until the takeover request

was issued. Differences in how a driver responded to the warnings in the present experiments may have been attributed to their level of responsibility in maintaining control of the vehicle. Due to the active engagement and high level of responsibility in Experiment 3, the perceptual-cognitive demands of the task (both driving and using their smart phone) may have been too high to allow them to fully process the motion information contained in the warning. On the contrary, the passive nature of Experiment 4 may have given the driver the necessary processing resources to utilize the motion information contained in the warning. Additionally, driver controlling the vehicle manually, as in Experiment 3, may have been more conscious of their lack of attention on the roadway resulting in quicker responses to warnings when presented closer to their area of focus, near their smart phone. Conversely, a driver passively monitoring an automated vehicle, as in Experiment 4, may have reacted similarly in ALL warning conditions based on the assumption that they are not fully responsible for the driving performance of the vehicle.

Moreover, the differences between the outcomes in both Experiments 3 and 4 may have been attributable to the warning timing. In Experiment 3 drivers were given a relatively late warning (e.g., TTC less than 3 seconds) while in Experiment 4 drivers were given a relatively early warning (e.g., TTC of 5 seconds). As Straughn et al. (2009) demonstrated, the timing of a warning prior to the critical event can make a difference how a driver may react. When the warning is given early enough, drivers are more able to assess the situation and act in a more appropriate manner as compared to drivers given late warnings who must react immediately without fully assessing the situation. Experiment 3's late warning may have contributed to drivers reacting in a

more erratic manner as well as causing drivers to become more reliant on the origination of the warning's location for the response. Conversely, Experiment 4's early warning may have contributed to drivers reacting in a more calm manner due to more processing time to process the information that was conveyed as well as allowing drivers to respond to any warning despite the location it originated.

Theoretical Implications

Lee (2014) proposed an account of warning a distracted driver which involves "managing interruptions." Of the four stages, our study is concerned with the first three; *detect, interpret, and shift attention.* The present results have several important implications for this theory. First, the results of the present experiments suggest that a driver's ability to successfully *detect* a warning is highly dependent on the nature of the secondary task being performed. While drivers in previous research have been found to not respond to auditory warnings when engaging in auditory tasks, these tasks were generally active in nature, such as talking with a passenger or on their cell phone (Mohebbi, et al., 2009). In the present experiments, drivers were passively processing auditory information from videos which may have essentially given them more processing capacity to detect auditory warnings Similarly, the tactile warnings used in the present study (which have shown to be highly effective in previous research involving hands-free secondary tasks) were ineffective in reducing BRTs. Thus, that act of having to actively hold an object (e.g., their smart phone) may change a driver's ability to detect tactile warnings.

Secondly, in this set of experiments, distracted drivers differed in their ability to accurately *interpret* directional information conveyed in the warning based on their driving task responsibility (i.e., manual or passive driving) as well as the timing of the warnings (i.e., early or late). When drivers were a passive supervisor of an autonomous vehicle and given an early warning, they were more likely to benefit from the warnings that conveyed motion versus static warnings. There was no such warning benefit when drivers controlled the vehicle manually and were given a late warning. These findings suggest that the nature of the driving task may directly influence the interpretation of warning signals.

Similarly, these findings revealed that distracted drivers differed in their ability to *shift their attentional focus* depending on, again, the driver responsibility type. For manual drivers, a warning that was given at the location near the driver's smart phone, as compared to given on the dash was more likely to have the ability to re-orient the driver's attention to the roadway, not towards the phone, as would be predicted by Posner (1980). On the other hand, for passive drivers, the origination location did not appear to improve re-orientation ability (i.e., demonstrated by brake and steer reaction times in response to static warnings). These findings illustrate that the level of responsibility/control may have an influence on how a driver re-orients their attention.

Thirdly, one of the most intriguing findings to come from these experiments was that drivers of autonomous vehicles were able to improve SA through the use of an informative warning. Specifically, with informative auditory warnings were given (e.g. that originated at the source of distraction and ended at the location of the danger) drivers significantly improved their brake and steer reaction times to a critical event.

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This finding suggests that the signal aided in their ability to quickly evaluate the situation and has theoretical implications for the theory of SA in which informative warnings may be able to successfully improve one's SA when supervising an autonomous vehicle. Further testing should be explored to understand these capabilities and limitations.

Lastly, the results of these experiments have theoretical implications for the theory of mind-wandering while driving (McVay & Kane, 2009). Our results were consistent with Stothart et al., (2015) findings that a person may show performance decrements after hearing an alert on their phone while engaged with a primary task as well as consistent with Yanko and Spalek's (2013) findings that notifications while driving can prompt task-irrelevant thoughts. These results extended these theories such that, a drivers overall driving performance was shown to be reduced when drivers THINK about the possibility of receiving a message, but do not actually hear the alert. These findings are in accordance with the FoMo theory (Przybylsk et al., 2013) and extend to drivers on their smart phones.

Practical Implications

The present set of experiments had important practical guidelines for automotive design for information presentation. These were as follows (1) when presenting information to a driver via a visual display use images instead of text whenever possible. (2) When attempting to restrict incoming messages or alerts to a driver be aware of the timing they are received by the driver as well as the implications for

withholding their ability to engage with the device. These findings will are important to take into account when designing how to present information to a driver.

Furthermore, these experiments had practical guidelines for how to design warnings for a driver, specifically, a distracted MANUAL driver that is engaged with a device. (1)Warnings given near the location of their attentional focus can be beneficial method to break a driver's attention with their device. (2) Drivers using their smart phone for audio/visual tasks will respond quicker to an auditory alert than a tactile alert. (3) Static warnings are equally beneficial as warnings that convey motion. These findings will be important to take into account when designing and implementing new methods to warn a manual distracted driver.

In the near future, the prevalence of autonomous vehicles on the roadways will increase. Therefore, understanding how drivers respond during a take-over request with an autonomous vehicle will increasingly important issue. This research was aimed at understanding and applying warnings to drivers of autonomous vehicles that are distracted, as they may differ from manual driving distracted and waring behaviors. These findings too have practical implications for warning design of autonomous vehicles in the future. Specifically (1) an automated drivers SA might actually be improved by giving them an informative motion warning and (2) improved SA at TOR can be accomplished by warning the driver first near or at their device and then near the location of the danger.

Limitations

Although these set of experiments contained many interesting findings they are not without limitations. First, it would have been beneficial to have included an analysis of eye gaze and eye glance behavior via an eye-tracking system. Gaze and glance behavior has been shown to provide insight as to what a driver's level of trust in a system as well as an indicator of their level of SA. Our main focus for assessing a driver's distraction level in these experiments was the overall brake reaction and steer reaction times. If we had the analysis of the time it took drivers to look up after getting an alert this would have provided a more complete picture of the re-orienting response. Furthermore, it would have allowed us to determine whether the responses to the warnings differed depending on whether the driver was looking at their phone or at the roadway.

Another potential limitation of these experiments was the frequency of the events that the driver was required to respond to. In Experiments 1-3, a potential rear-end collision occurred roughly once every 2 minutes while in Experiment 4, the take-over request from the automated driving system occurred after 2-6 minutes of driving. These are; of course, at much higher frequencies than we would expect in real driving and thus may have made drivers in the present study unnaturally attentive (Ho, Gray & Spence, 2014).

Future Research

Future research is necessary to explore how information can be best conveyed so that a driver may quickly *interpret* and most effectively *shift their attention* to the roadway in a critical event. Different warning methods that aim to improve a driver's SA are worth future investigation, such as manipulating the informative warning or combining modalities. The auditory modality could be improved to provide more tones or auditory messages with explicit instructions on what is happening or through the use of auditory 3-D mapping. Future research could also investigate the use of visual warning modalities such as visual LED strips to direct attention, visual messages on the phone itself, or hologram visual images overlaid on the windshield. The tactile modality could be more heavily explored such as stronger tactile warnings embedded in the seat belt, embedded in the driver's seat or in a contained in a glove or mounted to the back of the smart phone. A wide range of options could result in faster reaction times and may be used in conjunction with a novel app design.

As we discovered, a driver's perceived responsibility with the vehicle (i.e., either manual or automated control) plays a role in how they respond to the warnings. Future research that manipulates the driver's expectancies and responsibilities while simultaneously being warned is worthwhile. This could achieved by either providing instructions about the vehicles capabilities prior to engagement or by alternating the mode (i.e., either manual or automated) after they begin their driving session.

CHAPTER 7

CONCLUSION

The prevalence of drivers engaging with a smart phone for a variety of tasks is becoming a real world concern. From the perspective that drivers ARE engaging with their smart phone while driving, the goal of this study was to determine the most effective methods for warning a distracted dirver. First, we were interested in what smart phone tasks are the most distracting to the driver. Our results demonstrated that text-based app's/tasks contributed to the worst driving performance. Also, we found additional evidence that is consistent with the notion that people do not want to be removed from social connectivity or disconnected form work productivity (FoMo, Przybylsk et al., 2013). Our results revealed that as engagement with app's that block or restrict incoming information that drivers are thinking about can actually lead to impaired driving performance.

Once these initial findings were established, we had drivers engage in a distracting task of watching videos on their smart phone while driving either manually or as a supervisor of an autonomous vehicle. Novel to the warnings design was that they were presented to a distracted driver via sounds or vibrations that were given near the source of the distraction, their smart phone, in hopes to reveal an increase in their reaction times to a critical event. The warnings attempted to convey directional information of either moving towards the driver, away from the driver or no movement and to understand what modality (auditory or tactile) was most effective. Specifically, results found that warnings that were presented near a driver's smart phone were only beneficial to manual drivers (Experiment 3) and that simulated motion were only

beneficial to drivers in an autonomous vehicle (Experiment 4). While warning a

distracted driver proves to be challenging, hopefully more applied studies such as these

may shed light on alternative, novel and beneficial methods for alerting a distracted

driver.

References

Abe, G., & Richardson, J. (2006). Alarm timing, trust and driver expectation for forward collision warning systems. *Applied Ergonomics*, *37*(5), 577-586.

Ahtamad, Spence, Meng, Ho, McNabb & Gray (under review). Examining the effect of driver distraction and tactor location on the effectiveness of tactile collision warnings.

Aldrich, F. K., & Parkin, A. J. (1989). Listening at speed. *British Journal of Visual Impairment*, *7*(1), 16-18.

ATT&T Newsroom. (2015, October). Retrieved from http://about.att.com/story/smartphone_use_while_driving_grows_beyond_texting.html

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. *The psychology of learning and motivation*, *8*, 47-89.

Basacik, D., Reed, N., & Robbins, R. (2012). Smartphone use while driving: a simulator study. Berkshire, UK: Transport Research Laboratory.

Belz, S. M., Robinson, G. S., & Casali, J. G. (1999). A new class of auditory warning signals for complex systems: Auditory icons. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *41*(4), 608-618.

Ben-Yaacov, A., Maltz, M., & Shinar, D. (2002). Effects of an in-vehicle collision avoidance warning system on short-and long-term driving performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*,*44*(2), 335-342.

Bliss, J. P., & Acton, S. A. (2003). Alarm mistrust in automobiles: how collision alarm reliability affects driving. *Applied ergonomics*, *34*(6), 499-509.

Botzer, A., Musicant, O. & Perry, A. (2017). Driver behavior with a smartphone collision warning application – A field study. *Safety Science, 91*, 361-372.

Burgett, A. L., Carter, A., Miller, R. J., Najm, W. G., & Smith, D. L. (1998, June). A collision warning algorithm for rear-end collisions. In *16th International Technical Conference on Enhanced Safety of Vehicles (ESV), Windsor, Canada*.

Caird, J. K., Johnston, K. A., Willness, C. R., Asbridge, M., & Steel, P. (2014). A meta-analysis of the effects of texting on driving. *Accident Analysis & Prevention*, *71* (October), 311-318.

Caird, J. K., Willness, C. R., Steel, P., & Scialfa, C. (2008). A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis & Prevention*, *40*(4), 1282-1293.

Centers for Disease Control and Prevention. Injury Prevention & Control: Motor Vehicle Safety, Distracted Driving. Available at http://www.cdc.gov/motorvehiclesafety/distracted_driving/ Accessed June 7, 2015

Cooper, J. M., Ingebretsen, H., & Strayer, D. L. (2014). Mental Workload of Common Voice-Based Vehicle Interactions across Six Different Vehicle Systems.

Denton, G. G. (1980). The influence of visual pattern on perceived speed. Perception, 9(4), 393-402.

De Pisapia, N., & Braver, T. S. (2006). A model of dual control mechanisms through anterior cingulate and prefrontal cortex interactions. *Neurocomputing*,*69*(10), 1322-1326.

Dixon, N. F., & Spitz, L. (1980). The detection of auditory visual desynchorony. *Perception*, *9*(6),719-721.

Drews, F. A., Pasupathi, M., & Strayer, D. L. (2008). Passenger and cell phone conversations in simulated driving. *Journal of Experimental Psychology: Applied*, *14*(4), 392.

Drews, F. A., Yazdani, H., Godfrey, C. N., Cooper, J. M., & Strayer, D. L. (2009). Text messaging during simulated driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 51*(5), 62-762. doi:10.1177/0018720809353319

Edworthy, J. (1994). The design and implementation of non-verbal auditory warnings. *Applied ergonomics*, *25*(4), 202-210.

Edworthy, J., Stanton, N., & Hellier, E. (1995). Warnings in research and practice. *Ergonomics 38*(11), 2145-2154.

Ferris, T., Penfold, R., Hameed, S., & Sarter, N. (2006, October). The implications of crossmodal links in attention for the design of multimodal interfaces: A driving simulation study. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 50, No. 3, pp. 406-409). Sage Publications.

Fitch, G. M., Kiefer, R. J., Hankey, J. M., & Kleiner, B. M. (2007). Toward developing an approach for alerting drivers to the direction of a crash threat. *Human Factors: The Journal of the Human Factors and Ergonomics Society*,*49*(4), 710-720.

Fricke, N., & Thüring, M. (2009, October). Complementary audio-visual collision warnings. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 53, No. 23, pp. 1815-1819). Sage Publications.

Friedenberg, J., & Silverman, G. (2011). *Cognitive science: An introduction to the study of mind*. Sage.

Graham-Little, E. (1934). The Human Factor in Road Accidents. *British medical journal, 1*(3824), 730.

Graham, R. (1999). Use of auditory icons as emergency warnings: evaluation within a vehiclecollision avoidance application. *Ergonomics*, *42*(9), 1233-1248.

Gray, R. (2005). The use and misuse of visual information for "go/no-go" decisions in driving. Hennessy, D. & Wiesenthal, D. (Eds.).*Contemporary Issues in Traffic Research and Road User Safety. pp. 125-133.* New York: Nova Science Publishers.

Gray, R. (2011). Looming auditory collision warnings for driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *53*(1), 63-74.

Gray, R., Ho, C., & Spence, C. (2014). A comparison of different informative vibrotactile forward collision warnings: Does the warning need to be linked to the collision event? *PLoS ONE 9(1):* e87070. doi:10.1371/journal.pone.0087070

Gray, R., & Tan, H. Z. (2002). Dynamic and predictive links between touch and vision. *Experimental Brain Research*, *145*(1), 50-55.

Hanowski, R., & Kantowitz, B. (1997). Driver memory retention of in-vehicle information system messages. *Transportation Research Record: Journal of the Transportation Research Board*, (1573), 8-16.

Hawkins Jr, H., Womack, K. N., & Mounce, J. M. (1993). Driver comprehension of regulatory signs, warning signs, and pavement markings. *Transportation research record*, (1403).

He, J., Chaparro, A., Nguyen, B., Burge, R. J., Crandall, J., Chaparro, B., ... & Cao, S. (2014). Texting while driving: Is speech-based text entry less risky than handheld text entry?. *Accident Analysis & Prevention*, *72*, 287-295.

Ho, C. C., Gray, R., & Spence, C. (2014). Reorienting driver attention with dynamic tactile cues. *Haptics, IEEE Transactions on*, *7*(1), 86-94.

Ho, C., Gray, R., & Spence, C. (2014). To what extent do the findings of laboratory-based spatial attention research apply to the real-world setting of driving? *IEEE Transactions on Human-Machine Systems, 44*, 524-530

Ho, C., Santangelo, V., & Spence, C. (2009). Multisensory warning signals: when spatial correspondence matters. *Experimental Brain Research*, *195*(2), 261-272.

Ho, C., & Spence, C. (2005). Assessing the effectiveness of various auditory cues in capturing a driver's visual attention. *Journal of experimental psychology: Applied*, *11*(3), 157.

Ho, C. and C. Spence (2008). *The multisensory driver: Implications for ergonomic car interface design*. Aldershot: Ashgate.

Ho, C., Spence, C., & Gray, R. (2013). Looming auditory and vibrotactile collision warnings for safe driving. *Proceedings of 7th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 551-557, Bolton Landing, NY.

Ho, C., Reed, N., & Spence, C. (2006). Assessing the effectiveness of "intuitive" vibrotactile warning signals in preventing front-to-rear-end collisions in a driving simulator. *Accident Analysis & Prevention*, *38*(5), 988-996.

Ho, C., Reed, N., & Spence, C. (2007). Multisensory in-car warning signals for collision avoidance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *49*(6), 1107-1114.

Holmes, N. P., & Spence, C. (2005). Multisensory integration: space, time and superadditivity. *Current Biology*, *15*(18), R762-R764.

Horrey, W. J., Lesch, M. F., & Garabet, A. (2008). Assessing the awareness of performance decrements in distracted drivers. *Accident Analysis & Prevention*,*40*(2), 675-682.

Horrey, W. J., & Wickens, C. D. (2006). Examining the impact of cell phone conversations on driving using meta-analytic techniques. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *48*(1), 196-205.

Horrey, W. J., Wickens, C. D., & Alexander, A. L. (2003). The effects of head-up display clutter and in-vehicle display separation on concurrent driving performance. In *Proceedings of the   Human Factors and Ergonomics Society Annual Meeting* (Vol. 47, No. 16, pp. 1880-1884). SAGE Publications.

Hosking, S. G., Young, K. L., & Regan, M. A. (2009). The effects of text messaging on young drivers. *Human Factors: The Journal of the Human Factors and Ergonomics society, 51*(4), 582-582.

Jones, W. D. (2002). Building safer cars. *Spectrum, IEEE*, *39*(1), 82-85.

Kahneman, D. (1973). *Attention and effort* (p. 246). Englewood Cliffs, NJ: Prentice-Hall.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic bulletin & review*, *9*(4), 637-671.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of experimental psychology: General*, *132*(1), 47.

Klüver, M., Herrigel, C., Heinrich, C., Schöner, H. P., & Hecht, H. (2016). The behavioral validity of dual-task driving performance in fixed and moving base driving simulators. *Transportation research part F: traffic psychology and behaviour*, *37*, 78-96.

Kiefer, R. J. (2000). Developing a forward collision warning system timing and interface approach by placing drivers in realistic rear-end crash situations. In Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society (Vol. 3, pp. 308–311). Santa Monica, CA: Human Factors and Ergonomics Society

Lee, J. D. (2014). Dynamics of driver distraction: The process of engaging and disengaging. *Annals of advances in automotive medicine*, *58*, 24.

Lee, J. (2014). *Integrating the saliency map with distract-r to assess driver distraction of vehicle displays* (Doctoral dissertation, THE UNIVERSITY OF WISCONSIN-MADISON).

Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *44*(2), 314-334.

Lee, J. D., Regan, M. A. & Young, K. L. (2008). Defining driver distraction. *Driver distraction: Theory, effects, and mitigation*, 31-40.

Lee, J. H., & Spence, C. (2008, September). Assessing the benefits of multimodal feedback on dual-task performance under demanding conditions. In *Proceedings of the 22nd British HCI Group Annual Conference on People and Computers: Culture, Creativity, Interaction-Volume 1* (pp. 185-192). British Computer Society.

Louw, T., Merat, N., & Jamson, H. (2015). Engaging with highly automated driving: to be or not to be in the loop. In *8th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.

Louw, T., & Merat, N. (2017). Are you in the loop? Using gaze dispersion to understand driver visual attention during vehicle automation. *Transportation Research Part C: Emerging Technologies*, *76*, 35-50.

Maretzke, J., & Jacob, U. (1992). Distance warning and control as a means of increasing road safety and ease of operation. In *XXIV FISITA CONGRESS, 7-11 JUNE 1992, LONDON. HELD AT THE AUTOMOTIVE TECHNOLOGY SERVICING SOCIETY. TECHNICAL PAPERS. SAFETY, THE VEHICLE AND THE ROAD. VOLUME 1 (IMECHE NO C389/359 AND FISITA NO 925214)*.

Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science*, *315*(5810), 393-395.

McCartt, A. T., & Geary, L. L. (2004). Longer term effects of New York State's law on drivers' handheld cell phone use. *Injury prevention*, *10*(1), 11-15.

McEvoy, S. P., Stevenson, M. R., & Woodward, M. (2007). The contribution of passengers versus mobile phone use to motor vehicle crashes resulting in hospital attendance by the driver. *Accident Analysis & Prevention*, *39*(6), 1170-1176.

McNabb, J., & Gray, R. (2016). Staying connected on the road: a comparison of different types of smart phone use in a driving simulator. *PLoS one*, *11*(2), e0148555.

McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*,*35*(1), 196.

Meng, F., Gray, R., Ho, C., Ahtamad, M., & Spence, C. (2015). Dynamic vibrotactile signals for forward collision avoidance warning systems. *Human factors*, *57*(2), 329-346.

Meng, F., & Spence, C. (2015). Tactile warning signals for in-vehicle systems. *Accident Analysis & Prevention*, *75*, 333-346.

Merat, N., Jamson, A. H., Lai, F. C., Daly, M., & Carsten, O. M. (2014). Transition to manual: Driver behaviour when resuming control from a highly automated vehicle. *Transportation research part F: traffic psychology and behaviour*, *27*, 274-282.

Mohebbi, R., Gray, R., & Tan, H. Z. (2009). Driver reaction time to tactile and auditory rear-end collision warnings while talking on a cell phone. *Human Factors: The Journal of the Human Factors and   Ergonomics Society*, *51*(1), 102-110.

Musicant, O. & Lotan, T. (2016). Can novice drivers be motivated to use a smartphone based app that monitors their behavior? *Transportation Research Part F: Traffic Psychology and Behaviour, 42*, 544–557

Nasar, J., Hecht, P., & Wener, R. (2008). Mobile telephones, distracted attention, and pedestrian safety. *Accident Analysis & Prevention*, *40*(1), 69-75.

National Highway Traffic Safety Administration. (2013). *Traffic safety facts 2013: A compilation of motor vehicle crash data from the fatality analysis reporting system and the general estimates system* (NHTSA Publication No. DOT- HS-810-818). Washington, DC: U.S. Department of Transportation.

Navarro, J., Mars, F., & Hoc, J. M. (2007). Lateral control assistance for car drivers: a comparison of motor priming and warning systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *49*(5), 950-960.

Parasuraman, R., Hancock, P. A., & Olofinboba, O. (1997). Alarm effectiveness in driver-centred collision-warning systems. *Ergonomics*, *40*(3), 390-399.

Patterson, R. D. (1989). Guidelines for the design of auditory warning sounds. In *Proceedings of the Institute of Acoustics 1989 Spring Conference* (Vol. 11, No. 5, pp. 17-24).

Peters, G. A., & Peters, B. J. (2001). The distracted driver. *The journal of the Royal Society for the Promotion of Health*, *121*(1), 23-28.

Pew Research http://www.pewinternet.org/fact-sheets/mobile-technology-fact-sheet/

Posner, M. I. (1980). Orienting of attention. *Quarterly journal of experimental psychology 32*(1), 3-25.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of experimental psychology: General*, *109*(2), 160.

Przybylski, A. K., Murayama, K., DeHaan, C. R., & Gladwell, V. (2013). Motivational, emotional, and behavioral correlates of fear of missing out. *Computers in Human Behavior*, *29*(4), 1841-1848.

Regan, M. A., & Strayer, D. L. (2014). Towards an understanding of driver inattention: taxonomy and theory. *Annals of advances in automotive medicine*, *58*, 5.

Sahayadhas, A., Sundaraj, K., & Murugappan, M. (2012). Detecting driver drowsiness based on sensors: a review. *Sensors*, *12*(12), 16937-16953.

Sanbonmatsu, D. M., Strayer, D. L., Behrends, A. A., Ward, N., & Watson, J. M. (2016). Why drivers use cell phones and support legislation to restrict this practice. *Accident Analysis & Prevention, 93, 22-33*

Santangelo, V., & Spence, C. (2007). Multisensory cues capture spatial attention regardless of perceptual load. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(6), 1311.

Saiprasert, C., Supakwong, S., Sangjun, W., & Thajchayapong, S. (2014). Effects of smartphone usage on driver safety level performance in urban road conditions. 1-6. doi:10.1109/ECTICon.2014.6839778

Salvendy, G. (2012). *Handbook of human factors and ergonomics*. John Wiley & Sons.

Salvucci, D. D., Zuber, M., Beregovaia, E., & Markley, D. (2005, April). Distract-R: Rapid prototyping and evaluation of in-vehicle interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 581-589). ACM.

Scott, J. J. & Gray, R. (2008). Comparison of visual, auditory and tactile warnings for rear-end collision prevention in driving. *Human Factors*, *50*, 264-275.

Selcon, S. J., Taylor, R. M., & McKenna, F. P. (1995). Integrating multiple information sources: Using redundancy in the design of warnings. *Ergonomics*,*38*(11), 2362-2370.

Simons, D. J., Chabris, C. F., (2015, October). A Simple Solution for Distracted Driving. *The Wall Street Journal.* Retrieved from http://www.wsj.com/articles/a-simple-solution-for-distracted-driving-1446218317

Six Annual State Farm Distracted Driving Survey (2014). http://www.multivu.com/players/English/7292854-state-farm-distracted-driving-survey cellphone-use/

Smith, P., Shah, M., & da Vitoria Lobo, N. (2003). Determining driver visual attention with one camera. *IEEE Transactions on Intelligent Transportation Systems, 4*(4), 205-218. doi:10.1109/TITS.2003.821342

Sojourner, R. J., & Antin, J. F. (1990). The effects of a simulated head-up display speedometer on perceptual task performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *32*(3), 329-339.

Spence, C., & Driver, J. (1997). Cross-modal links in attention between audition, vision, and touch: Implications for interface design. *International Journal of Cognitive Ergonomics, 1*(4), 351-373.

Spence, C., & Ho, C. (2012). *The multisensory driver: Implications for ergonomic car interface design*. Ashgate Publishing, Ltd..

Spence, C., & Squire, S. (2003). Multisensory integration: maintaining the perception of synchrony. *Current Biology*, *13*(13), R519-R521.

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. The MIT Press.

Stothart, C., Mitchum, A., & Yehnert, C. (2015). The attentional cost of receiving a cell phone notification. *Journal of experimental psychology: human perception and performance,41*(4), 893.

Straughn, S. M., Gray, R., & Tan, H. Z. (2009). To go or not to go: Stimulus-response compatibility for tactile and auditory pedestrian collision warnings. *Haptics, IEEE Transactions on*, *2*(2), 111-117.

Strayer, D. L. (2015). Is the Technology in Your Car Driving You to Distraction?. *Policy insights from the behavioral and brain sciences*, *2*(1), 157-165.

Strayer, D. L., Cooper, J. M., & Drews, F. A. (2004, September). What do drivers fail to see when conversing on a cell phone?. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 48, No. 19, pp. 2213-2217). SAGE Publications.

Strayer, D. L., & Drews, F. A. (2007). Cell-phone–induced driver distraction.*Current Directions in Psychological Science*, *16*(3), 128-131.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of experimental psychology: Applied*, *9*(1), 23.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological science*, *12*(6), 462-466.

Stutts, J., Feaganes, J., Rodgman, E., Hamlett, C., Reinfurt, D., Gish, K., ... & Staplin, L. (2003). The causes and consequences of distraction in everyday driving. In *Annual Proceedings/Association for the Advancement of Automotive Medicine* (Vol. 47, p. 235). Association for the Advancement of Automotive Medicine.

Sundeen, M. (2005). Cell Phones and Highway Safety. In *National conference of state legislatures* (p. 2).

Van Erp, J. B., & Van Veen, H. A. (2004). Vibrotactile in-vehicle navigation system. *Transportation Research Part F: Traffic Psychology and Behaviour*,*7*(4), 247-256.

vanWinsum, W., & Heino, A. (1996). Choice of time-headway in car-following and the role of time- to- collision information in braking. Ergonomics, 39(4), 579-592.

Watson, J. M., & Strayer, D. L. (2010). Supertaskers: Profiles in extraordinary multitasking ability. *Psychonomic Bulletin & Review*, *17*(4), 479-485.

Wickens, C. D., Martin-Emerson, R., & Larish, I. (1993). Attentional tunneling and the head-up display.

Wilson, F. A., & Stimpson, J. P. (2010). Trends in fatalities from distracted driving in the United States, 1999 to 2008. *American journal of public health*,*100*(11), 2213-2219.

Yanko, M. R., & Spalek, T. M. (2013). Driving with the wandering mind the effect that mind-wandering has on driving performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 0018720813495280.

Young, K. L., Rudin-Brown, C. M., Patten, C., Ceci, R., & Lenné, M. G. (2014). Effects of phone type on driving and eye glance behaviour while text-messaging. *Safety Science, 68*, 47-54. doi:10.1016/j.ssci.2014.02.018

Zeeb, K., Buchner, A., & Schrauf, M. (2015). What determines the take-over time? An integrated model approach of driver take-over after automated driving. *Accident Analysis & Prevention, 78*, 212-221.

Zeigarnik, B. (1938). On finished and unfinished tasks. *A source book of Gestalt psychology*, *1*, 300-314.

APPENDIX A

NASA-TLX TASK

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand How mentally demanding was the task?

Very Low   Very High

Physical Demand How physically demanding was the task?

Very Low   Very High

Temporal Demand How hurried or rushed was the pace of the task?

Very Low   Very High

Performance How successful were you in accomplishing what you were asked to do?

Perfect   Failure

Effort How hard did you have to work to accomplish your level of performance?

Very Low   Very High

Frustration How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low   Very High

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APPENDIX B

PERMISSION OF USE

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McNabb, J., & Gray, R. (2016). Staying connected on the road: a comparison of different types of smart phone use in a driving simulator. *PLoS one*, *11*(2), e0148555.