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Texting while driving: Is speech-based text entry less risky than handheld text entry?

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ABSTRACT

Research indicates that using a cell phone to talk or text while maneuvering a vehicle impairs driving performance. However, few published studies directly compare the distracting effects of texting using a hands-free (i.e., speech-based interface) versus handheld cell phone, which is an important issue for legislation, automotive interface design and driving safety training. This study compared the effect of speech-based versus handheld text entries on simulated driving performance by asking participants to perform a car following task while controlling the duration of a secondary text-entry task. Results showed that both speech-based and handheld text entries impaired driving performance relative to the drive-only condition by causing more variation in speed and lane position. Handheld text entry also increased the brake response time and increased variation in headway distance. Text entry using a speech-based cell phone was less detrimental to driving performance than handheld text entry. Nevertheless, the speech-based text entry task still significantly impaired driving compared to the drive-only condition. These results suggest that speech-based text entry disrupts driving, but reduces the level of performance interference compared to text entry with a handheld device. In addition, the difference in the distraction effect caused by speech-based and handheld text entry is not simply due to the difference in task duration.

1. Introduction

Texting while driving is a growing public safety hazard (Caird et al., 2013; Wilson and Stimpson, 2010). For example, a multivariate regression analysis based on the Fatality Accident Reporting System (FARS) database found that the percentage of distraction-related fatalities increased from 10.9% in 1999 to 15.8% in 2008. One reason for the increases in fatalities from 2002 to 2007 was the increased frequency of texting while driving, which was estimated to result in 16,141 additional fatalities in this period (Wilson and Stimpson, 2010). A survey by the American Automobile Association (2008) reported that 14.1% of all drivers and 48.5% of young drivers aged 18–24 admitted that they text while driving. Naturalistic studies of cell phone use suggest that driver distraction increases crash risk by 2.8–5 times (Klauer et al., 2006; Redelmeier and Tibshirani, 1997; Violanti, 1998; Violanti and Marshall, 1996), risk-levels comparable to drunk driving (Redelmeier and Tibshirani, 1997). The increasing usage of cell phones has been accompanied by an accelerating increase in the number of traffic accidents (Alm and Nilsson, 1994; Wilson and Stimpson, 2010; Strayer and Johnston, 2001; World Health Organization, 2011). The risk posed by texting while driving has attracted the attention of legislators, automakers, and safety researchers.

A common misperception underlying legislative efforts is that the task of holding a phone represents the primary source of interference with driving, despite evidence showing that that hands-free cell phone use still impairs driving performance (McEvoy et al., 2005; Strayer and Johnston, 2001). This assumption has influenced automotive interface design and legislation in the United States. Thirty-nine states have passed laws banning texting while driving and ten states have banned handheld cell phone use for all drivers. However, interestingly, all states still allow hands-free cell phone use while driving (National Highway Traffic Safety Administration, 2010). In addition, automotive manufacturers are designing speech-based systems to replace handheld interaction (Lee et al., 2001). A critical question underlying these legislative and system design decisions is “whether texting using a speech-based phone is less risky than using a handheld phone?”

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According to one theoretical account termed as the manual and visual *structural interference hypothesis*, the effect of cell phone use on driving performance derives from the manual distraction of holding the phone and pressing the keys, and the visual distraction caused by the need to move the eyes and attention between the cell phone and the road scene (Wickens, 1980). Driving is primarily a visual–spatial–manual task, requiring frequent steering control (Strayer and Drews, 2007; Wickens, 2002). Handheld cell phone use requires the same manual and visual resources as driving, causing structural interference (Wickens, 1980, 1984). Manual manipulation tasks such as dialing and answering the phone, tuning the radio and DVD player are known to negatively impact driving performance (Briem and Hedman, 1995; Brookhuis et al., 1991; Hatfield and Chamberlain, 2005; Horberry et al., 2006; Tsimhoni et al., 2004).

According to the structural interference hypothesis, task interference will be reduced if two tasks share fewer common resources (Wickens, 1980). For example, a secondary task requiring, say a vocal response, will interfere with driving performance less than another secondary task, which requires a manual response. It follows that speech-based cell phone use should be less disruptive of driving performance than traditional handheld cell phone. In agreement with the structural interference hypothesis, performance advantages of speech-based cell phone over handheld cell phone have been reported previously (McCallum et al., 2004; Strayer et al., 2003). For example, Owens, McLaughlin and Sudweeks (2010) reported that speech-based interaction reduced the number of glances, the total glance durations and subjective mental demand compared to handheld interactions for the dialing and music track selection tasks. The frequency and duration of “eyes off the road” glances increased when talking or texting (Hosking et al., 2009; Tsimhoni et al., 1999). Drivers using a speech-based personal digital assistant (PDA) were faster in responding to an emergency than when they are required to interact manually with the PDA. Reactions times in both speech-based and manual interaction conditions were slower than the drive-only condition (McCallum et al., 2004). In addition, a recent study showed that performing a secondary speech comprehension task may not affect the primary task performance of lane keeping, although concurrent comprehension increased drivers’ mental workload and reduced drivers’ capability to comprehend speech correctly (Cao and Liu, 2013).

An alternative perspective is that speech-based texting may provide little advantage over handheld texting, because the bottleneck of performances for driving while texting is at the cognitive process, rather than the visual perception or manual response processes. Cognitive distraction is associated with the central executive component of working memory (Kunar et al., 2008; Levy et al., 2006). We refer to this hypothesis as the *cognitive interference hypothesis* hereafter. Interference between driving and other tasks (i.e., talking or texting using a cell phone) is a direct result of the serial processing nature of the central executive. The central executive executes only one information-processing task at a time, such as language production or steering control but not both tasks concurrently (Kunar et al., 2008; Strayer and Johnston, 2001). If one task (such as texting) occupies the central executive, other tasks (such as steering control component of driving) need to wait in the queue until the central executive is freed up, therefore creating a performance decrement of either or both tasks. Although speech-based interaction reduces manual distraction compared to handheld interaction, the cognitive demand of texting in unavoidable for both speech-based and handheld cell phone, which is regarded as the major cause of task interference by the cognitive interference hypothesis. Thus, this hypothesis predicts similar levels of driving performance decrement for both speech-based and handheld cell phone.

The cognitive interference hypothesis is supported by meta-analytic and empirical studies of cell phone conversation while driving. These findings reveal that a speech-based cell phone conversation provides little performance benefit over handheld conversation (Caird et al., 2008; Horrey and Wickens, 2006; Levy et al., 2006; McEvoy et al., 2005;). Levy et al. (2006) reported similar brake response times for manual and verbal responses to a choice task. Similarly, it has been shown that performance in a simulated driving task was not impaired by listening to radio broadcasts, listening to a book on a tape, or by a continuous shadowing task using a handheld cell phone (Strayer and Johnston, 2001). In contrast, a word generation task hindered driving performance (Strayer and Johnston, 2001). These data imply that cognitive interference, rather than structural interference, is the major cause of the performance decrement caused by distracted driving due to talking. Cell phone conversations disrupt driving performance by diverting attention to cognitive tasks (Strayer and Johnston, 2001).

Most of the abovementioned studies used non-texting tasks, such as cell phone conversations. Although texting and conversations using cell phones have some elements in common, it is important to acknowledge their differences. For instance, a manual texting task requires the driver to look at the phone and press the correct buttons, while a handheld cell phone conversation imposes less visual and manual distraction. Drivers who are manually texting can choose when to text, whereas a driver engaging in a cell phone conversation may feel obligated to maintain the conversation (Crisler et al., 2008; Hosking et al., 2009). The task interference found in hands-free versus handheld cell phone conversation may not apply to texting while driving directly (Drews et al., 2009).

Despite its importance, few studies have compared the distracting effect of speech-based and handheld texting directly (for limited number of examples, see Drews et al., 2009 and Jamson et al., 2004). These studies did not equate the task durations when comparing the distracting effects of the secondary tasks. The overall level of task interference represents the interactive effects of the duration of secondary tasks and the type of attentional demand (Drews et al., 2009). Secondary tasks such as texting, which requires task switching and extended periods of secondary task duration, can impair driving performance more severely than secondary tasks that are short in task duration. Moreover, duration-related driving performance measures often co-vary to some extent with task duration (Burns et al., 2010). Burns et al. (2010) emphasized the importance of controlling task duration stating that “*Any metric that ignores task duration and duration-related metrics in the assessment of visual-manual tasks will have an incomplete and possibly misleading, estimation of distraction risk*” (Burns et al., 2010, p. 17). Thus, for a fair comparison of speech-based and handheld texting, the duration of the secondary texting task needs to be controlled. This study addresses the confounding variable of task duration of speech-based and handheld texting by controlling the duration of the texting tasks to be exactly the same using a smartphone texting application (Burns et al., 2010; Tsimhoni et al., 1999). This study uses a car following task which is motivated by research showing that mobile users have a higher risk of rear-end collisions (Wilson et al., 2003) and that cell phone use has a larger effect on driver reaction time than tracking performance (Horrey and Wickens, 2006).

2. Methods

2.1. Participants

Thirty-five college-age participants (11 men and 24 women, $M = 21.6$ years of age, $SD = 3.67$ years of age) from the community of Wichita State University volunteered to participate in this driving experiment. All participants were screened prior to participation to

Fig. 1. Setup of the driving simulator.

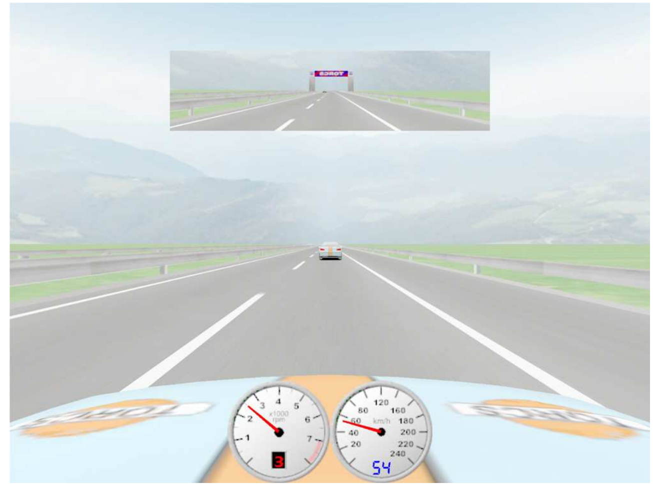

Fig. 2. Car following task simulated using TORCS.

ensure normal or corrected-to-normal vision. All participants were active drivers with at least 2 years of driving experience (M = 6.34 years; SD = 3.56 years) and were required to own a touch screen smartphone to ensure familiarity with the cell phone used in the experiment. Participants reported sending 102.06 text messages on average per day (SD = 111.24) with a median of 50.00 messages. The texting frequency of our population was comparable to the texting frequency of young drivers nationally, but significantly higher than adult drivers (Smith, 2011).

2.2. Apparatus and stimuli

Driving behavior was assessed in a driving simulator, consisting of a driver's seat, a Logitech Driving Force GT steering wheel and pedals, as shown in Fig. 1. The steering wheel's spring effect, damper effect, and centering spring strength were at 50% and had 900° of rotation. Customized simulation software using the framework of the Open Racing Car Simulator (TORCS; torcs.sourceforge.net, version 1.3.3) was used for the driving simulation. The simulated driving task was displayed on a 60″ Sharp AQUOS 3D HD LCD television, with a resolution of 1080 × 1920 and a refresh rate of 60 Hz. The visual angle of the viewable driving scene was 15.30° by 10.22°. The simulator showed road and traffic information from inside the car and through a rear-view mirror. The simulation program has been used to examine the lane-keeping performances of drivers with different levels of driving experience (Cao et al., 2013).

A 4.3″ HTC ThunderBolt touch-screen smartphone running the Android 2.3.4 operating system was used for the texting task. The buttons on the keyboard of the smartphone were arranged in a QWERTY layout.

A RCA RP5120 audio recorder was used to record the audio response for the speech-based texting task.

2.3. Experiment tasks

2.3.1. Car following task

A car following task was used to measure driving performance under distraction (He et al., 2011; He and McCarley, 2011; Kubose et al., 2006; Strayer et al., 2006). Participants were instructed to follow a lead vehicle while maintaining a safe distance, as shown in Fig. 2. The lead vehicle drove at a target velocity of 30 miles per hour and braked at random time intervals, which followed a uniform distribution with the range of 30–60 s. During a brake event, the lead vehicle decelerated at the rate of 3 m/s^2 for 5 s and then returned to the target velocity of 30 mph afterwards. If the participants drove too slowly with a headway distance greater than 100 m, the lead vehicle would gradually slow down at the deceleration rate of 0.5 m/s^2 until the headway distance was smaller than 80 m. Participants were asked to observe all traffic rules. Vehicle dynamics, including headway distance, lane position, steering wheel position, and speed, were recorded during the execution of the driving scenario.

The simulated driving scenario consisted of an 8000 m long two-lane highway (with straight and curved portions). Traffic included the participant's vehicle and a lead vehicle.

2.3.2. Texting task

A texting task was used to compare the distracting effects of handheld versus speech-based texting on driving performance. Participants were instructed to repeat a text message, either verbally or manually on the cellular phone. The text message consisted of a 10-digit telephone number presented to participants via a texting application installed on the HTC Android smartphone. The texting task consisted of 10-digit numbers and was chosen because it simulated the cognitive process and manual entry of a cell-phone dialing or texting task while also allowing the measurement of secondary texting performance. Similar digit-entry tasks were commonly used to study the effect of distraction on driving performance (Horrey and Wickens, 2004; Reed and Green, 1999; Salvucci and Macuga, 2002).

The arrival of an incoming texting message was signaled by a sound that was played at a random time interval, which followed a uniform distribution in the range of 40–60 s. Upon hearing the incoming texting message sound, participants started the texting application, which displayed a 10-digit telephone number. Participants replied by repeating the same telephone number either manually or verbally. The text message was displayed for 10 s, after which the program would automatically close, and participants were instructed to stop texting. The ending of the texting task was cued by a beep sound. If participants responded to an entire message before the message application closed, another random 10-digit number was presented. This ensured that the texting task lasted for exactly the same duration. A digital voice recorder was used to record participants' verbal responses to the text messages.

2.4. Procedure

Once the participants arrived at the lab, the nature and purpose of the experiment was explained and a written consent to participate was obtained. Next, they were asked to complete a questionnaire regarding driving experience and cellular phone use, and

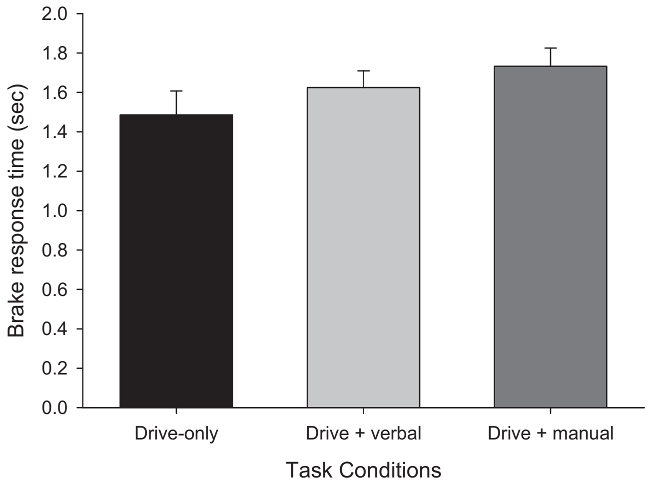

Fig. 3. Brake response time. Error bars in all figures indicate within-subject standard errors based on the main effect of task (Loftus and Masson, 1994).

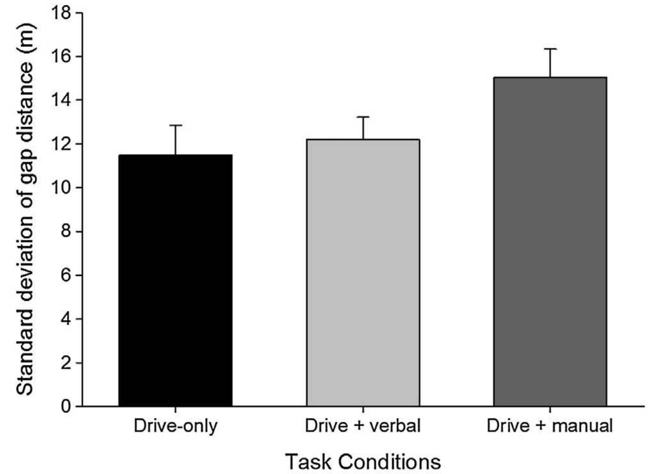

Fig. 4. Standard deviation of gap distance.

their Snellen visual acuity was measured to ensure they had 20/20 visual acuity.

There were five counterbalanced conditions (balanced Latin square). These included a driving-only condition, two dual-task conditions in which participants drove while texting manually (drive + manual) or verbally (drive + verbal), and two texting-only conditions in which participants only did the manual or speech-based texting task.

The session began with a short practice session in order for the participants to get accustomed to the control of the simulator and the cell phone. Participants practiced each of the conditions for 2 min, for a total of 10 min of practice. After the practice, participants began the experimental part of the session. Each condition lasted about 12 min. The entire session lasted about 90 min and participants were informed that they could withdraw from participation at any time. At the end of the experiment, subjects were thanked and rewarded with course credits.

2.5. Data analysis

Two aspects of driving performance were assessed, car following and lane keeping. The measurements for car following performance included brake response time, braking response rate, mean and standard deviation of headway distance, mean and standard deviation of speed. Brake response time was measured from the onset of the lead vehicle braking until the initiation of a braking response by participant vehicle. A brake response was operationally defined as a minimal depression of 1% of the brake pedal (Strayer et al., 2006). A lack of braking response was defined as a failure to brake within 5 s after the lead vehicle braked. The gap distance was measured from the rear of the lead vehicle to the bumper of the subject vehicle (Green, 2013).

The measures of lane keeping performance included the mean and standard deviation of lane position. The zero reference point of lane position was the center of the right lane. Larger value of the standard deviation of lane position indicates poorer lane-keeping performance with higher risks of lane departure and collisions with vehicles in the side lanes. A positive value of lane position indicates a position left of the center of the right lane. Increased standard deviation of steering wheel position indicates decreased vehicular control and increased workload (Dingus, 1995; McLaughlin et al., 2009). Steering holds were defined as periods of no steering activities, i.e., no change of steering wheel position, longer than 400 ms consecutively (Ranney et al., 2005).

The texting performance was measured using both the texting accuracy and number of texting entries. Texting accuracy was measured using the Levenshtein distance of two strings (simply termed as edit distance) (Levenshtein, 1966). The edit distance is the number of discrete steps required to make the strings identical, including insertions, deletions, switching and substitutions. Larger edit distance means larger difference between the two strings, or more texting errors. For example, the numbers 2,525,775,848 and 525,775,845 have a Levenshtein distance of two. The pair of numbers can be made identical by inserting a 2 at the beginning (insertion) and substituting the last 5 into 8 (substitution) for the later digits.

All driving performance measurements were submitted to one-way analyses of variance with task conditions as the only within-subject factor. All secondary texting performances were submitted to two-way analyses of variance with task load (dual versus single task) and secondary task type (verbal versus manual texting) as within-subject factors. IBM SPSS v18.0 was used in the statistical analysis. Any post hoc comparisons used a Bonferroni correction.

3. Results

3.1. Car following

Brake response time differed significantly across task conditions, $F(2, 68) = 4.14$, $p = 0.02$, $\eta_p^2 = 0.11$. As shown in Fig. 3, post hoc comparisons show that the brake response time under drive-only condition ($M = 1.49$ s, $SD = 0.56$ s) was significantly shorter than that under the drive + manual condition ($M = 1.73$ s, $SD = 0.48$ s), $t(34) = 2.52$, $p = 0.02$. The brake response time did not differ between the drive-only and drive + verbal condition ($M = 1.63$ s, $SD = 0.47$ s), and the drive + verbal and drive + manual condition, $t(34) = 1.50$, $p = 0.14$ and $t(34) = 1.69$, $p = 0.10$ respectively.

Analysis of braking response rate did not produce any significant results, $F(2, 68) = 0.92$, $p = 0.40$, $\eta_p^2 = 0.03$.

The standard deviation of gap distance also produced a significant main effect of task conditions, $F(2, 68) = 6.90$, $p = 0.002$, $\eta_p^2 = 0.17$. As shown in Fig. 4, the standard deviation of gap distance in the drive + manual condition ($M = 15.36$ m, $SD = 7.45$ m) was significantly larger than that in the drive-only condition ($M = 11.36$ m, $SD = 6.49$ m) and the drive + verbal condition ($M = 12.72$ m, $SD = 5.43$ m), $t(34) = 3.34$, $p = 0.002$ and $t(34) = 2.69$, $p = 0.01$ respectively. However, the standard deviation of gap distance did not differ for the drive-only and drive + verbal condition, $t(34) = 1.25$, $p = 0.22$.

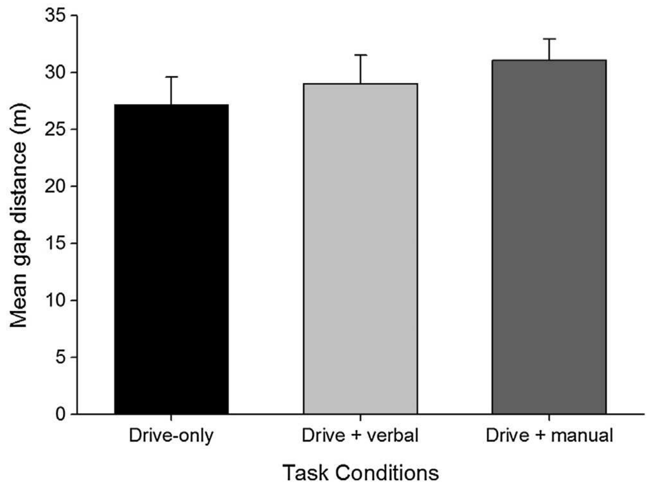

Fig. 5. Mean gap distance.

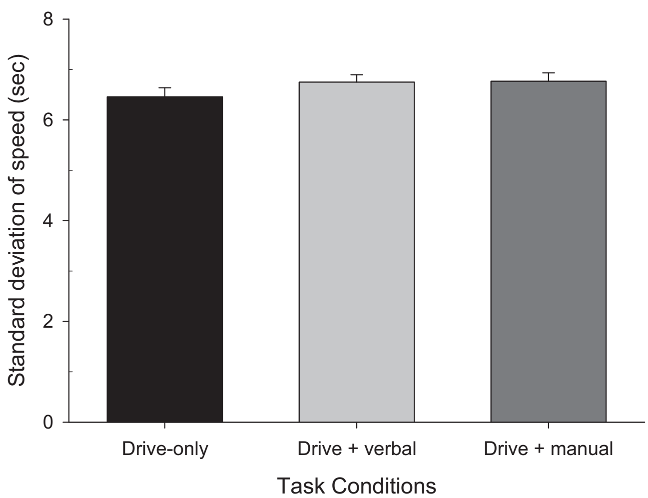

Fig. 6. The standard deviation of speed.

The mean gap distance was significant across task conditions, $F(2, 68) = 3.17$, $p = 0.048$, $\eta_p^2 = 0.09$. As shown in Fig. 5, the mean gap distance in drive + manual condition ($M = 31.30$ m, $SD = 11.18$ m) was significantly larger than that in the drive-only condition ($M = 26.45$ m, $SD = 11.00$ m), $t(34) = 2.86$, $p = 0.01$. The mean gap distance did not differ between the drive – only and drive + verbal conditions ($M = 29.26$ m, $SD = 11.95$ m), $t(34) = 1.25$, $p = 0.22$, nor did it for the drive + verbal and drive + manual conditions, $t(34) = 1.13$, $p = 0.27$.

The standard deviation of speed produced a significant main effect of task conditions, $F(2, 68) = 3.04$, $p = 0.05$, $\eta_p^2 = 0.08$. As shown in Fig. 6, the standard deviation of speed in the drive-only condition ($M = 6.46$ mph, $SD = 0.84$ mph) was significantly smaller than in the drive + verbal condition ($M = 6.75$ mph, $SD = 0.97$ mph) and marginally smaller than in the drive + manual condition ($M = 6.77$ mph, $SD = 1.15$ mph), $t(34) = 2.09$, $p = 0.04$ and $t(34) = 1.99$, $p = 0.055$ respectively. The standard deviation of speed did not differ between the drive + verbal and drive + manual conditions, $t(34) = 0.15$, $p = 0.89$. The intermittent texting tasks increased the standard deviation of speed by about 0.29 mph, a distraction effect comparable to other distraction tasks (Becic et al., 2010; Kubose et al., 2006). For example, a story-retelling task increased the standard deviation of speed by about 0.36 mph (Becic et al., 2010).

Mean speed did not differ across task conditions, $F(2, 68) = 0.75$, $p = 0.48$, $\eta_p^2 = 0.02$. The data suggest that distracted drivers did not

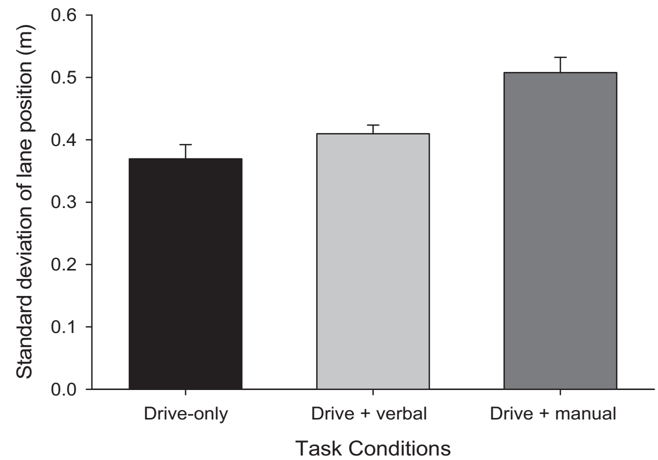

Fig. 7. The standard deviation of lane position.

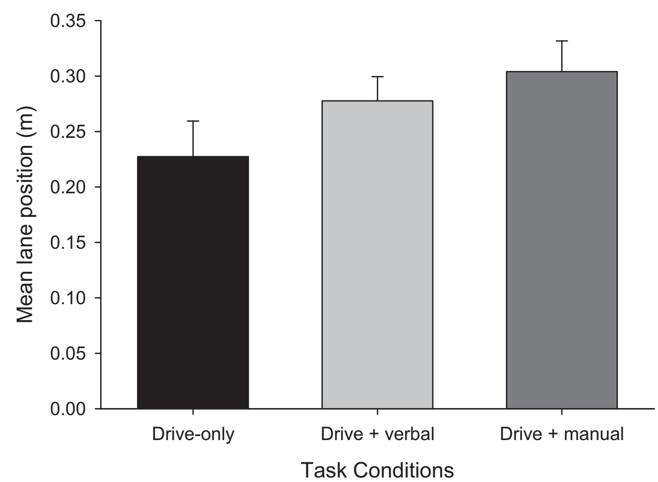

Fig. 8. Mean lane position as a function of task.

compensate for the increasing risks of driving while texting by reducing their driving speed.

3.2. Lane keeping

The standard deviation of lane position was significantly different across task conditions, $F(2, 68) = 31.95$, $p < 0.001$, $\eta_p^2 = 0.48$. As shown in Fig. 7, the standard deviation of lane position in the drive-only condition ($M = 0.37$ m, $SD = 0.12$ m) was significantly smaller than that in the drive + verbal condition ($M = 0.41$ m, $SD = 0.10$ m) and drive + manual condition ($M = 0.51$ m, $SD = 0.15$ m), $t(34) = 2.84$, $p = 0.01$ and $t(34) = 6.22$, $p < 0.001$ respectively. The standard deviation of lane position in the drive + manual condition was also significantly larger than that in the drive + verbal condition, $t(34) = 6.14$, $p < 0.001$. We observed 0.04 m increase in standard deviation of lane position for the drive + verbal condition, and 0.14 m for the drive + manual condition, compared to the drive-only condition. The distraction effect of texting on standard deviation of lane position was compared to other distraction or impaired driving conditions (Cao and Liu, 2013; Lenné et al., 2010; Tsimhoni et al., 2004). For example, drivers taking alcohol increased their standard deviation of lane position by 0.05 m and drivers taking cannabis increased by 0.08 m (Lenné et al., 2010).

The mean lane position also differed significantly across task conditions, $F(2, 68) = 5.53$, $p = 0.01$, $\eta_p^2 = 0.14$. As shown in Fig. 8, the mean lane position in the drive-only condition ($M = 0.23$ m,

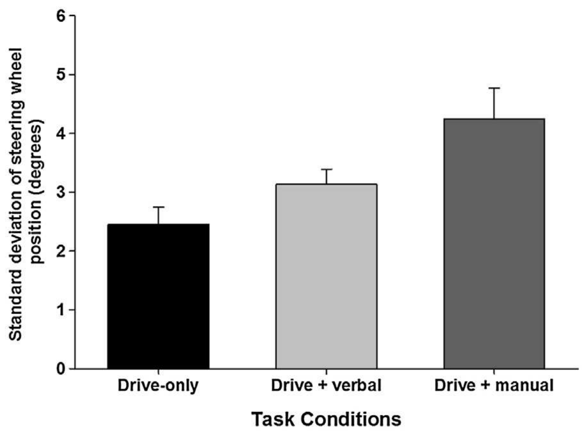

Fig. 9. Standard deviation of steering wheel position.

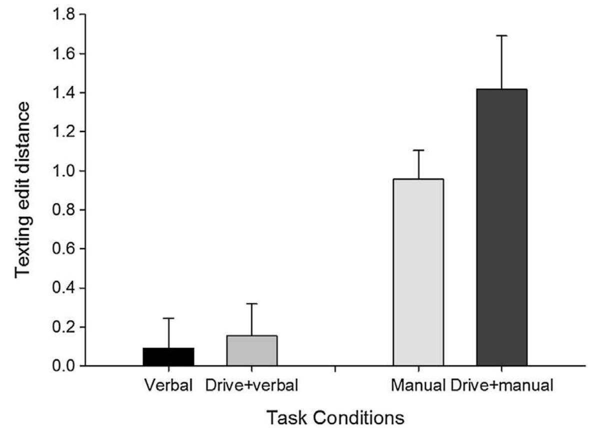

Fig. 11. Texting edit distance.

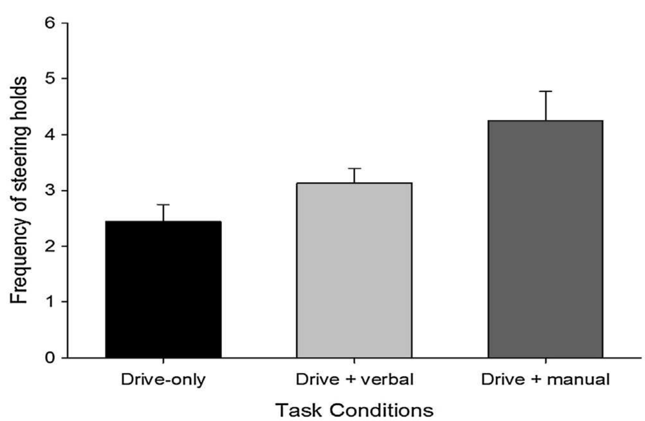

Fig. 10. The frequency of steering holds.

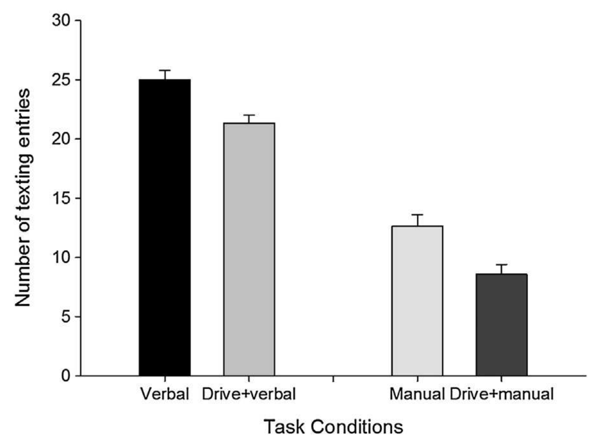

Fig. 12. The number of texting entries.

SD = 0.20 m) was significantly smaller than that in the drive + verbal condition (*M* = 0.28 m, *SD* = 0.21 m) and drive + manual condition (*M* = 0.30 m, *SD* = 0.19 m), $t(34) = 2.16$, $p = 0.04$ and $t(34) = 2.79$, $p = 0.01$ respectively. The mean lane position in the drive + verbal condition was not significantly different from the drive + manual condition, $t(34) = 1.41$, $p = 0.17$.

Similar to the result of lane position, the standard deviation of steering position was also significantly different across task conditions, $F(2, 68) = 15.59$, $p < 0.001$, $\eta_p^2 = 0.31$. As shown in Fig. 9, the standard deviation of steering position in drive-only condition (*M* = 2.39°, *SD* = 0.47°) was significantly smaller than that in the drive + vocal (*M* = 3.08°, *SD* = 0.79°) and drive + manual condition (*M* = 4.19°, *SD* = 2.58°), $t(34) = 6.91$, $p < 0.001$ and $t(34) = 4.46$, $p < 0.001$ respectively. The standard deviation of steering position in the drive + vocal condition was also significantly different from the drive + manual condition, $t(34) = 2.93$, $p < 0.01$.

The frequency of steering holds was also significantly different across task conditions, $F(2, 68) = 24.95$, $p < 0.001$, $\eta_p^2 = 0.42$. As shown in Fig. 10, the frequency of steering holds in drive-only condition (*M* = 0.08 Hz, *SD* = 0.01 Hz) was significantly smaller than that in the drive + verbal (*M* = 0.11 Hz, *SD* = 0.03 Hz) and drive + manual condition (*M* = 0.10 Hz, *SD* = 0.03 Hz), $t(34) = 6.56$, $p < 0.001$ and $t(34) = 5.50$, $p < 0.001$ respectively. The frequency of steering holds in the drive + verbal condition did not differ from the drive + manual condition, $t(34) = 0.75$, $p = 0.46$.

The results of the standard deviation of steering position and the frequency of steering holds suggest that drivers spent less effort in steering control when they drove while texting either manually or verbally compared to the drive-only condition.

3.3. Secondary texting task performance

The secondary texting task performance was measured using texting edit distance and number of texting entries. Two analyses of variance were carried out with task load (dual versus single task) and secondary task type (verbal versus manual texting) as the within-subject factors.

The analysis of texting edit distance produced a significant interaction effect of task load and secondary task type, $F(1, 34) = 5.79$, $p = 0.02$, $\eta_p^2 = 0.15$, and significant main effect of task load, $F(1, 34) = 12.17$, $p = 0.001$, $\eta_p^2 = 0.26$, and significant main effect of secondary task type, $F(1, 34) = 48.38$, $p < 0.001$, $\eta_p^2 = 0.59$. As shown in Fig. 11, post hoc comparisons show that the texting edit distance was larger in the drive + manual condition (*M* = 1.42, *SD* = 1.21) than that in the manual texting only condition (*M* = 0.96, *SD* = 0.76), $t(34) = 2.98$, $p = 0.005$; the texting edit distance was also larger in the drive + verbal condition (*M* = 0.15, *SD* = 0.03) than that in the verbal texting only condition (*M* = 0.09, *SD* = 0.01), $t(34) = 2.08$, $p = 0.05$. Larger texting edit distance in the dual task conditions than the texting only conditions suggested more texting errors when drivers need to text while driving.

The analysis of number of texting entries did not produce a significant interaction effect of task load and secondary task type, $F(1, 34) = 0.37$, $p = 0.55$, $\eta_p^2 = 0.01$. As shown in Fig. 12, the main effect of task load was significant, $F(1, 34) = 107.36$, $p < 0.001$, $\eta_p^2 = 0.76$. The main effect of secondary task type was also significant, $F(1, 34) = 389.17$, $p < 0.001$, $\eta_p^2 = 0.92$. The number of texting entries was smaller in the drive + manual condition (*M* = 8.56, *SD* = 0.36) than that in the manual texting only condition (*M* = 12.62, *SD* = 0.55),

$t(34) = 6.28$, $p < 0.001$; The number of texting entries was also smaller in the drive + verbal condition ($M = 21.36$, $SD = 0.71$) than that in the verbal texting only condition ($M = 24.99$, $SD = 0.77$), $t(34) = 10.73$, $p < 0.001$.

The texting performance data indicate that driving impairs secondary texting performance too, by reducing the texting accuracy and texting input speed.

4. Discussions

The results of this study indicate that both handheld and speech-based texting significantly affect driving performance. Handheld texting increased brake response time, increased variation in gap distance and lane position. Drivers who texted using a handheld smartphone had greater following distances and drove further toward the left lane boundary. Longer following distances may represent a compensatory strategy chosen to offset the perceived risk of the secondary handheld texting task (Jamson et al., 2004; Horrey and Simons, 2007). Driving performance in the speech-based texting condition was less impaired compared to the handheld texting condition. Nevertheless, speech-based texting still affected driving performance, as demonstrated by a larger standard deviation of speed and lane position in the drive + verbal condition compared to the drive-only condition. No evidence of compensatory behaviors was observed in the drive + verbal condition.

Our driving performance results are consistent with previous studies reporting longer brake response time (McCallum et al., 2004; Drews et al., 2009), impaired lane-keeping (Crisler et al., 2008; Drews et al., 2009) and longer gap/headway distance (Drews et al., 2009; Hosking et al., 2009), when drivers engage in a texting task. Importantly, our study eliminates differences in task duration as a plausible explanation for the effects, as the duration of the handheld and speech-based texting tasks were equated by the custom-built Android application. We found that speech-based texting impaired driving less severely than handheld texting. The actual benefit of speech-based texting over handheld may be larger in real-world driving than the benefit observed in this study considering that texting duration for speech-based input may be shorter than handheld input (Owens et al., 2010, however, see Yager (2013) for example of longer task duration of speech-based input than handheld input). Several other studies reported similar levels of distracting effect by handheld and speech-based texting (e.g., Yager, 2013). The discrepancies of a true benefit versus null benefit of speech-based texting in the literature may be explained by the different duration of handheld and speech-based texting. In an on-road driving study which reported similar distracting effects of handheld and speech-based texting, Yager (2013) further pointed that it took drivers longer to complete the same texting task using speech-based texting (such as Siri or Vlingo smartphone application) than when texting manually. If the texting duration were equated, a benefit of speech-based texting might be found, as Yager's subjects subjectively felt safer using speech to text than manual texting. Another possible factor that may explain the difference in the findings is the accuracy of speech-to-texting technology. This study assumed perfect speech-to-texting recognition, while real speech-based texting applications in Yager's study did not yield perfect performance.

Besides the often-reported driving performance decrement by secondary tasks, we also found that driving impaired both handheld and speech-based texting performance by reducing the texting speed and increasing texting errors. Secondary task performance, such as texting, is not often reported in the driving safety literature. Other study has reported that driving impairs concurrent secondary performance, such as language production and comprehension in a story retelling task (Becic et al., 2010) and texting in this study.

Handheld texting had a greater detrimental effect on the drivers' performance than speech-based texting even after equating the task duration. Several driving studies have reported that manual and visual distractions hinder performance, a finding that supports the structural interference hypothesis (Owens et al., 2011). A recent on-road driving study also showed that the crash risk rate ratio for handheld (rate ratio = 1.73) cell phone use was larger than portable (rate ratio = 1.06) or integrated (rate ratio = 0.57) hands-free cell phone use (Fitch et al., 2013). This offers evidence that implementing speech-based technologies can reduce manual and visual interference compared to handheld texting.

Despite its advantage over handheld texting, this study shows that speech-based texting still impairs driving performance. This is consistent with the notion that the bottleneck at the later stages of cognitive processing (e.g., central executive) accounts for the majority of the distracting effects of secondary tasks (Kunar et al., 2008; Levy et al., 2006). Although speech-based texting reduces or removes structural interference, the performance effect on driving still persists, because of the cognitive load associated with the texting task.

Our results offer some evidence of drivers adopting compensatory driving strategies to offset the increasing driving risks associated with a secondary task (Jamson et al., 2004; Horrey and Simons, 2007). These strategies include increasing headway distance, reducing speed and anticipating the behaviors of lead vehicles and pedestrians. This behavior has been reported in several other studies (Drews et al., 2009; Hosking et al., 2009; Terken et al., 2011). However, distracted drivers do not always adopt compensatory strategies in response to increasing driving risks. For example, Alm and Nilsson (1994) reported that drivers engaging in a mobile telephone task did not compensate for slower reaction times by increasing their headway distances. Similarly we found that drivers in the drive + verbal condition did not increase their gap distance or reduce their speed.

A practical application of these finding for automakers and aftermarket in-vehicle system designers would be the implementation of speech-based systems to reduce the manual and visual structural interference, thereby reducing the impairment of driving performance by secondary tasks. However, it is important to keep in mind that speech-based texting while driving remains hazardous (Lee et al., 2001). Despite its performance advantage over handheld texting, hands-free texting is not a panacea that eliminates all the interference on driving performance. The best recommendation is that drivers avoid all distractions, including both speech-based and handheld texting, and focus on driving. A false belief or misleading advertisement that the speech-based interaction is safe for driving may increase the exposures to secondary tasks, thereby, overshadowing the potential benefits of speech-based interaction compared to handheld interactions and increasing traffic accidents.

This experiment assumed speech recognition was perfect in the speech-based texting condition, which is not representative of existing speech recognition technologies. The accuracy of speech recognition may be an important factor in determining the risks of speech-based texting to driving performance. In this experiment, subjects were just asked to repeat the digits shown in the smartphone, which was relatively low in cognitive load. Actual texting also involves information retrieval, decision making and response generation, which have higher cognitive load than the texting task used in this experiment (Strayer et al., 2006). Thus, the reported risks of speech-based and manual texting to driving may be underestimated.

This study compares sending/composing text messages via manual input or speech-based input methods. Besides writing messages, it is also important to compare how reading and writing text messages influence driving performance in future studies. Yager et al. suggested that reading and writing text messages may be equally dangerous to driving performance (Yager et al., 2012). The modalities of message delivery, such as read messages visually or hear the messages verbally using text-to-speech technology, may modulate the effect of reading messages on driving performance. Text-to-speech technology may potentially reduce the amount of visual distraction compared to looking down at the phone to read messages (Cuřín et al., 2011; Leventhal and Yaagoub, 2007). Since the current study focuses on the effect of different text sending methods, the same information-receiving component is used for both task conditions to rule out potential effects of information receiving methods. Future studies are needed to examine the effect of different information receiving methods and potential interaction between information receiving modalities and information sending modalities. Future studies can also explore how the accuracy of speech recognition technology changes driving performance and whether the compensatory behaviors are deliberate strategies or products of distraction resulting in reduced muscle tension and pressure on the gas pedal. Researchers can also investigate legislative, training, social and technological approaches to discourage risky driving behaviors, such as cell phone conversation and texting.

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