Applied Ergonomics 70 (2018) 156–166

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Does wearable device bring distraction closer to drivers? Comparing smartphones and Google Glass

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A R T I C L E I N F O

Keywords:
Texting while driving
Driver distraction
Multitasking strategy
Wearable devices
Head-mounted display
Google Glass

A B S T R A C T

Background: Head-up and wearable displays, such as Google Glass™, are sometimes marketed as safe in-vehicle alternatives to phone-based displays, as they allow drivers to receive messages without eye-off-the-road glances. However, head-up displays can still compromise driver performance (e.g., He et al., 2015b), as the distracting effect of interacting with any device will depend on the user's multitasking strategies. The present experiment examined drivers' interaction with a head-down smartphone display and a wearable head-up display.
Method: Participants performed a simulated driving task while receiving and responding to text messages via smartphone or the head-mounted display (HMD) on the Google Glass™. Incoming messages were signaled by an auditory alert, and responses were made vocally.
Results: When using Google Glass, participants' responses were quicker than that of smartphone, and the time to engage in a task did not vary according to lane-keeping difficulty. Results suggest that a willingness to engage more readily in distracting tasks may offset the potential safety benefits of wearable devices.

1. Introduction

Engaging in secondary tasks, such as talking on cell phone or texting, is a popular risky behavior while driving and one of the major factors that impair driving performance (Drews et al., 2009; 2014; 2015b; He et al., 2013b; Sawyer et al., 2014) and contribute to traffic crashes (Wilson and Stimpson, 2010). The number of accidents involving cell phone use has increased, which represents 26% of the total of motor vehicle accidents in 2014 (National Safety Council, 2014; National Highway and Transportation Administration, 2011). Wilson and Stimpson (2010) estimated that texting while driving caused 16,141 more driving fatalities than would have been otherwise expected from 2002 to 2007.

Driver distraction has been found to be as dangerous in some ways as drunk driving at the 0.08 blood alcohol level (Strayer et al., 2006), and impairs various aspects of driving performance (Caird et al., 2014; Caird et al., 2008). For example, drivers who talk or text over a cellphone while behind the wheel produce longer braking response times (Drews et al., 2009; He et al., 2014) and take longer to recover speed after braking (Strayer et al., 2006). Those who text also show higher lane and speed variability (Alosco et al., 2012; He et al., 2014, 2015a; Hosking et al., 2009). Distracted drivers also report higher workload (He et al., 2015b; Owens et al., 2011) and make longer off-road glances (Hosking et al., 2009; Libby et al., 2013; Owens et al., 2011) than undistracted drivers. Drivers who talk while driving increase their crash risk by about three times (Klauer et al., 2006), and those who text while driving increase their risk by as much as 8 to 23 times (Olson et al., 2009). The recent booming of wearable devices, such as Google Glass and smartwatches, may exacerbate these trends, by bringing more distracting devices into the vehicle (Beckers et al., 2014; Giang et al., 2015; He et al., 2015b; Sawyer et al., 2014) and raising new questions for transportation safety.

Motivated by the potential safety benefits of speech-based inputs and head-mounted display, wearable devices (such as Google Glass) are intuitively believed to reduce the costs of distraction to driving performance, as compared to conventional hand-held cellphones. Preliminary studies have provided evidences for some benefits of wearable devices (Beckers et al., 2014; Giang et al., 2014; Giang et al.,

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https://doi.org/10.1016/j.apergo.2018.02.022
Received 4 February 2017; Received in revised form 11 February 2018; Accepted 21 February 2018
Available online 20 March 2018
0003-6870/

2015; He et al., 2015b; Sawyer et al., 2014). For example, Sawyer et al. (2014) asked participants to drive following a lead vehicle while texting using either Google Glass or a smartphone. Drivers who texted through Google Glass showed a lower standard deviation of lane position (SDLP) than those texting through a smartphone, implying lower driving risk. Google Glass users also returned to the roadway speed more quickly after texting, and maintained shorter following distances. Studies reported that drivers using Google Glass showed lower costs to driving performance than those using a smartphone (He et al., 2015b; Sawyer et al., 2014). The two studies provided important preliminary evidence of the effects of Google Glass use on driving performance. Nevertheless, neither study directly examined distracted drivers' multitasking strategies.

Studies have shown, though, that the costs of distraction to driving performance depend on the duration of secondary task (Burns et al., 2010), the location and format of the secondary task display (head-up vs head-down vs head-mounted, e.g., He et al., 2015b; Horrey et al., 2006; Liu and Wen, 2004; Sawyer et al., 2014), and the secondary task input modality (speech-based versus manual entry; He et al., 2014; Maciej and Vollrath, 2009; Weinberg et al., 2010). Message entry using hands-free, speech-based inputs is often reported to be less distracting than hand-held, manual message entry, as it requires less motor and visual resources (He et al., 2014). Similarly, drivers generally show less of a performance decrement when viewing information on a head-mounted or head-up display, or on displays at small retinal eccentricity, than when viewing information on a head-down display or at large eccentricity (He et al., 2015b; Horrey and Wickens, 2004; Liu and Wen, 2004; Sawyer et al., 2014), as a result of fewer and shorter glances off-road.

More research is needed to uncover the whole picture of the potential effect of wearable devices on driving performance for two major reasons. First, wearable devices may have very different effects than conventional cell phones and other forms of distracting technologies that have already been well studied. The proximity of a wearable display to the human body and eyes may reduce the effort needed to initiate a secondary task, encouraging drivers to multitask more than they might with a conventional cell phone. Tactile and auditory alerts from a wearable device may be harder to ignore than visual and auditory alerts from a cellphone (Calhoun et al., 2004; Lee and Starner, 2010), and the onset of new visual information with a wearable display may tend to draw drivers' attention reflexively away from the road (Yantis and Jonides, 1990). Transparent wearable displays may also reduce text contrast, making information difficult to read and engendering longer shifts of visual attention away from the driving task. Conversely, wearable interfaces rely primarily on speech input, which tends to be less distracting than manual inputs that is typically used for smartphones (He et al., 2013a, 2014, 2015b). A comparison of the difference between smartphone and Google Glass in the driving context is shown in Table 1.

Second, compared to the emphasis on driving performance, secondary task performance and strategy of multitasking have received relatively little attention in the literature. But driving performance can hardly be thoroughly investigated without considering drivers' multitasking strategy. Multitasking strategy can also moderate the costs of a secondary task driving performance (Horrey and Lesch, 2009; Liang et al., 2012). More specifically, distracted drivers can potentially moderate the multitasking demands by delaying, interrupting, or abbreviating the secondary task (Becic et al., 2010). Two important variables need to be compared to provide a fair comparison of the effect of HMDs and smartphones on driving performance and describe the multitasking strategy: *time-to-engagement* and *time-on-task*.

Time-to-engagement is defined as the period between when the message is sent to the device and when drivers make their first reaction (visual glance, movement, or button clicks) towards the device (Giang et al., 2014) (See Fig. 1 for an illustration). In this study, time-to-engagement was operationally defined as the time from the auditory alert

Table 1
Comparisons of smartphone and Google Glass in the driving context.

	Drive with a smartphone	Drive with HMD (e.g. Google Glass)
Saliency	Low	High
Eccentricity	Far	Close
Effort	High	Low
Values	Task-dependent, low for texting while driving	Task-dependent, low for texting while driving
Size	Mostly at least 720 × 1280 pixel resolution with 4.3–6 inch physical size	640 × 360 pixels (equivalent of a 25 in/64 cm screen from 8 ft/2.4 m away
Contrast	Good	Poor for the transparent display
Tactile alerts	Most often not, if phone is not vibrating in the pocket or vibrating on the dashboard	Yes
Auditory alerts	Yes	Yes
Visual onset	No, if not in the field of view	Yes
Input methods	Manual, vocal	Vocal

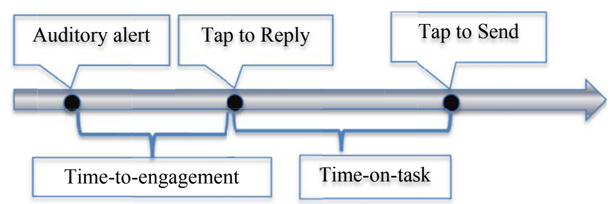


Fig. 1. The Definition of time-to-engagement and time-on-task of a texting task.

signaling that a message had arrived until participants clicked the "Time to Replay" button. Time-on-task was the duration of the secondary task. The two variables were used to describe the reaction and time taken on the secondary distraction task. Because wearable devices, such as HMDs and smartwatches, are situated on the human body and sometimes directly in front of the eyes, the effort required to initiate a secondary task on a wearable device may be smaller than needed on a smartphone task or a dashboard task. This may make wearable device users more likely to initiate a secondary task, producing shorter time-to-engagement. To the best of our knowledge, only one study has investigated the time-to-engagement for smartwatch, reporting that the time-to-engagement was shorter for a smartwatch task than a smartphone task (Giang et al., 2014). The rejection or the delay of a distraction task can be an adaptive strategy to accommodate the increased workload of multitasking (Iqbal et al., 2011; Liang et al., 2012; Schömig et al., 2011), but is a behavior that drivers may not always use (Horrey &Lesch, 2009). For example, Liang and colleagues found that drivers sometimes avoided transitioning from low-demand driving tasks to high-demand driving tasks when initiating secondary tasks with in-vehicle devices (Liang et al., 2012). However, they did not intentionally start the secondary task in a low-demand driving scenario, and they did not delay the secondary task when driving demands have been already high. These studies demonstrated that the multitasking strategy of when to initiate a distraction task might be specific to the driving context and the adaptive anticipatory delaying of a secondary task may not be perfect, especially in the high driving load condition. However, till now, no efforts have been made to investigate the time-to-engagement for drivers who use a wearable HMD.

Time-on-task may also modulate the distracting effects of in-vehicle technology use (See Fig. 1 for an illustration). Burns et al. (2010) emphasized 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). If drivers intuitively believe wearable devices are less distracting to driving performance, they may spend longer times interacting with wearable devices than with smartphones, offsetting any potential benefits of wearable devices.

The current study aims to answer four important questions concerning the influence of wearable devices on driving performance. First, which display medium is less compromising to driver performance, HMD or smartphone? Second, does an HMD display's proximity to human body and eyes encourage shorter time-to-engagement or higher chance to engage in a distraction task than a smartphone? Third, will drivers spend longer time interacting with an HMD than with a traditional smartphone? Fourth, will drivers interacting with either an HMD or a smartphone adapt their secondary task behaviors in response to changing levels of driving demand (Liang et al., 2012)?

2. Methods

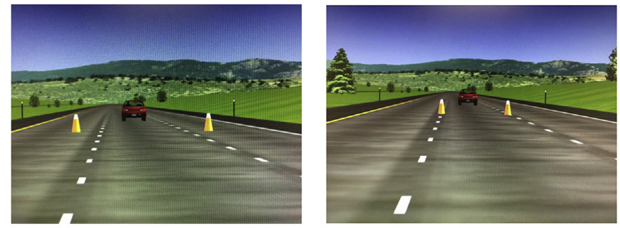
2.1. Participants

Participants were twenty-nine students recruited from a midwestern university (eighteen females and eleven males; mean age = 23.5,*SD* = 6.2, range = 18–43 years) who received course credit as remuneration for their participation. Only students who possessed a valid driver's license and had been driving for at least two years were invited to participate. Their average driving experience was 5.71 years, and they drove 238.63kilometers (km) weekly. Each participant was required to pass a standardized vision test to ensure that they had at least 20/20 vision ability with or without corrective contact lenses. Participants wearing corrective glasses were not able to participate in the experiment due to the potential structural interference with Google Glass. All participants reported that they owned a smartphone. Twenty-six participants reported experience using a smartphone while driving and the other three participants did not. Twenty-five of the participants were right-handed, three were left-handed and one participant was ambidextrous. We also explored to exclude the few participants with left-handed and ambidextrous handedness. Our data showed that handedness did not change the results of the texting performance. No the effect of handedness was reported in previous known studies on Google Glass (Drews et al., 2009; He et al., 2013b, 2014, 2015b; Sawyer et al., 2014). Participants were also required to be fluent English speakers with Midwestern-American accents and to own a smartphone.

2.2. Apparatus and tasks

Driving simulator. The simulated driving task and scenarios were created using HyperDrive Authoring Suite™ Version 1.6.1 and Drive Safety's Vection Simulation Software™ Version 1.6.1 (see Fig. 2.). The driving simulator consisted of three 26-inch ASUS monitors (1920 × 1080) and a Logitech Driving Force GT steering wheel and pedals. Drivers sat approximately two meters away from the front monitor. The monitors simulated the driving environment through front and side windows. Vehicle dynamics were sampled at 60 Hz.

Fig. 2. Setup of the driving simulator with a participant wearing Google Glass.



(a). Easy Lane Keeping (b). Difficult Lane Keeping

Fig. 3. Lane-keeping difficulty manipulated by cone distance.

The driving conditions featured a straight three-lane highway. Participants were instructed to follow a lead car, a red Toyota Celica sedan with a width of 1.728 m, in the middle lane. The lane-keeping difficulty was manipulated by pairs of cones that were intermittently placed on either side of the center lane (see Fig. 3.). The lateral distance between cones in each pair was 3.3 m for the difficult lane-keeping condition and 5.3 m for the easy lane-keeping condition. The width of the lane was 4 m, identical for the easy and difficult lane-keeping conditions. This manipulation was inspired by the work of Liang et al. (2012) who used cones to manipulate driving difficulty in their closed track study. Lateral wind gusts also intermittently caused vehicles to sway simulating natural conditions. The manipulation of the lateral wind was inspired by previous work studying lateral lane keeping performance (Andersen and Ni, 2005; He et al., 2013a,b). The direction of the wind was randomly determined. The strength of the wind followed a delayed exponential distribution, with a range of 2000–3000 Newtons. The interval between adjacent lateral wind events was 2.5–75 s. The same lateral wind existed in both the easy and difficult lane-keeping conditions.

Secondary verbal texting task. Under distracted driving conditions, participants performed a secondary verbal texting app to receive, read, and respond to messages, using either a Samsung touch-screen smartphone (Android)with an 800 × 480 resolution Super AMOLED™ display or an HMD (Google Glass) with a 640 × 360 resolution (see Fig. 4.) The Google Glass display was placed in front of the right eye, which was adjusted into a comfortable view angle.

In the smartphone condition, the phone remained at a marked location on a table between messages. An auditory notification alerted the participant when a message arrived, after which the participant was required to pick up the phone and tap the “Tap to Reply” button (See Fig. 5, left panel) to display the message on the phone's screen. The participant was required to dictate a response to the message verbally, and then tap the “Tap to Send” button (See Fig. 5, right panel). After responding, the participant returned the smartphone to the marked location. This procedure was intended to simulate the process of placing and retrieving a cellphone from the dashboard or console in a vehicle.

In the HMD condition, a notification again alerted the driver when a message arrived. The driver was then required to tap the side of the Google Glass spectacle frame near the right temple to display to the message. After the message appeared on the Google Glass screen, participants verbalized their responses before tapping again to send.

Incoming messages were selected at random without replacement from a set of 112 questions. The time interval between messages was sampled from a uniform distribution with a range of 40–60 s. Participants received about 11 messages during any given task involving the smartphone or HMD. The app, which displayed the texting messages, also recorded participants' time-to-engagement and time-on-task.

The 112 questions were created by two graduate students with a consideration that college age students have the knowledge and willingness to answer. No sensitive information about race, gender, culture or religion is asked. Exemplar questions are like “What were your favorite parts of high school?”, “Why did you choose to live on or off campus?”, “What do you like to learn about?”, and “What do you like

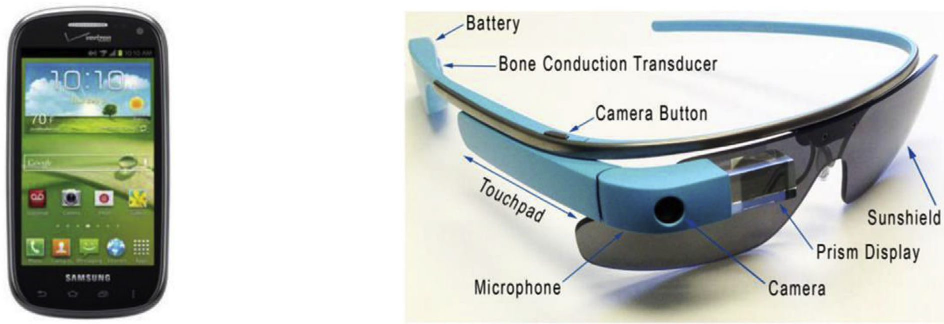


Fig. 4. Examples of smartphone (left) and Google Glass (right).

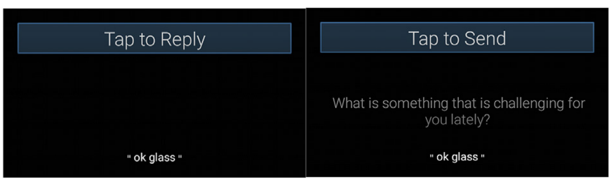


Fig. 5. The verbal texting app for Google Glass and Android phone. (Left: participants press "Tap to Reply" button to read the message; Right: participants read the message and press "Tap to Send" button when finish).

about summer?". The questions have 41.94 characters on average with a standard deviation of 11.15 characters. The question database has been used in previous publications, such by He et al (2015b). Participants can answer the questions in any way they wanted, as long as they responded in a full sentence. We did not allow participants to respond in a short phrase majorly because the average text message length is 46.06 characters for the SMS corpus collected by the Cyber Security Lab (O'Day and Calix, 2013). Thus, providing a full sentence response was more realistic to natural texting behaviors.

The Susceptibility to Driver Distraction Questionnaire (SDDQ) was administered at the end of the experiment (Feng et al., 2014). The SDDQ is a 39- item tool that compiles self-reported information about distraction engagement, attitudes and beliefs about voluntary distraction, and susceptibility to involuntary distraction. The scale was used with an intent to correlate the susceptibility to distraction in the scale with actual multitasking strategy, more specifically, the time-to-engagement and time-on-task. However, the survey results showed that participants' responses were mostly either 3 or 4 for the five-option questionnaire, without a wider distribution of responses, which did not allow correlational analysis. Thus, the results of SDDQ scale are not reported or discussed further in the RESULTS section.

2.3. Experimental design

This study employed a within-subject repeated measures design, with Driving Difficulty, Task Load, and text device as factors. Two aspects of data were collected: driving performance and texting behaviors. See Table 2 for a summary of the dependent variables. To measure driving performance, the dependent variables included: mean and standard deviation of lane position (SDLP), steering reversal rate, and the standard deviation of steering wheel position. The independent variables were Drive Difficulty (Easy versus Hard lane keeping difficulty) and Task Load (Drive-only, Drive + Phone, Drive + Glass). A 3 × 2 repeated-measures ANOVA with Drive Difficulty and Task Load as factors was performed on each dependent variable.

The *mean lane position* represents the average position (in meters) that the participants maintained relative to the midline of the center lane. Positive values indicate offset to the right, and negative values indicate offset to the left. Larger values of the *SDLP* indicate poorer lane-keeping performance and higher risks of lane departure. Following Ranney et al. (2005) and Tijerina et al. (1995), a steering reversal was defined as a change of steering wheel position larger than 2° within the time that steering wheel velocity left and then reentered zero-velocity band. The *steering reversal rate* was defined as the number of steering reversals per second. Higher steering reversal rates indicate more corrections to steering wheel position, which suggest more effort in maintaining lane position (MacDonald & Hoffman, 1980). Increased *standard deviation of steering wheel position* implies decreased vehicular control and increased workload (Dingus, 1995; McLaughlin et al., 2009).

Multitasking strategy for texting while driving was assessed using time-to-engagement and average time-on-task per message (Giang et al., 2014, 2015; Liang et al., 2012). *Time-to-engagement* was measured from the start of the auditory alert that signaled an incoming message until participants clicked the "Tap to Reply" button on the devices (see Fig. 1.). *Total task engagement time* per *message* was defined as the time period from participants clicked the "Tap to Reply" button until they clicked "Tap to Send" button on the devices (see Fig. 1.). Using a 3 × 2 repeated-measures design, the independent variables included Texting Device (smartphone, Google Glass) and Task load (Texting - Only, Drive + Phone, Drive + Glass). IBM SPSS v18.0 was used in the statistical analysis. Bonferroni adjustments were included to correct for multiple comparisons. Mean differences were considered significant at the .05 alpha level.

2.4. Procedure

After granting informed consent and showing proof of a valid driver's license, participants finished a vision ability test. Only people with at least two years driving experience and a normal vision or corrected vision ability of at least 20/20 were allowed to participate. Afterwards, they completed a demographic survey, asking their age, gender, and driving experience. Each participant practiced driving with the simulator, texting with the smartphone, and texting with Google Glass prior to beginning the experiment for five minutes each. A previous study indicated that after five minutes of practice on Google Glass, texting performance was almost equal to that using an Android (MacArthur et al., 2014). The practice drive followed a commonly accepted protocol, which train drivers to follow a lead vehicle with a two second headway time (Kubose et al., 2006).

After practicing using the smartphone, Google Glass and the driving simulator, participants completed the experimental conditions. Each task condition lasted for approximately ten minutes, and the experiment (including time allotted for practice and administering surveys) lasted approximately two hours in total. Each participant completed all eight task conditions, with the order of the conditions counter-balanced using a Latin square design. Upon completion of the experiment, participants were asked to complete the SDDQ scale, then they were debriefed about the purposes of experiment, and rewarded with course credits for their participation.

Table 2
Summary of dependent variables.

Category of Measurement	Dependent Variable	Unit	Description
Driving performance	Mean lane position	meter	The *average* position that the participants maintained relative to the midline of the center lane. Positive values indicate offset to the right, and negative values indicate offset to the left.
	Standard deviation of lane position (SDLP)	meter	The *standard deviation* of position that the participants maintained relative to the midline of the center lane.
	Steering reversal rate	Hz	The number of steering reversals per second. Higher steering reversal rates indicate more corrections to steering wheel position, which suggest more effort in maintaining lane position.
	Standard deviation of steering wheel position	°	The *standard deviation of steering wheel position* implies decreased vehicular control and increased workload.
	Mean speed	kph	The *average* speed.
	Standard deviation of speed	kph	The *standard deviation* of speed, which implies the stability of car following performance.
Texting behavior	Time-to-engagement	second	The time measured from the start of the auditory alert that signaled an incoming message until participants clicked the "Tap to Reply" button on the devices
	Total task engagement time	second	The time period from participants clicked the "Tap to Reply" button until they clicked "Tap to Send" button on the devices

3. Results

3.1. Driving performance

Initial analyses compared driver performance across conditions to gauge the distracting effects of texting with the smartphone and HMD interfaces.

The mean lane position (as shown in Fig. 6) showed a significant main effect of Driving Difficulty, $F(1, 28) = 4.35$, $p = .05$, $\eta_p^2 = 0.13$, with the Easy conditions ($M = -0.04$ m, $SD = 0.14$ m) producing mean lane position farther left than that of the Hard conditions ($M = 0.01$ m, $SD = 0.11$ m). The main effect of Task Load was not significant, $F(2, 56) = 0.91$, $p = .41$, $\eta_p^2 = 0.03$, nor was the interaction, $F(2, 56) = 0.05$, $p = .96$, $\eta_p^2 = 0.002$.

SDLP (Fig. 7) showed a significant main effect of Task Load, $F(2, 56) = 12.09$, $p < .001$, $\eta_p^2 = 0.30$, indicating less lane-keeping variability in the Drive-Only condition ($M = 0.28$ m, $SD = 0.05$ m) than in either the Drive + Phone ($M = 0.33$ m, $SD = 0.08$ m) or the Drive + Glass ($M = 0.33$ m, $SD = 0.06$ m) condition, $t(28) = 3.98$, $p < .001$ and $t(28) = 4.49$, $p < .001$. SDLP did not differ significantly between the Drive + Phone and Drive + Glass conditions, $t(28) = 0.60$, $p = .55$. Neither the main effect of Driving Difficulty, $F(1, 28) = 0.57$, $p = .46$, $\eta_p^2 = 0.02$, nor the interaction, $F(2, 56) = 0.02$, $p = .99$, $\eta_p^2 = 0.001$, reached statistical significance.

Steering reversal rate (Fig. 8) showed a significant main effect of Task Load, $F(2, 56) = 24.45$, $p < .001$, $\eta_p^2 = 0.47$. Pairwise comparisons showed that the steering reversal rate was lower in the Drive-Only ($M = 0.36$ Hz, $SD = 0.10$ Hz) than in the steering reversal rate in the Drive + Glass conditions ($M = 0.39$ Hz, $SD = 0.11$ Hz) or the Drive + Phone condition ($M = 0.45$ Hz, $SD = 0.14$ Hz), $t(28) = 2.17$, $p = .04$ and $t(28) = 6.18$, $p < .001$ respectively. The steering reversal rate in the Drive + Glass conditions was also lower than that in the Drive + Phone conditions, $t(28) = 5.73$, $p < .001$. Data also showed a significant main effect of Driving Difficulty, $F(1, 28) = 24.02$, $p < .001$, $\eta_p^2 = 0.46$, with Easy conditions ($M = 0.38$ Hz, $SD = 0.11$ Hz) producing lower values than Hard conditions ($M = 0.41$ Hz, $SD = 0.11$ Hz). There was no significant interaction effect between Task Load and Driving Difficulty, $F(2, 56) = 1.52$,

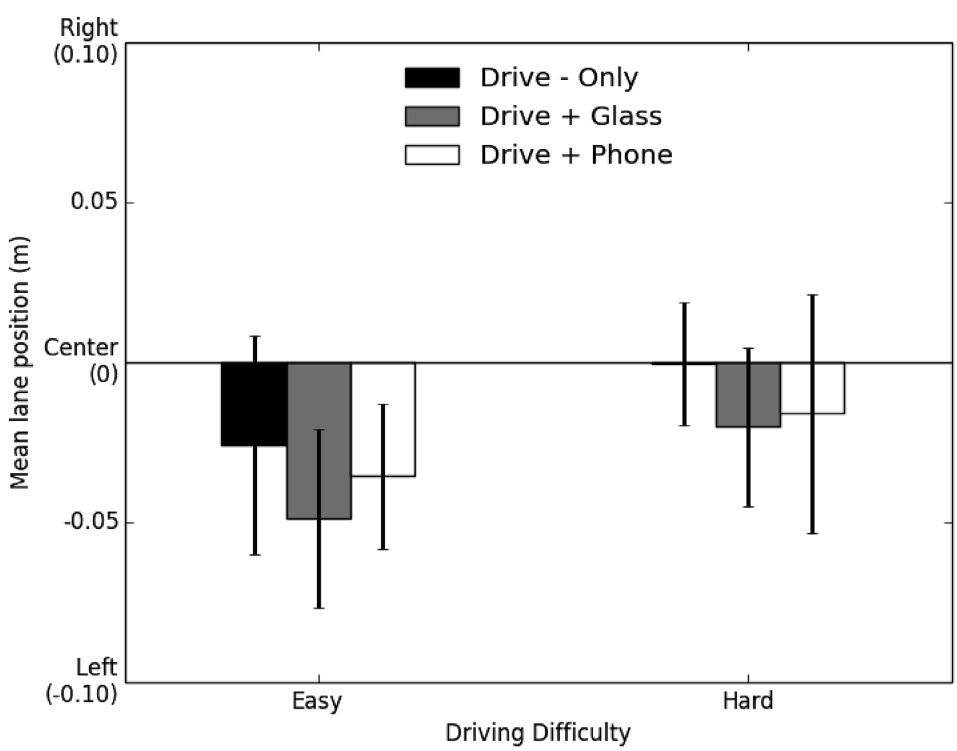


Fig. 6. Mean lane position (m). Error bars in all figures indicate within-subject 95% confidence intervals based on the main effect of task conditions (Loftus and Masson, 1994).

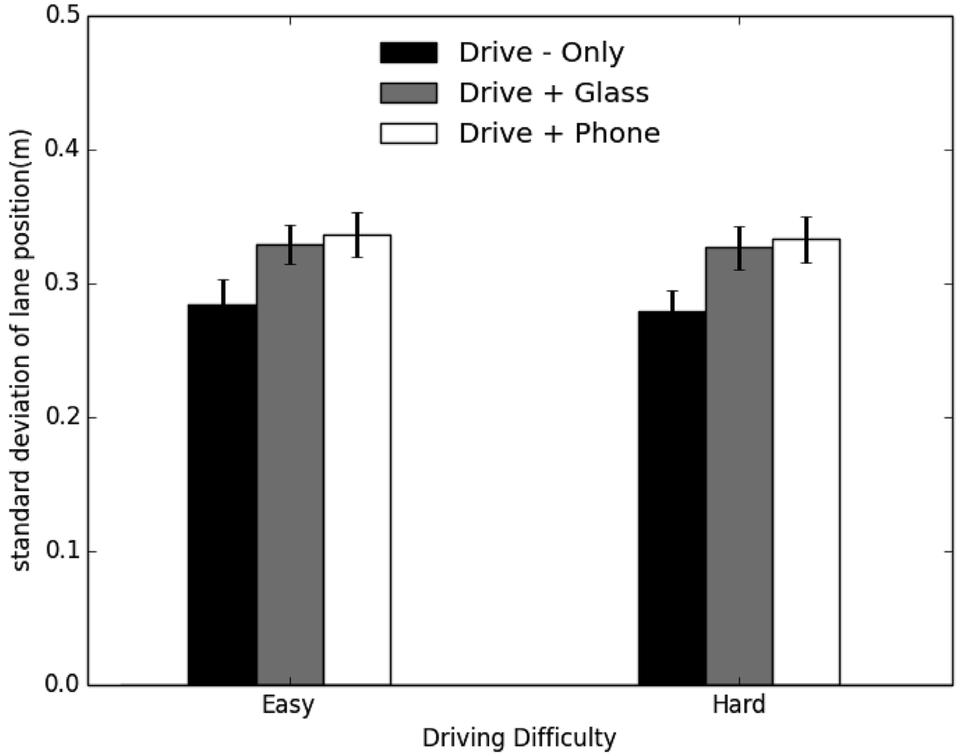


Fig. 7. The standard deviation of lane position.

p = .23, $\eta_p^2 = 0.05$.

The standard deviation of steering wheel position (Fig. 9) produced a significant main effect of Task Load, F (2,56) = 24.02, p < .001, $\eta_p^2 = 0.46$. Pairwise comparisons showed that the standard deviation of steering wheel position in the Drive-Only conditions (M = 2.17°, SD = 0.57) was smaller than that in either the Drive + Phone conditions (M = 3.25°, SD = 1.40) or the Drive + Glass conditions (M = 2.80°, SD = 0.88), t (28) = 6.10, p < .001 and t (28) = 5.82, p < .001 respectively. Additionally, the standard deviation of steering wheel position in Drive + Phone conditions was larger than that in that in the Drive + Glass conditions, t (28) = 2.56, p = .02. The main effect of Driving Difficulty was also significant, F (1,28) = 25.11, p < .001,

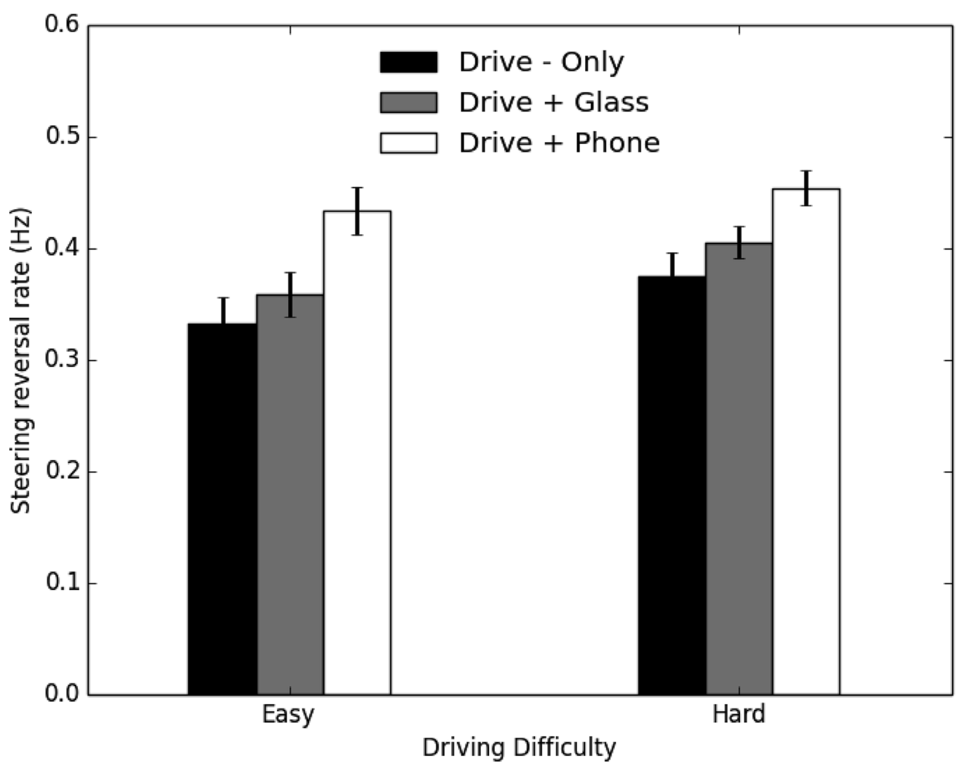


Fig. 8. The steering reversal rate.

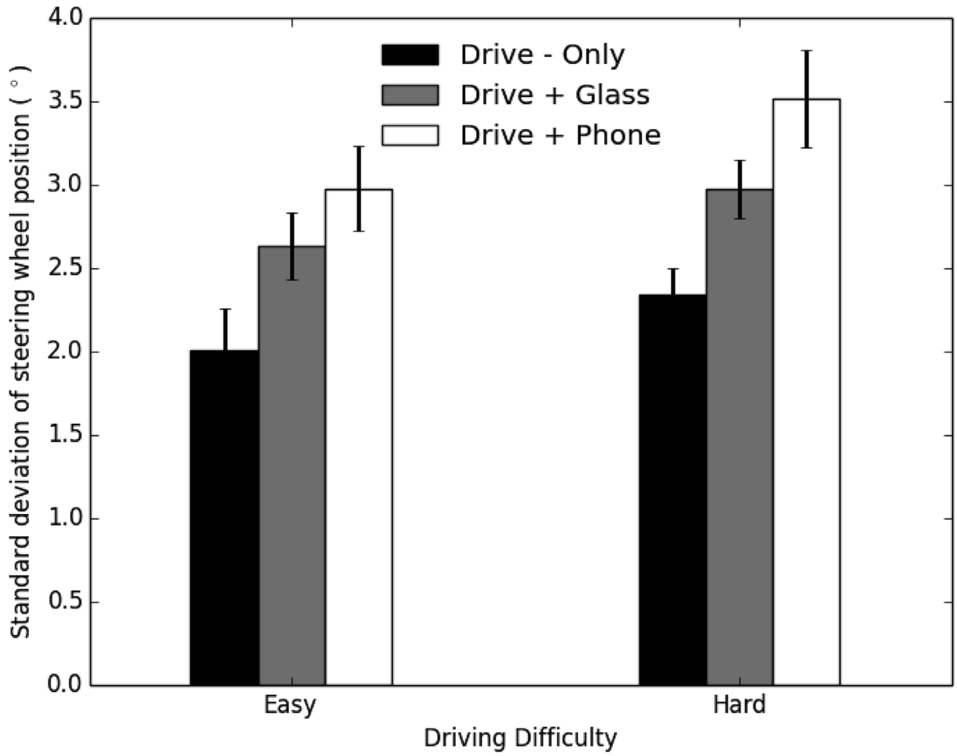


Fig. 9. The standard deviation of steering wheel position.

$\eta_p^2 = 0.47$, with Easy conditions ($M = 2.54°$, $SD = 0.92$) produced significantly smaller standard deviation of steering wheel position than Hard conditions ($M = 2.94°$, $SD = 0.90$). The interaction was not significant, F (2,56) = 0.87, $p = .42$, $\eta_p^2 = 0.03$.

Mean speed (Fig. 10) produced a significant main effect of Task Load, F (2, 56) = 9.01, $p < .001$, $\eta_p^2 = 0.24$. Pairwise comparisons showed that the mean speed in the Drive-Only conditions (M = 72.24 kilometers per hour (kph), SD = 3.01 kph) significantly faster than Drive + Glass (M = 68.06 kph, SD = 5.17 kph)and the Drive + Phone conditions (M = 69.80kph, SD = 4.18 kph), t (28) = 4.21, $p < .001$ and t (28) = 2.73, p = .01 respectively. Mean speed in the Drive + Glass conditions did not differ significantly from that in the Drive + Phone conditions, t (28) = 1.62, $p = .12$. No significant main effect of Driving Difficulty was found, F (1, 28) = 1.63, $p = .21$, η_p^2 =

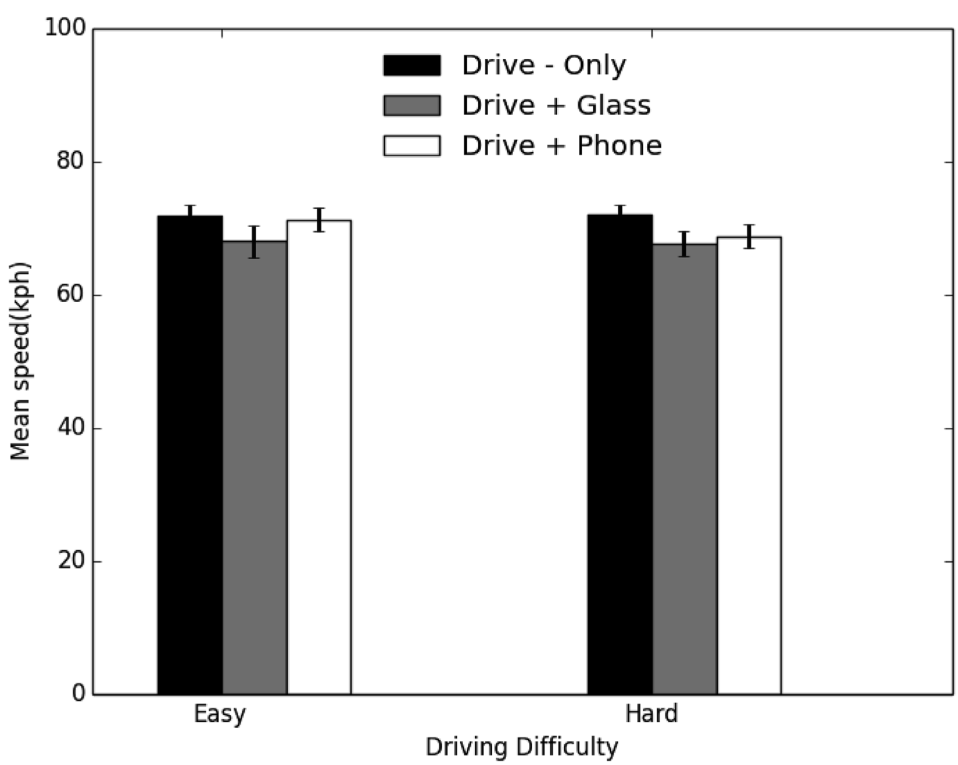


Fig. 10. The mean speed.

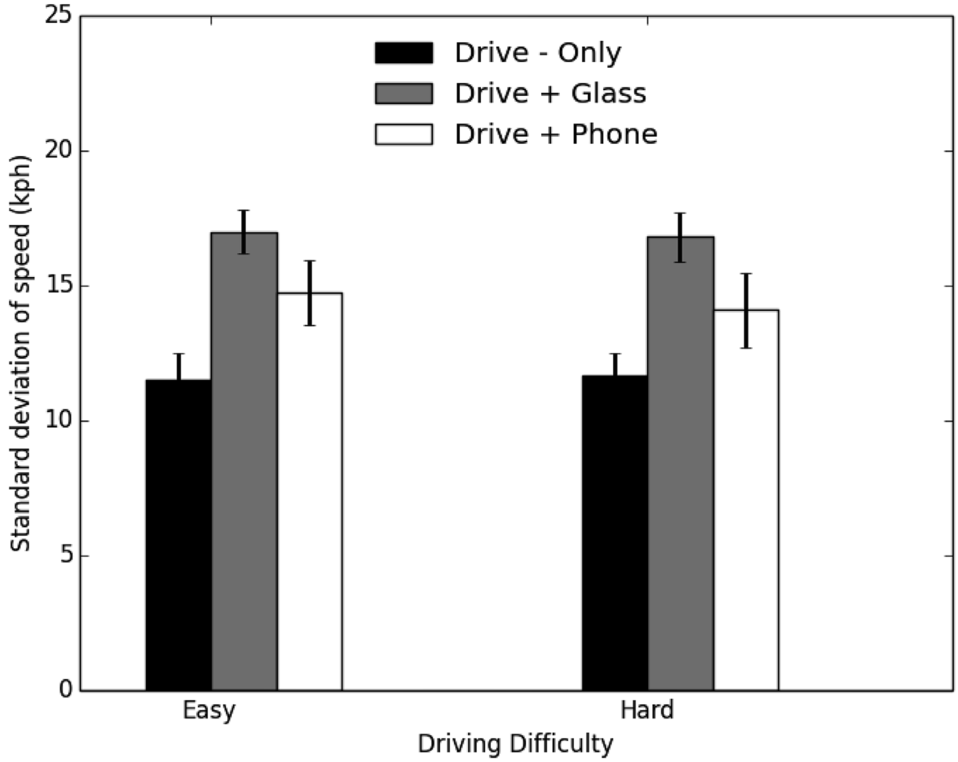


Fig. 11. The standard deviation of speed.

0.06, nor was a significant interaction, $F\ (2,\ 56) = 0.62$, $p = .54$, $\eta_p^2 = 0.02$.

The standard deviation of speed (as shown in Fig. 11) produced a significant main effect of Task Load, $F\ (2,\ 56) = 37.36$, $p < .001, \eta_p^2 = 0.57$. Pairwise comparisons showed that the standard deviation of speed was significantly lower in the Drive-Only conditions ($M = 11.31$ kph, $SD = 1.51$kph) than in either the Drive + Phone ($M = 14.32$ kph, $SD = 1.95$ kph) or the Drive + Glass conditions ($M = 16.43$ kph, $SD = 3.91$ kph), $t\ (28) = 7.37$, $p < .001$ and $t\ (28) = 7.51$, $p < .001$ respectively. The standard deviation of speed was also smaller in the Drive + Phone conditions than the Drive + Glass conditions, $t\ (28) = 3.21$, $p = .003$. Neither main effect of driving difficulty, $F\ (1,\ 28) = 0.25$, $p = .62, \eta_p^2 = 0.01$, nor the interaction of driving difficulty by task load, $F\ (2,\ 56) = 0.59$, $p = .56, \eta_p^2 = 0.02$, was significant.

Table 3 summarizes the driving performance. Texting using an HMD and a smartphone both impaired lane-keeping performance by increasing the standard deviation of lane position, the steering reversal rate, and the standard deviation of the steering wheel position.

3.2. *Texting strategy*

The mean time-to-engagement (as shown in Fig. 12.) did not produced a significant main effect of Task Load, $F\ (2,56) = 2.24$, $p = .12$, $\eta_p^2 = 0.07$, but did show a significant main effect of Texting Device, $F\ (1,28) = 84.89$, $p < .001, \eta_p^2 = 0.75$, qualified by a significant interaction, $F\ (2,56) = 5.43$, $p = .007$, $\eta_p^2 = 0.16$. Simple effects tests explored these effects. When texting with Google Glass, the simple main effect of Task Load was not significant, $F\ (2,56) = 0.28$, $p = .76$, $\eta_p^2 = 0.01$. In contrast, when texting with a smartphone, the simple effect of Task Load was significant, $F\ (2,56) = 6.55$, $p = .003$, $\eta_p^2 = 0.19$, indicating that the time-to-engagement in a smartphone-based texting task increased when they were texting while driving using a smartphone (comparing Texting - Only with a smartphone versus Texting + Easy Drive and Texting + Hard Drive). The time-to-engagement did not vary between the Texting + Easy Drive and Texting + Hard Drive conditions when using a smartphone, which indicate that increasing driving difficulty did not affect time-to-engagement.

The *mean time-on-task* (Fig. 13) showed no significant main effect of either Task Load, $F\ (2,56) = 1.36$, $p = .27$, $\eta_p^2 = 0.05$, or Texting Device, $F\ (1,28) = 1.69$, $p = .20, \eta_p^2 = 0.06$, and no significant interaction, $F\ (2,56) = 0.52$, $p = .60, \eta_p^2 = 0.02$.

Table 3
Comparisons of driving performance under different driving conditions.

	Drive + Glass vs. Drive – Only	Drive + Phone vs. Drive – Only	Drive + Phone vs. Drive + Glass
Mean lane position	≅	≅	≅
Standard deviation of lane position	↑	↑	≅
Steering reversal rate	↑	↑	↑
Standard deviation of steering wheel position	↑	↑	↑
Mean speed	↓	↓	≅
Standard deviation of speed	↑	↑	↓

Note: ↑ indicates significant increases for the first condition over the second condition in the comparing condition pairs; ↓ indicates significant decreases for the first condition over the second condition in the comparison condition pairs; ≅ indicates no statistically significant change.

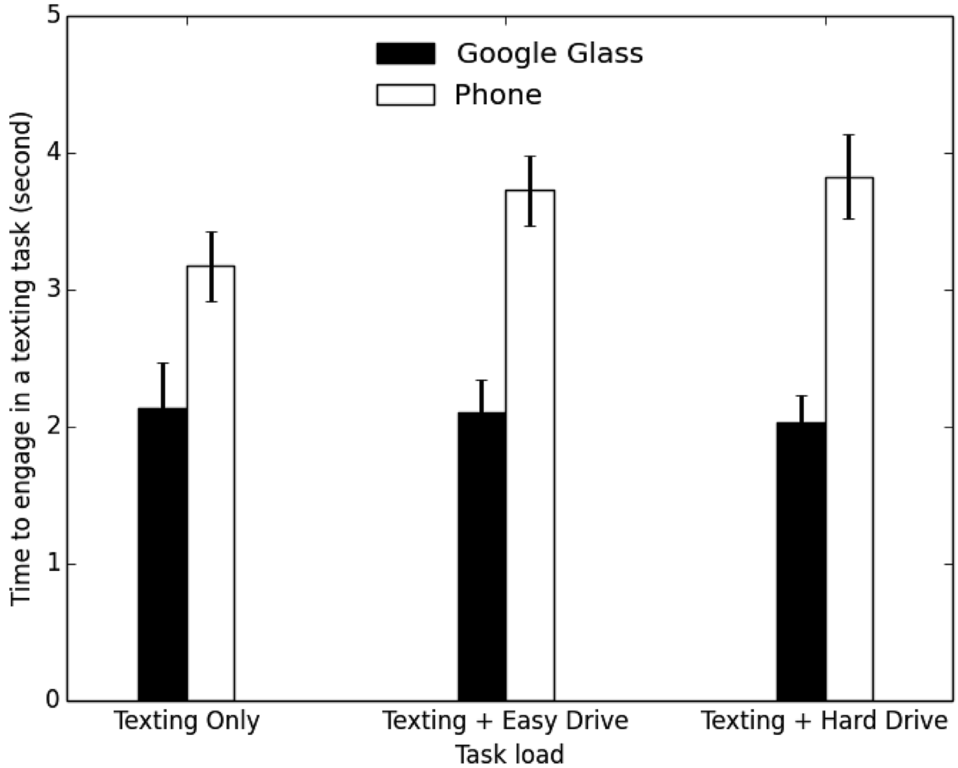


Fig. 12. Mean time-to-engagement. Error bars in all figures indicate within-subject 95% confidence intervals based on the main effect of texting task load.

4. Discussions

As a follow-up of the earlier work on HMD use while driving (He et al., 2015b; Sawyer et al., 2014), this study compared the impacts of HMD versus smartphone on driving performance, with an emphasis on the multitasking strategy to initiate and engage in a secondary texting task while driving. Both HMD and smartphone impaired driving performance by increasing the standard deviation of lane position (SDLP), the standard deviation of steering wheel position and the steering reversal rate. These findings raise safety concerns due to the higher risks of lane departure. The standard deviation of speed, an indication of stability of keeping headway distance, was also higher during distracted

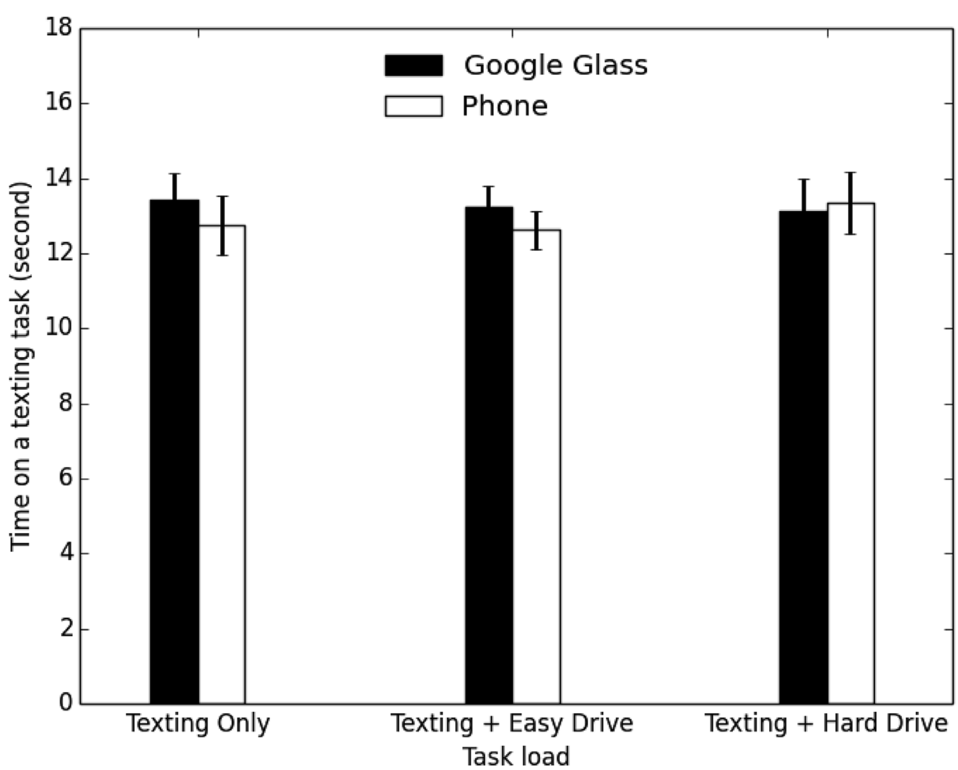


Fig. 13. The time on task.

driving for both Google Glass and smartphone. As a comparison between the two devices, Google Glass might have had less negative impact than smartphone, reflected by smaller standard deviation of steering wheel position and steering reversal rate. These results resonated with previous findings comparing HMD and smartphones (Beckers et al., 2014; He et al., 2015b; Sawyer et al., 2014). This study also reveals one indicator, the standard deviation of speed, was larger in the Drive + Glass conditions than the Drive + Phone conditions, which suggests that HMDs may be more disruptive to driving performance than HDDs in a smartphone. This measurement was not significant between the Drive + Glass and Drive + Phone conditions in a previous study (He et al., 2015b), or not measured in several other studies (Beckers et al., 2014; Sawyer et al., 2014; Wu et al., 2016). It is important to use diversified matrix and driving scenarios to measure performance so we can have all-sided perspectives on how technologies impact driving performance.

Another important goal for the current study was to investigate drivers' multitasking strategy by comparing time-to-engagement and time-on-task for different forms of texting interface. HMD users initiated the secondary task more quickly than smartphone users. Additionally, initiation times for HMD users were statistically similar across task conditions, whereas initiation times for smartphone users increased when participants were driving. Shorter time-to-engagement has also been also reported in other wearable devices, like smartwatches (Giang et al., 2014). The data confirmed our hypothesis that wearable devices indeed encouraged quicker response to initiate a distraction task for Google Glass than smartphones. The time to initiate a secondary task while driving for smartphone users increased as total task load increased, which showed an anticipatory strategy to accommodate secondary texting task and driving tasks, and this finding is consistent with some of previous studies (such as Schömig et al., 2011). In contrast, the time to engage a secondary task while driving for Google Glass users did not change according to the task load, which showed no cues of anticipatory behaviors for increasing driving difficulty (Horrey and Lesch, 2009). Previous studies have reported mixed finding on whether drivers have anticipatory behaviors to initiate a secondary task or not (Horrey and Lesch, 2009; Schömig et al., 2011). The inconsistency on the existence of anticipatory behavior might be that such behavior depends on the driving difficulty (Liang et al., 2012), the secondary task demand, and the overall multitasking load. Liang et al. (2012) reported that drivers could delay initiation of a secondary task when transitioning from low demand to high demand contexts, but not when their driving demand was already high. The current study further elucidated that drivers could exhibit such anticipatory behavior to delay a secondary task when they believed a smartphone was too distracting for driving, but not such behavior if they thought intuitively that Google Glass was just a little bit distracting, or not distracting enough to deserve delaying an important text message (He et al., 2015b).

For the time-on-task in a secondary texting task, we did not find difference between HMD and smartphone. If drivers believe HMD is less distracting than a smartphone and there is a need to engage in longer texting or conversation, it is possible that they might spend longer time on Google Glass. Drivers in current study did not showed a difference in the task duration when using Google Glass or smartphone, perhaps because our secondary verbal texting task did not require longer replies. Future studies can further test the hypothesis that whether a relatively easy texting method can encourage users to texting indulgently and spend longer time. Researchers can consider using a conversation task,a story-retelling task, or destination entry task, which may allow drivers to spend different amount of time on the texting task depending on the driving demand (Becic et al., 2010;; Beckers et al., 2014; Gaspar et al., 2014).

Google Glass has been demonstrated to be less disruptive to driving performance (Beckers et al., 2014; He et al., 2015b; Sawyer et al., 2014; Young et al., 2016). And its voice recognition technology and head-mounted display can indeed reduce the disruptive effect on driving performance compared to other means of interactions, such as manual interaction and head-down displays (He et al., 2013a, 2015b; Liu and Wen, 2004). However, if drivers intuitively believe or are frequently told that Google Glass is less disruptive to driving performance than smartphones, our current data showed that frequent use and quick access to wearable devices (such as Google Glass) in actual daily driving may potentially put wearable device users at higher risks than smartphone users.

And misuse or technology complacency may encourage users to engage more often in a distraction task, or initiate the distraction task quicker, which may eventually reduce or even overshadow the benefits that are brought by the advancement of technology. Thus, it is important to emphasize that although wearable devices, voice recognition and head-mounted display, are designed in a hope to reduce visual and manual distraction and these technologies do work to some extents, however, these technologies are not distraction-free or risk-free (He et al., 2015b; Sawyer et al., 2014). Drivers are discouraged to engage in distraction tasks not just in a smartphone, but also Google Glass and smartwatch, as all these devices impair driving performance.

Future studies shall consider studying the possibility of inattentional blindness for Google Glass usage while driving. Although Google Glass' head-mounted display can facilitates viewing of the road and the display, however, drivers' ability to attend to both the road and the transparent display of Google Glass may be limited, causing inattentional blindness or looked-but-failed-to-see error (Clabaux et al., 2012; Hyman et al., 2010; Krupenia and Sanderson, 2006). For example, two studies have reported that Google Glass users missed more targets than smartphone users (Beckers et al., 2014; Young et al., 2016). Future studies may also consider investigating the impacts of Google Glass on real-world or closed-track driving performance, as existing studies on Google Glass are all based on driving simulation.

Acknowledgment

This research work was supported by the National Science Foundation (NSF) under award number CNS-1637290.

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