Google Glass: A Driver Distraction Cause or Cure?

Ben D. Sawyer, University of Central Florida, Orlando, **Victor S. Finomore**, Air Force Research Laboratory, Wright Patterson Air Force Base, Ohio, **Andres A. Calvo**, Ball Aerospace, Wright Patterson Air Force Base, Ohio, and, **P. A. Hancock**, University of Central Florida, Orlando

Objective: We assess the driving distraction potential of texting with Google Glass (Glass), a mobile wearable platform capable of receiving and sending short-message-service and other messaging formats.

Background: A known roadway danger, texting while driving has been targeted by legislation and widely banned. Supporters of Glass claim the head-mounted wearable computer is designed to deliver information without concurrent distraction. Existing literature supports the supposition that design decisions incorporated in Glass might facilitate messaging for drivers.

Method: We asked drivers in a simulator to drive and use either Glass or a smartphone-based messaging interface, then interrupted them with an emergency brake event. Both the response event and subsequent recovery were analyzed.

Results: Glass-delivered messages served to moderate but did not eliminate distracting cognitive demands. A potential passive cost to drivers merely wearing Glass was also observed. Messaging using either device impaired driving as compared to driving without multitasking.

Conclusion: Glass in not a panacea as some supporters claim, but it does point the way to design interventions that effect reduced load in multitasking.

Application: Discussions of these identified benefits are framed within the potential of new in-vehicle systems that bring both novel forms of distraction and tools for mitigation into the driver's seat.

Keywords: attention, mobile, wearable, SMS, texting

Address correspondence to Ben D. Sawyer, University of Central Florida, 4111 Pictor Lane, Psychology Building, Ste. 320, Orlando, FL 32816; e-mail: sawyer@inhumanfactors.com.

HUMAN FACTORS
Vol. 56, No. 7, November 2014, pp. 1307–1321
DOI: 10.1177/0018720814555723
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INTRODUCTION

Google Glass (hereafter, Glass) represents the forefront of a growing class of connected devices positioned for use by individuals in motion, a user population that potentially includes drivers. Such first-generation wearable computers are already affixed to the faces of thousands of early adopters, and each can perform many of the same tasks as a smartphone. This digital prowess comes at the cost of courting distracted driving, now a well-documented risk (Caird, Johnston, Willness, Asbridge, & Steel, 2014; Crisler et al., 2008; Hosking, Young, & Regan, 2009) and the subject of full or partial bans in many states (Fitch et al., 2013). Critics of Glass are concerned about facilitating driver access to distractions both known and novel. In initial discussions of potential legislation efforts, both texting and Internet cat videos (see National Public Radio [NPR], 2014) were suggested dangers. Supporters maintain that Glass's unique interface is designed to deliver information without the significant elevation of such concurrent risks (NPR, 2014).

In the argument over whether Glass is a cause or cure of driver distraction, messaging in particular is perhaps the critical issue (Fitch et al., 2013; NPR, 2014). Using Glass or a smartphone draws on many of the same attentional resources as driving itself (Wickens, 2002), and so such multitasking limits the stable load level that can be sustained over time (Hancock & Warm, 1989). Overloaded, distracted drivers move more slowly (He, McCarley, & Kramer, 2014; Törnros & Bolling, 2006), fail to maintain proper lane keeping (Brookhuis & de Waard, 1993), experience longer psychological refractory periods (Levy, Pashler, & Boer, 2006), and compensate for the elevated risk of collision by maintaining a greater following distance (Fitch

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et al., 2013; He et al., 2014). How and whether this adaptive compensation helps is still a matter of contention and remains under fierce debate. A recent National Highway Traffic Safety Administration naturalistic driving study showed that messaging-related interaction with smartphones more than doubled crash risk (Fitch et al., 2013).

Glass's head-mounted display (HMD) is one reason to suspect that the device could facilitate texting for drivers. HMDs are a subcategory of head-up displays (HUDs), and although it is important to note that HMDs are uncoupled from viewpoints such as a vehicle windshield, both technologies present information on transparent surfaces in line with the environment. These devices and forbearers, like the reflex sight (*Elementary Optics*, 1977), have been a feature of cockpits since before World War II. Aviation HUD research has generally revealed mixed benefits: Although the technology augments performance, there are costs to, for example, detection of unexpected obstacles (see Fischer & Haines, 1980; Wickens & Long, 1994). Windshield HUDs have been available in production automobiles for more than 20 years (Weihrauch, Melony, & Geosch, 1989). Driving with these technologies has likewise been investigated, revealing benefits to HUD users in terms of vehicle control and detection of roadway events that fall in line with HUD imagery (Flannagan & Harrison, 1994; Kiefer, 1995; Kiefer & Gellatly, 1996). However, there is evidence that these benefits do not hold under the high workload of unexpected events, during which HUD users experience detriment to both the driving task and roadway event response (Fadden, Wickens, & Ververs, 2000; Horrey, Wickens, & Alexander, 2003). One possible explanation for these similar patterns of findings in aviation and automotive HUD technologies is that forward vision does not necessarily guarantee forward attention. In other words, watching the roadway does not mean a distracted driver will react to events that occur on it (Strayer, Drews, & Johnston, 2003).

Enhanced forward vision is not the only reason to believe that the novel interface typified by Glass could facilitate texting for drivers. The device's voice recognition capabilities further suggest a reduction in workload (He et al., 2014), in part because such automation eliminates the manual demands of message input and the collateral visual attention that such a task diverts from the roadway. From the theoretical standpoint of visual and manual *structural interference*, such manual manipulation is the principal contributor to messaging-based driving detriment (see Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009, and by implication Fitch et al., 2013). A *cognitive interference* theoretical standpoint would propose that it is working memory and collateral cognitive demands related to the load of language that are responsible for the majority of messaging-based driving detriment. The distinction is important; once information is delivered to a driver, technology can make little difference in what resources are necessary to process the message and cognitively synthesize a reply. Even if Glass reduces the attentional resources necessary to multitask while reading and replying to messages, it cannot minimize the impact of information that unduly occupies a driver's mind (e.g., an emergency at home). Notably, He and colleagues (2014) compared manual and speech recognition–facilitated text-messaging and found the speech interface, although superior, still impaired driving. These authors suggested their findings were in support of a cognitive interference view of messaging while driving, a finding mirroring now well-established research on vocal cell phone communication (Strayer et al., 2003).

The actual informational content of messages in multitasking-while-driving studies tends to vary widely. Naturalistic conversation is one example, as in the study by Drews and his colleagues (2009), which involves questions regarding plans later in the day. A more controlled but less ecologically valid technique involves verbal recall, as in Sawyer and Hancock's (2013) use of completion of common rhymes and sayings. The use of mathematical tasks as a proxy for language is an approach that provides high experimental control; difficult tasks, such as counting backward by 17s, have been shown to be a reliable way to induce consistent workload (Siegenthaler et al., 2014). The argument against these latter approaches centers

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not only on the artificiality of the task but on findings that such arithmetic tasks produce greater degradation of the driving task than do naturalistic conversations (Shinar, Tractinsky, & Compton, 2005). However, magnitude aside, patterns of driving degradation observed in each of the above studies, using the differing tasks, prove to be rather similar. Resources involved in the method and modality of delivery may in fact be one of the most important factors in differing patterns of demand and resultant detriment to the driving task. Finally, the contents of messages in the real world are highly diverse, encompassing a wide variety of potential cognitive demands and emotional impacts. In naturalistic settings, mathematical questions join spatial, temporal, social, and strategic queries representing diverse informal and intrinsic demands, which impair the driving and messaging public.

The experience of messaging while driving with Glass warrants examination, if only anecdotally, as it necessarily guided choices made in designing our present experiment. Incoming messages are announced with a chime delivered through a bone conduction audio system. Such messages can be summoned to the screen with a brief up-down head gesture. Glass's optics project the screen at a working distance of 3.5 m (~11.5 feet; see "Frequently Asked Questions," 2014); focusing on the display and then back to the roadway does require an act of eye accommodation. If one wishes to respond to a displayed message, Glass must be invoked vocally with the key phrase "OK, Glass," followed by "Reply." Users then speak their message, which is transcribed on the display as it is recognized by Google's speech engine. At this point, assuming a satisfactory reply is displayed, no further action is necessary; Glass sends the message. Our initial evaluation study with Glass found that performance of novices using this messaging interface plateaued after only 5 min of training, as compared to performance at 10 and 15 min (MacArthur, Greenstein, Sawyer, & Hancock, 2014). Indeed, using Glass's interface behind the wheel begins to feel easy in a remarkably short period of time. But is this feeling of ease deceptive? That is, does Glass in fact provide some relief from the detriment of multitask driving, or does it represent a fallacious "easing of demand"?

Our present study was designed to test the aforementioned propositions with drivers under conditions of multitasking and normal driving in the presence of either Glass or a smartphone. For the multitasking condition, we chose the experimental control and consistent workload of messages containing arithmetic tasks. Previous research has established a strong link between multitasking and levels of cognitive load that lead to driving detriment (Caird et al., 2014; Fitch et al., 2013; He, McCarley, et al., 2014; Horrey & Wickens, 2003; Hosking et al., 2009; see especially Wickens, 2002). Prior experimental research on driving while messaging has employed both response dependent variables, such as response time (Sawyer & Hancock, 2013; Strayer et al., 2003), and also continuous dependent variables, such as standard deviation of lane position (SDLP; as in He et al., 2014; Hosking et al., 2009). Each of these approaches has its advantages and drawbacks; here we use both.

We evaluated drivers first through response times collected during a simulated unexpected brake event. We used a variation of the "pace car" task in which participants are instructed to follow a vehicle (as in Strayer et al., 2003). Multitasking-elevated workload might conceivably have no immediate effect upon the driving task, but the overall increased chronic level of workload under such circumstances effectively limits the sustainable stable load level (Hancock & Caird, 1993; Hancock & Warm, 1989). A spike in overall driver workload is therefore more likely to lead to dynamic instability and an observable failure in the driving task. As discussed, we had reason to believe Glass could facilitate the messaging task, leaving drivers with greater capacity to respond to the unexpected braking event. This supposition was predicated on two assumptions: (a) that compared to the smartphone, Glass's HMD display would increase visual attention to the road ahead and (b) that its voice input would decrease manual requirements and requisite visual attention. Therefore, we reasoned, participants driving with Glass would have a greater chance to detect the necessity to brake early and react more

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quickly. Therefore, in regard to response dependent variables, we hypothesized a significant interaction such that participants who engaged in only driving would show no significant differences between the devices when responding to a brake event but that among participants who engaged in multitasking, Glass would provide significant advantages over the smartphone. Specifically, these advantages were hypothesized to entail lower response time and higher minimum time to collision (TTC_{min}). Such a hypothesis is in line with the notion of structural interference.

Also of importance in high-workload situations is the period after a high-workload event during which a driver returns to normalcy in the driving task (as in Morgan & Hancock, 2011). The slower this recovery rate, the more vulnerable the driver is to further elevated workload and resultant dynamic instability (Levy et al., 2006; Hancock & Warm, 1989). To investigate this recovery, following each brake event, we defined three epochs in which to collect continuous driving data: first a braking epoch during the brake event, then a replying epoch from the lowest point of speed until the device interaction was complete, and finally, a 2-s recovery epoch. We anticipated that drivers responding to the unexpected event would experience the greatest impact of Glass's advantages to visual attention while recovering from braking. Therefore, in regard to continuous dependent variables, we hypothesized an interaction between device, multitasking, and epoch such that Glass would provide a significant advantage over the smartphone in the course of the replying and recovery epochs. Specifically, this would entail lower SDLP, an average speed closer to the posted limit of 45 mph (likely higher, as the load of multitasking should produce slower drivers), and a lower following distance, reflecting drivers' assessment of reduced risk. This hypothesis was likewise in line with the previously stated ideas of structural interference.

Finally, in the high-workload environment of multitasking, we were interested in the subjective experience of using each device. It was phenomenologically clear how accessible messaging with Glass felt, and thus we looked to evaluate whether this experience was shared by our participants. We therefore measured each driver's subjective assessments of workload with the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) both prospectively and retrospectively. These data were anticipated to reveal an interaction such that before driving, our participants would rate the familiar device, the smartphone, as incurring lower workload but, after driving, would instead apply that relative rating to Glass.

METHOD

Participants

Twenty-four female and 16 male participants (N = 40; mean age = 20.47 years, SD = 4.76) were recruited from the university undergraduate population and compensated for their time with class credit. On average, participants had been driving 4.54 years (SD = 4.65). All were over 18 years of age, having both a valid driver's license and normal or corrected-to-normal vision.

Apparatus and Stimuli

To test the postulated hypotheses, we employed a driving simulator. Three 52-inch screens, each projected at a resolution of 1,024 × 768 pixels at 60 Hz, provided a 270° presentation of the virtual environment, complete with simulated rearview and side mirrors. Participants were seated in a cab complete with dash and steering wheel from an actual vehicle. Simulator data were likewise captured at 60 Hz. (For more detailed information on this facility, see Sawyer & Hancock, 2012.) The NASA-TLX and demographic surveys were administered via Qualtrics.com, presented on a 15-inch LCD monitor at a separate station adjacent to the simulator.

The Glass used in this study, which ran software version XE11, was worn by participants in the fashion described in Figure 1 and pictured in Figure 2. Incoming message alerts were in the form of a chime played through Glass's bone conduction audio. The head-tilt gesture used to "unlock" the device was set to a threshold of 30°. Unlocking revealed the stock Glass messaging interface, which visually displayed only the current message. Replies required participants to speak a key phrase, words Glass uses to

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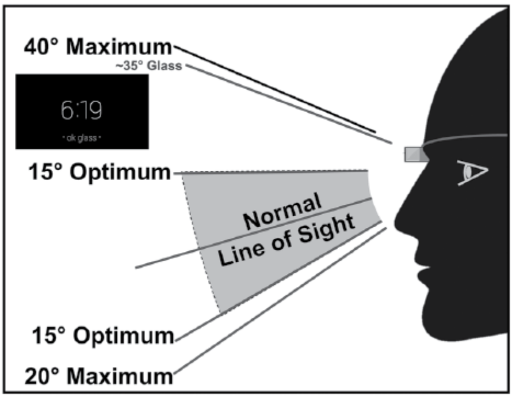

Figure 1. A properly positioned Google Glass, worn high on the bridge of the nose, produces a translucent display approximately 35° elevated from the primary position of the eye (Department of Defense, 1999; Kress & Starner, 2013). This display is set to a working distance of 3.5 m (see "Frequently Asked Questions," 2014) and so minimizes, but does not eliminate, acts of accommodation by an eye shifting visual focus between the roadway and the display.

understand when to respond to the user's commands. In the context of the task we used, after speaking the key phrase "OK, Glass," the user could say, "Reply," and speak any answer he or she wished. "Locking" after task completion turned off the display and was accomplished through a vertical downward stroke on a touch sensor located on the right side of the device. (It should be noted that this gesture in fact signifies *back*, with the furthest-back position being a state with screen off. After task completion, a single downward stroke entered this locked state.)

The Galaxy Nexus smartphone used in this study ran stock Android 4.3. Participants held the phone in their hand while operating it. Incoming message alerts were in the form of a chime played through the phone's speaker. A left-to-right thumb slide was the "unlock" gesture, the default on Nexus and many other phone models. Unlocking revealed the stock Android messaging app, which visually displayed a thread of past messages with the most recent at the bottom. Replies were started by tapping in a field below the last message and were then typed on the stock Android soft keyboard. "Locking" turned off the screen and was accomplished by pushing the lock button, positioned at the top right-hand edge of the device.

Both devices were additionally loaded with a custom program that allowed the delivery of

Figure 2. A participant wearing Google Glass changes lanes to enter a stretch of virtual highway. In the next 1 km (0.62 miles), she will receive a message containing an arithmetic task, and 1,800 ms later, the car leading her will slam on its brakes. Inset: Participants were instructed on proper positioning and use of this novel device before experimentation. In piloting, many drivers chose to tilt their head so as to superimpose the Glass display over the road in their vision, a practice so common that in our own trial we had to specifically caution against such misuse.

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messages via wireless network while also recording and transmitting time stamps for messaging-related events. This software, built in cooperation with the Air Force's 711th Human Performance Wing, allowed us to conditionally target events in the driving environment with millisecond precision. In the present study, we used this capability to deliver text messages to participants, which, upon acceptance, would trigger an unexpected brake event from the lead vehicle, a variation on the pace car paradigm (as in Strayer et al., 2003). Our pace car drove at a constant 45 mph and braked sharply with a linear deceleration of 7.5 m/s^2. The simulated driving environment that was used comprised 8,046 m (5 miles) of three-lane freeway without curves, posted at 45 mph. Every 2,000 m (1.24 miles), a flashing arrow sign directed drivers to change lanes, providing a total of four stretches of highway. At a unique position in the first half of each stretch, an invisible positional trigger initiated a load condition–dependent interaction with the participant. In a driving-only condition, a trigger would cause the pace car to brake suddenly. In a multitasking condition, the participant would receive a message, and 1,800 ms after unlocking the device it had been delivered to, the pace car would brake suddenly. This timing was chosen through pilot experimentation as being the most likely to interrupt the participant in reading the message. Messaging stimulus consisted of an arithmetic task: a four-digit number minus 17 (e.g., 1,634 – 17; see Siegenthaler et al., 2014).

Procedure

Each session was divided into phases of arrival, training, experimentation, and release. Upon arrival and completing informed consent, participants were asked to turn off and surrender any electronic devices in their possession, including any smartphones. A demographic questionnaire was then administered. The training phase began with instruction in operating the driving simulator and a 5-min orientation drive during which the appropriate following distance for the study was visually presented and verbally described as "three car lengths." Subsequent training on the smartphone always preceded training on Glass, and training on each followed a set script. First, each participant was shown how to unlock the device, reply to a message, and lock the device. On Glass, this guidance included making sure the device was correctly seated on the participant's face (Figures 1 and 2).

Participants were guided through the messaging task in five steps. First, they waited for the audible alert and, when they were ready, unlocked the device as described earlier. Second, they read the incoming message from the trained device's display and computed the answer. Third, they spoke the answer aloud. (This step was added as a result of pilot findings to reduce the occurrence of participants' forgetting the number they had computed when they moved to the next step.) Fourth, using each respective device's interface, participants composed and sent a reply containing only the answer. Fifth and finally, they locked the device, again described earlier. Training used a set of eight simple mathematical problems (e.g., 1,017 – 17) and four or more following difficult problems like those used in the experimental phase (e.g., 1,634 – 17). Participants practiced with each device until they were able to complete the five steps four consecutive times without error. Four participants, unable to do so within 30 min, were removed from the study before the experimental phase began. They are not included in the sample described earlier.

For the experimental phase, participants were alternately assigned to either a smartphone first or Glass first group. As all participants had just finished training on Glass, those in the smartphone-first group were given a single message to reply to, which ensured they recalled how to use the smartphone. They then completed a prospective NASA-TLX, which asked for a prediction of performance while using the device and driving. They were then placed in the driving simulator, reminded of the appropriate following distance, and instructed to "follow the car ahead" as they drove through the scenario. Load condition order in the four stretches driven was counterbalanced between participants, as was message order. After the first experimental drive, participants completed a retrospective NASA-TLX before they traded the first device for the second. To ensure they could still reliably perform the task, all participants were again

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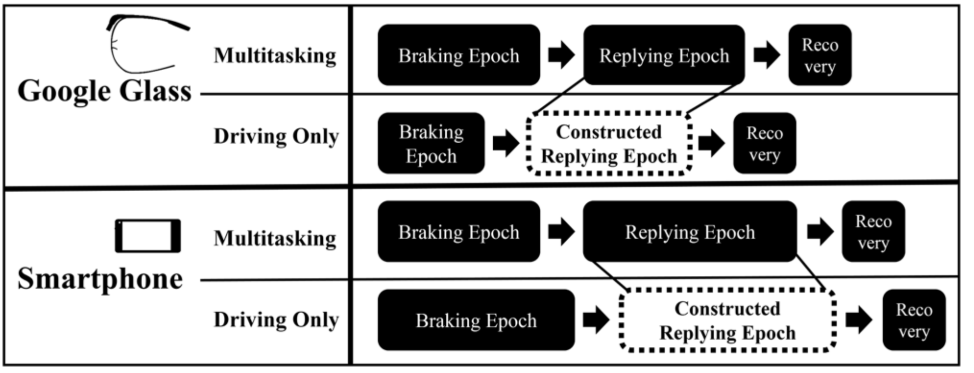

Figure 3. Continuous dependent variables were reported by epoch. The braking epoch spanned the time from pace-car brake to the lowest point of participant speed. The replying epoch spanned the time from the lowest point of speed until the participant locked the device. The recovery epoch spanned 2 s directly thereafter. Driving-only-condition replying epochs were constructed to be of the same length as their matching multitasking-condition replying epoch. Epochs were then compared between devices (Glass, smartphone) and between loads (multitasking, driving only).

given a single message to reply to. The second device session was modeled after the first. Upon exiting the simulator, participants took a brief questionnaire regarding their driving history. They were then debriefed and released.

Driving Measures

Each participant drove separately with each device, that is, a Glass drive and a smartphone drive. Each device drive consisted of four stretches of highway, among which each participant received a driving-only-condition brake event and a multitasking-condition brake event. Participants interrupted by the lead-car brake event while reading the multitasking-condition message universally waited until after the nadir, or lowest point, of their speed to reply. This consistency was not necessarily expected and is an interesting outcome of our study in its own right.

Continuous dependent variables included (a) lane keeping as measured by the SDLP in meters offset from lane center, (b) average speed in miles per hour, and (c) average following distance in meters. To understand how each device affected recovery, three epochs were constructed around the brake event (Figure 3). In temporal order, these were (a) the braking epoch, which spanned time from the pace-car brake onset to the lowest point (or nadir) of participant speed. Next, (b) the replying epoch spanned time from nadir of speed until the participant ended use of the device by locking it. Finally, (c) the recovery epoch spanned 2 s of driving after the device was locked. As participants in the driving-only condition did not use the device, their replying epoch was simply constructed to be the same length as the matching replying epoch from their multitasking drive. The recovery epoch windowed 2 s of driving after the end of the constructed replying epoch and was intended to sample the return to driving normalcy after the device interaction.

Response dependent variables included hybrid response time (HRT) and TTC_{min}. HRT was measured from the time the pace car braked. If a participant's foot was on the accelerator, HRT was calculated as time to accelerator release. If the participant's foot was off the accelerator, HRT was calculated as time to brake onset (for a detailed graphic, see Sawyer & Hancock, 2013).

TTC_{min} was measured as the lowest occurrence of following distance over speed and was represented in seconds. In the current study, TTC_{min} can be considered a continuous representation of forward impact, as a TTC_{min} value of zero indicated collision.

Statistical Analysis

Driving can involve highly interrelated variables. For example, time to collision is clearly

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TABLE 1: Response Dependent Variables in Brake Event

Dependent Variable	Device	Load	*M*	*SE*
HRT (ms)	Google Glass	Multitasking	1,698	110
		Driving only	1,283	65
	Smartphone	Multitasking	1,644	102
		Driving only	1,288	65
TTC_{min} (ms)	Google Glass	Multitasking	156	12
		Driving only	230	10
	Smartphone	Multitasking	175	8
		Driving only	232	10

Note. HRT = hybrid response time; TTC_{min} = minimum time to collision. Main effects were seen for HRT and TTC_{min}. Times are shown in milliseconds.

influenced by response time (i.e., our TTC_{min} and HRT in this work, respectively). As such, the present data were initially submitted to multivariate analyses of variance (MANOVA). This multivariate approach has the advantage of providing reliable analyses of unique variance and resultant effect sizes for the joint effects of each set of performance measures as a function of experimental conditions. In the present work, significant effects under each MANOVA were further examined through univariate analyses (ANOVA), allowing the contribution of each dependent variable to be understood (for work using a very similar approach, see Strayer et al., 2003).

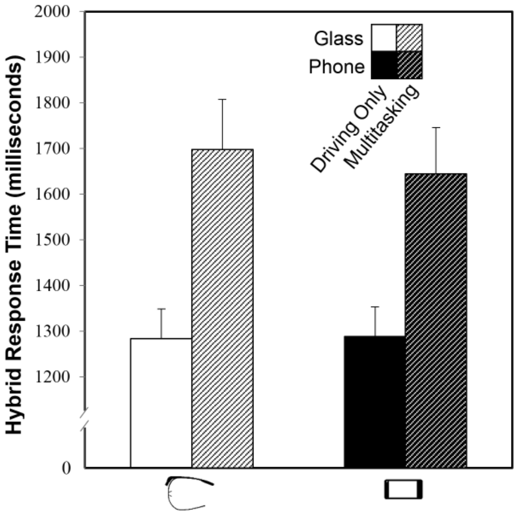

Figure 4. A main effect of load in hybrid response time. Drivers messaging with each device are measured against their performance with the device merely present. Error bars represent within-participants confidence intervals (Cousineau, 2005).

RESULTS

Response Dependent Variables

The following dependent variables were collected during the response to the brake event. Data from all 40 participants (n = 40) were included in the present analysis. Descriptive statistics for all response dependent variables are reported in Table 1. Two response variables (HRT, TTC_{min}) were analyzed using a within-participants MANOVA to assess the impact of two different manipulations in the 2 (device: Glass vs. smartphone) × 2 (load: multitasking vs. driving only) design. No significant interaction was seen; Wilks' lambda = .98, $F(2, 38) = .367$, $p = .70$, $\eta^2_p = .02$. There was, however, a significant main effect of load, Wilks' lambda = .583, $F(2, 38) = 13.58$, $p = .00$, $\eta^2_p = .417$. Univariate ANOVA results were therefore interpreted, revealing that both response variables were significant: HRT, $F(1, 39) = 20.06$, $p = .00$, $\eta^2_p = .34$ (Figure 4), and TTC_{min}, $F(1, 39) = 20.84$, $p = .00$, $\eta^2_p = .35$. These data indicate that participants reacted more slowly and preserved less headway in the multitasking condition than in the driving-only condition. There was no significant main effect of device, Wilks' lambda = .98, $F(2, 38) = 0.46$, $p = .63$, $\eta^2_p = .02$.

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TABLE 2: Epoch Window Length in Milliseconds

Device	Load	Braking Epoch		Replying Epoch	
		M	*SD*	*M*	*SD*
Glass	Multitasking	5,168	1,722	2,8608	7,246
	Driving only	4,905	1,430	—	—
Smartphone	Multitasking	5,337	1,193	2,4221	9,216
	Driving only	5,031	1,471	—	—

Note. The messaging task was performed only by multitasking drivers and spanned both of the epochs. Mean messaging task length was 33.77 s (*SD* = 8.97) for Google Glass and 29.56 s (*SD* = 10.41) for the smartphone. The recovery epoch is not shown here, as it covered 2 s.

Continuous Dependent Variables

The following dependent variables were collected continuously, from 1,800 ms after a participant first viewed a message until 2 s after they had completed responding to it. Four participants were removed from these data due to technical issues that prevented epoch time stamps from being recorded. Thus, 36 participants (n = 36) were included in the present analysis.

Three continuous dependent variables (SDLP, average speed, average following distance) were analyzed using a within-participants MANOVA that assessed the impact of two manipulations across three epochs in a 2 (device: glass vs. smartphone) × 2 (load: multitasking vs. driving only) × 3 (epoch: braking vs. replying vs. recovery) design. Epoch lengths are reported in Table 2. Descriptive statistics for all continuous dependent variables are reported in Table 3.

There was a significant interaction among device, load, and epoch (Figure 5), Wilks' lambda = .59, $F(6, 30) = 3.50$, $p = .01$, $\eta^2_p = .41$. Univariate ANOVA results were therefore interpreted, revealing the interaction was significant in SDLP (lane keeping), $F(1.43, 49.91) = 5.72$, $p = .01$, $\eta^2_p = .14$. Violations of sphericity were indicated by Mauchly's test, $\chi^2(2) = 17.51$, and therefore degrees of freedom have been adjusted using the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction, $\varepsilon = 0.72$. This interaction was not significant in average speed or average following distance. In respect to SDLP, these data show a differential effect by epoch. In the replying epoch, among participants in the driving-only condition, smartphone users show the lowest SDLP, followed by Glass. This pattern revealed a passive cost for participants merely driving while wearing Glass. In the multitasking condition, this pattern was reversed: Glass users show less elevation of SDLP, whereas smartphone users show more, actually exceeding the other group. This pattern revealed better lane keeping for multitasking Glass users. In the braking and replying epochs, lane keeping differs by load such that multitasking drivers have greater SDLP than those only driving. This pattern reveals only the cost of multitasking, and neither device shows an advantage.

There was a significant interaction between device and epoch, Wilks' lambda = .60, $F(6, 30) = 3.30$, $p = .01$, $\eta^2_p = .40$. Univariate ANOVA results were therefore interpreted, revealing two significant measures: average speed (Figure 6), $F(2, 70) = 7.08$, $p = .00$, $\eta^2_p = .17$, and average following distance (Figure 7), Mauchly's test, $\chi^2(2) = 14.38$, adjusted using Greenhouse-Geisser, $\varepsilon = 0.82$; $F(1.49, 52.05 = 6.74$, $p < .01$, $\eta^2_p = .16$. These average speed data revealed that Glass users returned to roadway speeds more quickly in the replying phase. The average following distance data revealed that smartphone users ultimately adopted greater following distances. There was a significant interaction between load and epoch, Wilks' lambda = .47, $F(6, 30) = 5.63$, $p = .00$, $\eta^2_p = 0.53$. Univariate ANOVA results were therefore interpreted, revealing two significant measures: average speed, Mauchly's test, $\chi^2(2) = 9.90$, adjusted using Greenhouse-Geisser, $\varepsilon = 0.80$; $F(1.60, 55.88) = 10.46$, $p = .00$, $\eta^2_p = .23$; and average following distance, Mauchly's test,

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TABLE 3: Continuous Dependent Variables by Epoch

Dependent Variable	Device	Load	Braking Epoch *M*	Braking Epoch *SE*	Replying Epoch *M*	Replying Epoch *SE*	Recovery Epoch *M*	Recovery Epoch *SE*
SDLP (meters)	Google Glass	Multitasking	0.13	0.01	0.19	0.01	0.06	0.01
		Driving only	0.08	0.01	0.18	0.01	0.04	0.01
	Smartphone	Multitasking	0.12	0.02	0.22	0.01	0.07	0.01
		Driving only	0.09	0.01	0.14	0.01	0.04	0.01
Average speed (mph)	Google Glass	Multitasking	30.91	0.47	39.25	0.51	48.19	0.73
		Driving only	32.73	0.57	39.76	0.56	47.28	0.60
	Smartphone	Multitasking	30.46	0.69	34.89	0.63	47.79	0.64
		Driving only	32.85	0.52	37.48	0.58	47.37	0.56
Average following distance (meters)	Google Glass	Multitasking	22.26	2.79	70.11	3.15	63.86	3.56
		Driving only	32.16	1.91	66.19	1.99	60.25	3.68
	Smartphone	Multitasking	29.07	2.35	77.94	4.07	89.98	4.89
		Driving only	32.78	2.21	64.71	2.30	68.02	3.59

Note. SDLP = standard deviation of lane position. SDLP was significant in the three-way interaction between device, load, and epoch. Average speed and average following distance were both significant in the two-way interaction between device and epoch as well as in the two-way interaction between load and epoch.

$\chi^2(2)$ = 11.06, adjusted using Greenhouse-Geisser, ε = 0.78; $F(1.57, 54.79) = 15.08$, $p = .00$, $\eta^2_p = .30$. These data reveal that drivers in the multitasking condition drove more slowly and adopted greater following distances than those in the driving-only condition.

Subjective Workload Variables

Five participants were removed from these workload data due to failure to complete the NASA-TLX fully or correctly. Thirty-five participants ($n = 35$) were thus included in the present analysis. Six dimensions of the NASA-TLX (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration) as well as the overall workload score were subjected to a within-participants ANOVA to assess the impact of two different times of administration across two devices in a 2 (prospective vs. retrospective) × 2 (device: Glass vs. smartphone) design. There was a significant main effect of device, Wilks' lambda = .51, $F(6, 29) = 4.57$, $p = .00$, $\eta^2_p = .49$. Univariate ANOVA results were therefore interpreted, revealing a significant effect only for physical demand, $F(1, 34) = 15.98$, $p = .00$, $\eta^2_p = .32$. Using a smartphone induced a significantly higher level of physical workload than using Glass. There was also a significant main effect for time of administration, Wilks' lambda = .50, $F(6, 29) = 4.83$, $p = .00$, $\eta^2_p = .50$. Univariate ANOVA results were therefore interpreted, revealing two significant measures: temporal demand, $F(1, 34) = 17.06$, $p = .00$, $\eta^2_p = .33$, and performance, $F(1, 34) = 15.60$, $p = .02$, $\eta^2_p = .31$. These data showed that participants found both devices less demanding in terms of time and had more success messaging with the devices than they had expected. There was no significant interaction, Wilks' lambda = .83, $F(6, 29) = 0.98$, $p = .46$, $\eta^2_p = .17$.

DISCUSSION

Our lead vehicle's sudden braking created a multitasker's worst-case scenario: a dangerous roadway event in the course of engaging with a distracting message (and see Hancock & deRidder, 2003). Epoch analysis revealed better lane-keeping performance for participants using Glass when replying, as compared to those using the smartphone. This finding is perhaps best framed in the voice recognition Glass afforded, which, as previously noted, has

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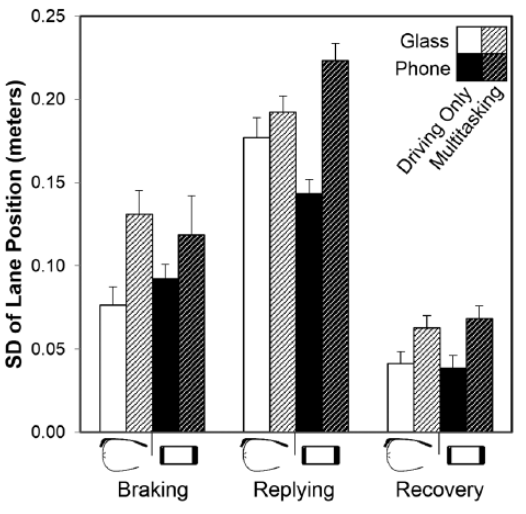

Figure 5. Lane keeping as represented by standard deviation of lane position in a significant three-way within-participants interaction between epoch (braking, replying, and recovery), device (Google Glass, smartphone), and load (multitasking, driving alone). Error bars represent within-participants confidence intervals (Cousineau, 2005).

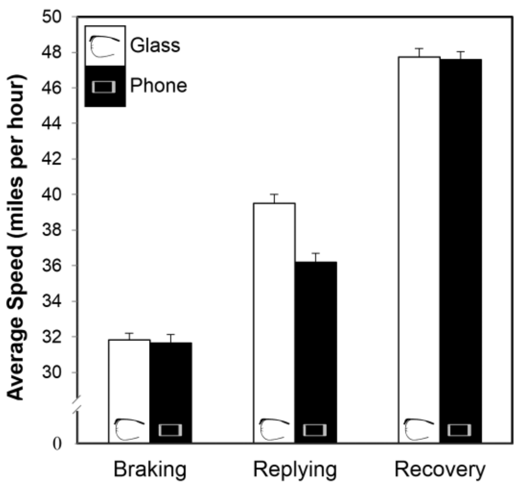

Figure 6. A significant interaction between device and epoch for average speed. Google Glass–using drivers returned toward the posted roadway speed of 45 mph sooner.

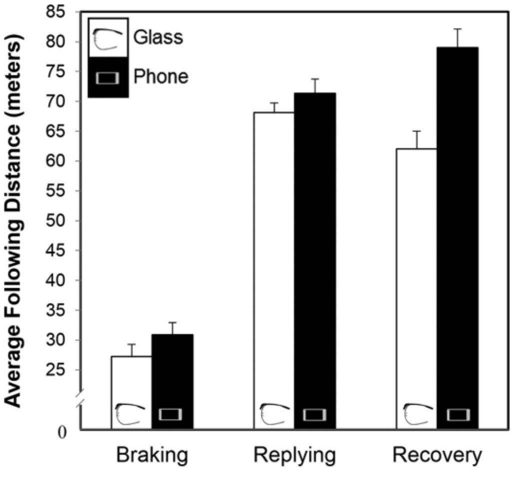

Figure 7. A significant interaction between device and epoch for average following distance. Google Glass–using drivers adopted a closer following distance, especially in the recovery epoch. Error bars for both figures represent within-participants confidence intervals (Cousineau, 2005).

been shown to reduce workload in and of itself (He et al., 2014). Glass users also returned to normal roadway speed sooner, a sign of reduced distraction (Törnros & Bolling, 2006). They further adopted closer following distances, suggesting a reduced perception of risk. These data are in support of our hypotheses regarding continuous dependent variables and highlight areas in which Glass's novel message delivery (i.e., HMD visual output and voice response) may moderate driving detriment.

Contrary to our continuous dependent variable hypotheses, average speed and following distance did not differ significantly under the aforementioned interaction. Moreover, what benefits were seen for Glass may have been offset by a passive cost to drivers, who were asked merely to wear the device. In the driving-only condition, those wearing Glass exhibited poorer lane-keeping performance than those driving with the smartphone, even though neither device was activated. Analysis of response to the brake event (via HRT) likewise revealed no benefit for either device. In summary, although Glass-using drivers demonstrated some areas of improved performance in recovering to the brake event, the device did not improve their response to the event itself.

Most importantly, for every measure we recorded, messaging with either device negatively impacted driving performance. Multitasking

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drivers reacted more slowly (per HRT), preserved less headway (per TTC_{min}) during the brake event, and subsequently adopted greater following distances (per average following distance). They showed poorer lane keeping in all epochs (per SDLP). The pattern of driving detriment and magnitude of costs seen here are in line with previously reported findings (e.g., Caird at al., 2014; He et al., 2014; Hosking et al., 2009; Sawyer & Hancock, 2013; Strayer et al., 2003). That this pattern was seen for both the smartphone and Glass, from a theoretical standpoint, is not highly supportive of the structural interference model of messaging-based driving detriment and, in fact, in a number of ways is more supportive of the cognitive interference model (for a similar example, see He et al., 2014). From a practical standpoint, these data serve to indicate that Glass-delivered messaging moderates some aspects of multitasking-induced load but does not eliminate it. Using Glass does not in any way render safe the act of messaging while driving.

The use here of mathematical transformations permits us an important degree of experimental control and certainly involves visual information assimilation and psychomotor output. The empirical question, however, remains, To what degree is such a loading task representative of language-based tasks that typically connote what actually occurs on the road? The resolution of this issue is directly contingent upon, and argues for the pragmatic incorporation of, neurophysiological theory. We believe each of these forms of secondary demand (i.e., math transformations and language operations) imposes common loads on short-term working memory and that, since mathematics itself is a form of symbolic language, it imposes demands on many brain structures common to language generation and reception. This view is supported by recent research (see especially Scheepers et al., 2011; but also Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Scheepers & Sturt, 2014). However, we fully accept the potential for, and arguments in favor of, a direct antithesis that emphasizes differences, including, for example, discrete brain regions apparently devoted to nonmathematical language. Note, however, that laboratory-based naturalistic linguistic tasks contain their own inherit ambiguities in both administration and in veridical measurement derivation (Shinar et al., 2005, touch on just some of these).

Our interim conclusion is that loading-task configuration has still to receive a sufficiently debated systematization and that as more evidence becomes available, ever more appropriate inferences can be drawn to real-world conditions. Suffice it to say that we believe the arithmetic loading task generalizes sufficiently, such that our present results are applicable to and informative of current real-world driving conditions.

Some of the most interesting findings of this study proved to be incidental to the main task. That participants universally addressed braking before replying is instructive, suggesting that task primacy in this critical multitask situation was obvious to all, despite their detriment. The subjective workload data (NASA-TLX) failed to conform to our hypotheses, with the exception of elevated physical workload for smartphone users over Glass users. The unexpected pattern found for the temporal demand and performance scales is fascinating. For both devices, participants predicted greater cost to use than they retrospectively reported after actual use. This assessment that multitasking while driving, in the words of one of our participants, “wasn’t so bad after all” was unexpected. It may simply suggest that people are not good predictors of their own performance (as in Lesch & Hancock, 2004) but may also signal that the transition from abstract belief in the dangers of roadway multitasking to equivocation and minimization of such dangers is quite rapid. Further investigation into this transition is warranted, especially in light of potential consequences (Fitch et al., 2013).

It is worth noting that our participants were trained to competency but not comfort with the Glass unit. This is to say that participants had progressed beyond declaratively encoding the steps necessary to operate Glass, and association between these steps and the practical task of sending a message had improved such that they could perform the task repeatedly without error. It is, however, unlikely that they had passed to the rapid, autonomous skill execution that is the hallmark of very experienced users (for discussions of skill acquisition, see Anderson, 1983;

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Fitts & Posner, 1967). Indeed, given the novelty of the device, very few experts in using Glass presently exist anywhere. Any fully enacted epidemiological assessment of impact must assume population expertise, and when such a population exists, this finding should be revisited. We further feel a measure of visual behavior, for example, eye tracking, could and will shed further light on the pattern in question and consider it a likely next step.

The safety debate surrounding Glass requires evaluations of features beyond messaging itself, which is only a small subset of the device's capabilities. Further, the mixed benefits seen for Glass users do not reveal this technology as a driving distraction panacea. However, they do show that design interventions have the ability to reduce some types of load in multitasking. The exact nature of these changes is not addressed in this empirically established foundational work. Our findings suggest future component-by-component analysis of the usability and distraction potential of each subsystem of Glass to help definitively quantify which design decisions were most beneficial. As distractive influences threaten to become more common and numerous in drivers' lives, we find the limited benefits provided by Glass a hopeful sign of technological solutions to come. Perhaps the true promise of devices Glass foreshadows is still to be built.

Technology, it should not be forgotten, can do much more than introduce distraction. Glass contains sensors that have the potential to assist driving. For example, this assistance can be achieved through estimating driver fatigue or attention declines and providing valuable corrective feedback (see Lee, 2009). Should this device become popular, the platform has unquestionable potential for safety interventions. This hopeful outlook is not limited to Glass; rather, this device heralds many coming attempts to better deliver information to driver through in-vehicle HUDs and HMDs and with growing context to the roadway environment (Gabbard, Fitch, & Kim, 2014). What is more, these technologies can be upgraded as new applications are found. For example, Tesla Motors vehicles now boast integration that allows dash controls to be viewed through Glass. Over-the-air upgrades to Glass, as with many onboard computer systems already deployed in the vehicle fleet, can be achieved with the same ease as disseminating a smartphone app. As ease of access to novel tasks for drivers continues to grow, we see Glass as an intermediary step toward delivering content with reduced disruption of some aspects of driving. We believe it can and should become a platform for enhancing driver safety. Finally, we suspect Glass, or devices like it, is likely to find a lasting place in the driving population's lives. We therefore propose further proactive assessments of such emerging technologies to understand their impact upon driving performance. Presumably, the hard decisions as to how society is to regulate them can thus be founded upon objective inquiry.

ACKNOWLEDGMENTS

This work was performed in cooperation with the Air Force's 771st Human Performance Wing. Data reported in the paper are archived at the University of Central Florida's MIT^2 Laboratory. For further information, please contact the corresponding author. We thank Szuhui Wu for troubleshooting as well as assistance with data consolidation and assurance. We thank James Szalma and Greg Funke for insight on analysis. We thank the entire Sawyer Team at the MIT^2 Laboratory for assistance in execution and collection.

KEY POINTS

- Google Glass–delivered messaging moderates, but does not eliminate, distractive cognitive demands during driving.
- Specifically, although Google Glass–using drivers demonstrated better recovery from an unexpected event, the device's use did not lead to improved response to the event itself.
- Benefits may be offset by a passive cost to drivers in merely wearing the device.
- Technology can do much more than introduce distraction. Google Glass contains sensors that have potential to estimate driver attention and fatigue to provide valuable corrective feedback.

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Ben D. Sawyer is a PhD candidate in applied experimental psychology and human factors at the University of Central Florida, where in 2014 he received a master of science in industrial engineering. He works through Oak Ridge Institute for Science and Education for the Air Force Research Laboratory. For more information, visit bendsawyer.com.

Victor S. Finomore is a research psychologist at the Air Force Research Laboratory. He received his PhD in experimental psychology from University of Cincinnati in 2008.

Andres A. Calvo works through Bell Aerospace as an engineer for the Air Force Research Laboratory. In 2012, he received two bachelors of science, one in computer science and one in computer engineering, both from University of Dayton.

P. A. Hancock is a Provost Distinguished Research Professor, Pegasus Professor, and University Trustee Chair at the University of Central Florida's Department of Psychology and the Institute for Simulation and Training. He received a PhD in human performance from University of Illinois in 1983 and a DSc in human–machine systems from Loughborough University in 2001.

Date received: May 9, 2014
Date accepted: September 12, 2014

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