Accident Analysis and Prevention 86 (2016) 68–75

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

In the eye of the beholder: A simulator study of the impact of Google Glass on driving performance

Kristie L. Young*, Amanda N. Stephens, Karen L. Stephan, Geoffrey W. Stuart

Monash University Accident Research Centre, 21 Alliance Lane, Clayton, Victoria 3800, Australia

ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
14 September 2015
Accepted 13 October 2015

Keywords:
Driver distraction
Google Glass
Head mounted display
Lane Change Test

ABSTRACT

This study examined whether, and to what extent, driving is affected by reading text on Google Glass. Reading text requires a high level of visual resources and can interfere with safe driving. However, it is currently unclear if the impact of reading text on a head-mounted display, such as Google Glass (Glass), will differ from that found with more traditional head-down electronic devices, such as a dash-mounted smartphone. A total of 20 drivers (22–48 years) completed the Lane Change Test while driving undistracted and while reading text on Glass and on a smartphone. Measures of lateral vehicle control and event detection were examined along with subjective workload and secondary task performance. Results revealed that drivers' lane keeping ability was significantly impaired by reading text on both Glass and the smartphone. When using Glass, drivers also failed to detect a greater number of lane change signs compared to when using the phone or driving undistracted. In terms of subjective workload, drivers rated reading on Glass as subjectively easier than on the smartphone, which may possibly encourage greater use of this device while driving. Overall, the results suggest that, despite Glass allowing drivers to better maintain their visual attention on the forward scene, drivers are still not able to effectively divide their cognitive attention across the Glass display and the road environment, resulting in impaired driving performance.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Wearable head-mounted displays (HMD) have been in use for decades in military and aviation domains to deliver primary flight or mission information (Rash, 1999). A HMD is a display that is incorporated into a helmet or other wearable head unit and used to project images onto the visual field of the user (Stuart et al., 2001). This configuration theoretically allows users to view information on the display while simultaneously being able to scan the environment. With the introduction of Google Glass (hereafter referred to as Glass), HMDs are now being marketed to the general population. Google Glass includes a small, monocular (single) transparent display mounted on a frame worn like a standard pair of glasses. While Glass has the ability to deliver many of the features of a smartphone in a hands-free, wearable unit, its use in various contexts, such as driving, has raised concerns about the potential for distraction (He, 2013; Klopott and Selway, 2014).

A wealth of research exists on the usability of HMDs and how they impact users' visual behaviour and cognitive load. The information provided on a HMD is projected in the users' field of view, allowing them to quickly shift between monitoring the outside world and viewing the displayed information (Prinzel and Risser, 2004). An advantage of HMDs over traditional displays is that they make information easily accessible, reducing the amount of time users spend looking down to scan information or instruments (Prinzel and Risser, 2004) and reducing operators' workload (Fadden et al., 2000).

Having an image projected in the line of sight can, however, mean that the ability of the user to look away from, or ignore the information presented on the display is limited. This can lead to a range of undesirable visual/perceptual and cognitive effects (Rash et al., 2009). For instance, overlaying information onto the user's view of the world can obscure objects in the environment, leading to a failure to detect hazards entirely, or in time to react to them effectively (Stuart et al., 2001; He, 2013). The information provided on HMDs may also disrupt users' visual scanning behaviour, with research showing that the size and range of users' eye and head movements can be restricted by the use of head-up symbology (Patterson et al., 2006; Stuart et al., 2001). HMDs can also cause problems with visual accommodation, or the focusing of the eyes. HMDs still required small shifts in eye movements (Stuart et al., 2001) and, in particular, repeated shifts in depth of gaze to focus and

* Corresponding author.
E-mail address: kristie.young@monash.edu (K.L. Young).

http://dx.doi.org/10.1016/j.aap.2015.10.010
0001-4575/© 2015 Elsevier Ltd. All rights reserved.

re-focus on near (display) and far (road environment) objects, can fatigue the muscles involved in accommodation (Sullivan, 2008). Edgar et al. (1994) also found that some users can focus inappropriately on HMDs, leading to misperceptions in the size and distance of objects in the real world and reduced target detection rates due to a loss of contrast sensitivity.

A potential drawback of HMDs from an attentional point of view is that the information displayed can capture user attention and they may consequently miss elements of the outside scene; a phenomenon termed *attention capture* (Rash et al., 2009; Ververs and Wickens, 1998). Even if users are capable of 'seeing' both the information on the display and the outside world, humans are not always capable of attending to both sets of information at the same time. Thus, if the user's attention is focussed on the HMD imagery, they may miss an event occurring in the outside world, possibly even if their gaze is fixated on it. This failure to detect an unexpected object or event is termed *inattentional blindness* (Mack and Rock, 1998). Research has found instances where the use of HMDs can cause inattentional blindness, such as delays in aircraft operators detecting and reacting to unexpected events (e.g., Fadden et al., 1998).

Of particular importance, is that the perceptual and attention issues observed with the use of HMDs have been found even when the information presented is task-relevant (e.g., flight coordinates for pilots) and the users are highly trained and highly experienced (e.g., Wickens and Long, 1995). It is unclear if, and to what extent, the presentation of non-relevant information, which is what can occur with Glass, could exacerbate the visual and cognitive issues observed with HMDs.

Reading text will be a key component of using Glass. Reading text on electronic devices is a task that requires a high level of resources, many of which are shared with driving (i.e., visual and manual). Indeed, research has found that text messaging on a mobile phone negatively impacts a range of driving behaviours, including longitudinal and lateral control, visual scanning and reaction time to hazards (Drews et al., 2009; Hosking et al., 2009; Owens et al., 2011; Young et al., 2014). It is currently unclear if the impact of reading text on a head-mounted display such as Glass will differ from that found with more traditional head-down displays such as a dash-mounted smartphone given that the information displayed is closer to the driver's line of sight. Compared to a phone, wearable technology such as Glass may increase visual attention to the forward roadway and facilitate the detection of hazards and signs. However, having the display in the driver's field of view may not be enough to facilitate attention switching and negate the impact of attention capture.

A small number of research studies have examined the impact of Glass on driving performance (Beckers et al., 2014; He et al., 2015; Sawyer et al., 2014; Tippey et al., 2014). Sawyer et al. compared voice-activated text messaging on Glass and a smartphone-based messaging interface. They found that, while the Glass moderated some aspects of driving detriment (e.g., better lane keeping when replying to a text and a faster return to normal speed), for many driving measures, texting on either device impaired performance compared to when driving and not texting. He et al. (2015) also found that reading text on Glass and a smartphone both increased lane position variation from baseline; however, drivers showed less lane variation when using the Glass, suggesting that the head-up display design may modulate the distracting effects of text reading to some extent. When then examining voice-activated destination entry on Glass and a smartphone, Beckers et al. (2014) found similar performance for the Glass and the smartphone; although, when using Glass, drivers completed destination entry faster, but missed a higher number of detection targets.

A notable aspect of previously published Glass driving research is that users have almost exclusively interacted with the device using voice activation (e.g., Beckers et al., 2014; Sawyer et al., 2014; Tippey et al., 2014). However, manual interaction with the device via the touchpad is also possible and, based on our initial pilot testing, may even be preferred over voice-activation by a large proportion of users. It is therefore important to examine how manual interaction with Glass impacts driving performance.

This study was designed to examine the performance and safety implications of driving while using Google Glass and, in particular, whether the head-up design of this device offers any advantages over a more traditional head-down display. Drivers were required to read text aloud on Glass and also, during a separate drive, on a dash-mounted smartphone while driving the Lane Change Test (LCT; Mattes and Hallén, 2009). This work extends the work of Sawyer et al. (2014) by using manual touch gestures to control Glass and using longer, more ecologically valid, text messages, as opposed to artificial tasks such as mathematical tasks. The current study also examined if familiarity with Glass moderates the impact of the device on driving performance. Previous research has found that users quickly become familiar with Glass, with performance plateauing after only 5 min (MacArthur et al., 2014). Approximately half of our sample had 1.5 h experience with Glass prior to completing the current study.

In relation to lateral control, we predicted that, compared to driving undistracted, driving while accessing and reading text on both Glass and the smartphone would be associated with more variable lateral control. This is based on evidence that activities requiring high levels of visual-manual input, such as accessing and reading text, have a particularly detrimental impact on lateral control (e.g., Engstrom et al., 2005; Young et al., 2011). It was also expected that drivers would correctly respond to fewer lane change signs when multitasking, but that they would make a greater number of correct lane changes when using Glass compared to when using the phone. This hypothesis is based on evidence that the use of head-up displays is associated with increased speed of detecting expected events, such as the lane change signs (Fadden et al., 1998). Finally, based on previous Glass findings (e.g., Sawyer et al., 2014), we anticipated that, in comparison to the smartphone, drivers would rate reading text on Glass as less demanding in terms of workload.

2. Method

2.1. Participants

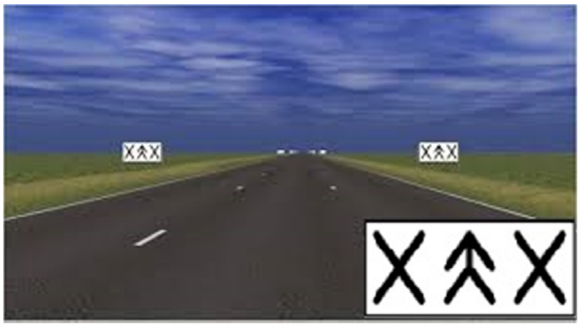
Twenty licensed drivers (16 male; 4 female) aged 22–47 years ($M = 32.2$, $SD = 6.3$) participated in the study. Table 1 provides demographic details of the sample. All participants were required to have a valid Australian (or equivalent) driver licence and have normal or corrected-to-normal visual acuity. All participants reported regularly text messaging and a large proportion reported reading text messages while driving despite this being illegal in Australia.

To examine if familiarity with Glass moderates the impact of the device on driving performance, a portion of the sample had prior Glass experience. Eight of the twenty simulator participants had taken part in a Glass usability study a week prior and, thus,

Table 1
Simulator study participant demographics.

Mean age (years)	32.2 (6.3)
Mean driving experience (years)	12.3 (6.4)
Mean hours driving per week	7.3 (5.8)
Mean hours using mobile phone each week	3.2 (3.6)
% who *read* texts while driving	75.0%
% who *send* texts while driving	40.0%

Standard deviation in parentheses.



(A)

(B)

Fig. 1. Panel (A) shows the LCT driving scene with an enlarged lane change sign as an insert bottom right. Panel (B) shows the driving simulator.

had gained approximately 1.5 h experience with the device. The remaining participants had no previous experience using Glass. Participant age, driving experience, kilometres travelled each week and phone use did not vary significantly across participants who had prior Glass experience and those who did not (all $p > .05$).

Participants were recruited through advertisements at Monash University. Approval for the study was granted by the Monash University Human Research Ethics Committee. Participants received $30 (AUD) for their time and expenses.

2.2. Apparatus and stimuli

2.2.1. Driving simulation

Driving performance was measured using the Lane Change Test (LCT; ISO 26022:2010). The LCT is a simple driving simulation designed to measure the level of driving performance degradation induced by performing a concurrent secondary task (Mattes and Hallén, 2009). It comprises a 3000 m straight, three-lane road with no other traffic present. Drivers are instructed which lane to drive in by signs that appear on each side of the road every 150 m, on average (range: 140–188 m). There are 18 pairs of signs presented in total. The six possible lane change configurations that can be made by drivers (e.g., from the middle to left lane) are counterbalanced across trials to limit learning effects. Speed is limited to 60 km/h, which participants are asked to maintain throughout the drive. The duration of each LCT drive is three minutes. The LCT driving scene is displayed in Fig. 1a.

The LCT was run on a driving simulator that comprises three 46″ LED LCD screens (see Fig. 1b). The visual scene was presented on the centre screen only. Control of the simulation was achieved through a Logitech G27 force feedback steering wheel with accelerator and brake foot pedals. The simulator was programmed so that drivers were able to maintain the required speed of 60 km/h by pressing the accelerator pedal to maximum.

The LCT has been widely used in research studies and has been found to be a valid and sensitive measure of driver distraction (Bruyas et al., 2008; Engström and Markkula, 2007; Harbluk et al., 2007, 2009; Young et al., 2011).

2.2.2. Secondary (reading) task

Participants used Google Glass (software version XE 22) and a Motorola Moto G to read pre-loaded text. Four text messages were loaded on each device. Participants read one text message on each device while not driving (static) and one message on each device while completing the LCT. The order of the messages and reading conditions was counterbalanced across participants to reduce order effects. Each message was exactly 300 words long and was taken from the Victorian '*Road to Solo Driving Part 4 rules and Responsibilities*' handbook to ensure that the length, content and style of writing were comparable across each message. The length of the messages also ensured that drivers would be reading for the entire three minute duration of the LCT. Participants were instructed to read the text aloud and at their own pace. During the drives, participants read as much of the text as they could during the three minute drive. In the few cases that all text was completed before the end of the drive, participants were instructed to scroll back and re-read the message. This ensured that participants were interacting with the devices continuously for the entire drive. For each message, the number of words read and errors made were recorded and compared across devices and the static and driving conditions.

The Glass was worn high on the bridge of participant's nose and the display arm adjusted for each participant so that the imagery was clearly positioned just above their normal line of sight. Participants were instructed to access the pre-loaded messages using manual gestures on the touchpad located on the right arm of Glass. This involved 'tap' gestures to unlock the device and open the relevant message card in the timeline. On task completion, participants exited the message using a series of downward strokes on the touchpad.

The smartphone was located to the left of the steering wheel at approximately the same height as the top of a car dashboard at a vertical visual angle of 9 degrees. Messages were accessed by tapping and swiping the screen to unlock the phone, tapping the "Hangouts" icon and using finger swipes to scroll through the relevant text. Tapping the 'back' button was used to exit messages.

While the content of each text was the same across the Glass and the phone, there were differences in the implementation of the text across the devices. On the Glass, each message was spilt across approximately 8 screens (38 words per screen on average), requiring a forward or backward horizontal stroke on the touchpad to scroll back and forth through the text. The text on the phone was presented across approximately 4.5 screens (67 words per screen on average) and required a vertical stroke on the touchscreen to scroll through the text. While these differences meant that the text layout and number of manual scrolling gestures required was different across devices, it was a true representation of the text layout of each device type.

2.2.3. Subjective workload questionnaire

The NASA – Raw Task Load Index (NASA-RTLX) (Byers et al., 1989) was used to measure subjective workload. This multidimensional rating scale provides an indication of the perceived workload associated with performing the LCT under single-task (driving only) relative to the dual-task (driving plus reading messages) conditions. A numerical score (from 0 to 20) is provided for six workload dimensions (mental, physical, and time demand, performance, effort, and frustration level) as well as an overall workload score, calculated by averaging scores across the six dimensions.

2.3. Procedure

After a brief explanation of the study, participants signed the consent form and then completed a demographic questionnaire. Participants were then shown Glass and the mobile phone, instructed how to access the text messages on each and then had a short (2 min) practice with each device. Next, participants completed a static (no driving) read through of one text message separately on each device. A verbal explanation of the LCT was then provided and participants completed 1–2 practice drives until they could change lanes according to the ISO instructions. Once participants were comfortable with the LCT, they completed four trial runs: baseline (driving only), Glass (no reading), reading with Glass and reading with the phone. For the reading text runs, participants opened the text message at the start of the drive and read each one aloud at their own pace. Participants read the text in its entirety or until they reached the end of the drive. A Dictaphone was used to record participants reading the text aloud and the transcripts were later used to determine the number and type of errors made on the texting tasks across the static (texting only) and dual-task (texting and driving) conditions. On completion of each LCT drive, participants completed the NASA-RTLX workload questionnaire. In the reading text conditions, participants were instructed to give priority to the driving task but to not ignore the reading text task.

2.4. Data analysis

Prior to all analyses, the data were checked for violations of statistical assumptions, missing data points and outliers, which were excluded from the analysis. A two-tailed α-level of .05 was used to determine statistical significance.

The LCT measures examined can be broadly categorised into lateral vehicle control measures and event detection measures.

2.4.1. Lateral control measures

Mean deviation (Mdev): Mean lateral deviation scores were compared using the basic LCT model that is automatically calculated by the LCT analysis software. The basic model compares each participants' actual driving course in each experimental condition to a normative driving path trajectory that represents an ideal lane change path. Mdev scores were calculated for each run over the entire length of the drive.

Lane excursions: The number of lane excursions made during each run was calculated by visually examining the lateral position trace schematics produced by the LCT analysis software. A lane excursion was defined as any instance where the participants' lateral position trace moved outside the bounds of the correct lane of travel (as defined by the lane markings) before moving back into the correct lane. The number of lane excursions made during each LCT run was manually counted. Sections of the drive where participants were making a lane change were not included in the excursion count.

2.4.2. Event detection measures

Lane change initiation (LCI): LCI is a measure of response time to the lane change signs and represents the difference (in metres) between the appearance of the lane change information and the point at which the driver initiated a lane change (Harbluk et al., 2007). LCI was analysed in the region of 60 m before each sign to 40 m past the sign. Missed or incorrect lane changes are excluded from this metric.

Number of correct lane changes: The number of lane changes correctly executed in each run was calculated as a measure of participant's ability to correctly respond to lane change instructions. In addition, the type of lane change errors made was qualitatively examined: missed lane changes (driver continued in current lane) and incorrect lane changes (driver executed a lane change, but into wrong lane).

The Mdev, lane change initiation and subjective workload measures were analysed using repeated-measures ANOVA with four conditions: baseline, Glass (no reading), texting on Glass and reading on phone. Generalised Estimating Equations (GEE) models were fitted to examine count data: number of lane excursions, correct lane changes, words read and reading errors. All GEE models were specified with a Poisson error function and a log link function which is appropriate for count data, which are non-negative integers that were not normally distributed. The inter-correlation between the repeated measures was specified as unstructured, apart for the model for number of reading errors, which was specified as exchangeable. The model for reading errors used the natural log of total words read as an offset variable. All analyses were carried out using IBM SPSS Statistics 22. The LCT data for one participant was excluded from analysis due to failure to perform the driving task to a required standard during a number of the test trials. Thus, all analyses involved 19 participants.

3. Results

3.1. Google glass familiarity analysis

Participants with and without previous experience with Glass were compared (for the Glass reading condition only) on all LCT measures to examine if practice has an impact on task sharing efficiency and driving performance. *t*-Tests were used for the Mdev and LCI data and Chi-squared tests used for the lane excursion and correct lane change count data. No significant differences were found across the two groups on any of the LCT metrics (all $p > .05$), suggesting that a limited amount of prior experience with Glass (~1.5 h) does not improve the ability to use Glass while driving. Given the lack of significant differences, all subsequent analyses were conducted with the data for the two familiarity groups combined.

3.2. Lateral control measures

3.2.1. Mean deviation (Mdev)

The Mdev scores for the entire drive are presented in Fig. 2. Mdev differed significantly across the task conditions (F (3,54) = 14.92, $p < .001$). Pairwise comparisons revealed that Mdev was lower in the baseline and Glass (no reading) conditions than in the two reading conditions (all $p < .05$). Mdev scores did not differ significantly across the two baseline conditions, or across the Glass and phone reading conditions (all $p > .05$).

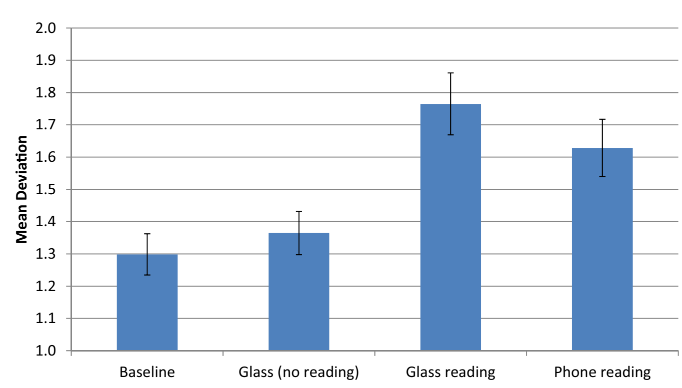


Fig. 2. Mean deviation (Mdev) in lane change path for each condition (standard error bars).

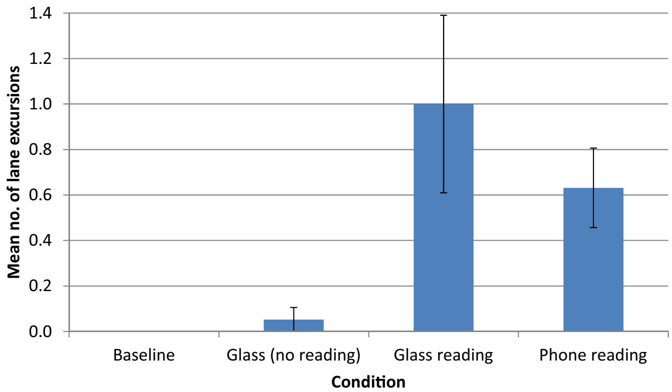


Fig. 3. Mean number of lane excursions made in each condition (standard error bars).

3.2.2. Lane excursions

The mean number of lane excursions made in each driving condition is displayed in Fig. 3. Due to issues with Hessian matrix singularity, the baseline condition (where no lane excursions were made) was dropped from the GEE model and the condition where participants wore Glass but did not read text, served as the baseline. Significant differences in the number of lane excursions made were found across conditions (Wald χ^2 (2) = 20.07, $p < .001$). The rate of lane excursions when reading text on Glass was 19 times the rate for the Glass (no reading) condition (incidence rate ratio (IRR) = 19.00, $p < .001$), while the lane excursion incidence rate when reading on the phone was 12 times that for the Glass (no reading) condition (IRR = 12.00, $p < .005$). The number of lane excursions made did not differ significantly across the Glass or mobile phone reading conditions.

3.3. Event detection and response measures

3.3.1. Number of correct lane changes

The mean number of correct lane changes made in each experimental condition was high, ranging from 18 (out of a possible 18) in the baseline condition to 16.9 in the Glass reading condition (Table 2). There was a significant difference in the percentage of correct lane changes made across the driving conditions (Wald χ^2 (3) = 18.69, $p < .001$), whereby drivers made significantly fewer correct lane changes when reading text on Glass compared to when reading text on the phone (IRR = 1.05, $p = .033$) and both the Glass (no reading) (IRR = 1.06, $p = .010$) and baseline (IRR = 1.07, $p = .003$) conditions.

Descriptive analysis was performed to examine the type of lane change errors made (missed or incorrect changes). The percentage of lane changes made in each condition that are attributable to each error type is contained in the two right columns of Table 2. This analysis revealed that of the small percentage of lane change errors made, most consisted of missed lane changes, suggesting a failure of drivers to detect the signs rather than misreading them.

Table 2
Mean (SD) number of correct lane changes (LC) and percentage of missed and incorrect changes across conditions.

Condition	No. correct LC	% correct LC	% missed LC	% incorrect LC
Baseline	18 (0)	100	0	0
Glass (no texting)	17.9 (0.3)	99.4	0.3	0.3
Glass texting	16.9 (1.6)	93.9	5.5	0.6
Phone texting	17.7 (0.6)	98.5	1.5	0

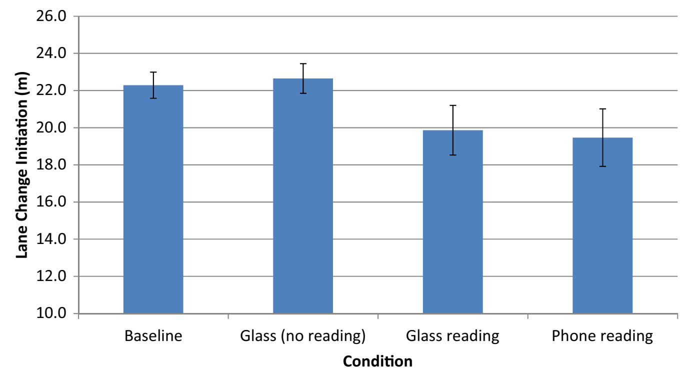


Fig. 4. Mean lane change initiation for each condition (standard error bars).

3.3.2. Lane change initiation (LCI)

The distance at which participants initiated a lane change from the appearance of the information on each sign was recorded and the means displayed in Fig. 4. Smaller LCI values means that drivers initiated their lane changes faster after sign information appeared and, thus, indicates faster response times. No significant effect of driving condition was found (F (3,54) = 1.95, $p = .133$), indicating that reading text on Glass or on the phone did not impact the time drivers took to respond to the lane change instructions.

3.4. Secondary task (reading) performance

Reading performance was recorded so that trade-offs in performance could be examined. When performing two tasks at once, people may assign priority to one task over another, essentially sacrificing performance on the lower priority task. By comparing performance on the driving and secondary tasks, information can be obtained on which task drivers in this study assigned priority to. For both Glass and the phone, performance on the reading task while driving was compared to reading performance on these devices while not driving. Two measures of reading performance were examined: the number of words read aloud in three minutes (the duration of each LCT run) and the number of errors made when reading the text (Table 3). Errors consisted of missed words or sentences and incorrect or mispronounced words.

The number of words completed in three minutes differed significantly across conditions (Wald χ^2 (3) = 29.82, $p < .001$). On both devices, participants read significantly less words in three minutes while driving compared to when not driving (both $p < .01$). Also, while the number of words read did not differ significantly across the Glass and the phone when not driving, participants read an average of 17% more words (51 words) on Glass than the phone while driving (IRR = 1.17, $p = .004$).

The number of errors made when reading text also differed significantly across the conditions (Wald χ^2 (3) = 75.58, $p < .001$). Drivers made 67% more reading errors on the Glass when driving compared to when not driving (IRR = 1.67, $p = .003$). Drivers also made 59% more errors on the smartphone compared to when not driving (IRR = 0.41, $p < .001$). Further, when driving, the number of reading errors made was significantly higher on the phone compared to the Glass (IRR = 0.68, $p = .044$). Taken together, these

Table 3
Mean (SD) number of text message words read and errors made across conditions.

Condition	No. of words	No. of errors
Glass baseline	297.9 (7.1)	4.1 (3.0)
Phone baseline	300 (0)	2.8 (2.5)
Glass driving	242.1 (70.1)	5.5 (3.9)
Phone driving	206.4 (67.1)	6.8 (4.9)

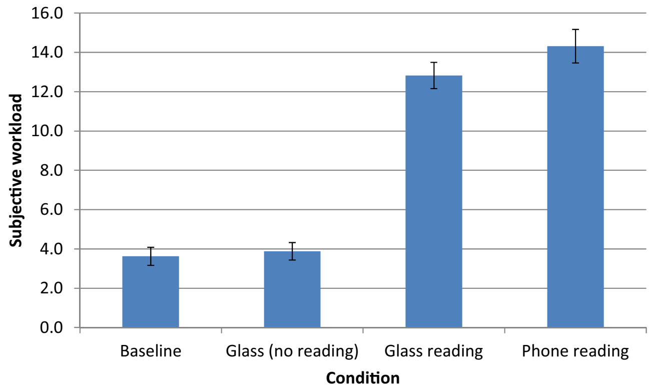


Fig. 5. Overall subjective workload for each condition (standard error bars).

findings suggest that participants were more error prone when using both devices while driving, but were more error prone when reading text on the phone than on the Glass.

3.5. Subjective workload

As displayed in Fig. 5, significant differences in overall subjective workload scores (NASA-RTLX) were found across conditions ($F(4,29) = 34.63$, $p < 0.001$). Overall workload was significantly higher in each of the reading conditions than in the baseline and Glass (no reading) conditions (all $p < .001$). Subjective workload was also significantly higher in the phone reading condition compared to the Glass reading condition ($p > 0.035$).

4. Discussion

With the popularity of wearable technology increasing, it is important to establish the impact of these devices on the performance of complex tasks, such as driving; including whether they can provide any safety benefits over more traditional, head-down forms of technology. Google Glass is one example of wearable technology now becoming available to the general and driving public. This study examined whether, and to what extent, driving is affected by reading text on Google Glass and compared this to reading text on a dash-mounted smartphone. Overall, the results indicate that Glass impacts a range of critical driving behaviours and offers few benefits over the head-down display of a smartphone.

As expected, drivers' lane keeping performance was significantly impaired by reading text on Glass and the smartphone. This was evidenced by an increase in both Mdev scores and the number of lane excursions made. These results are in line with the previous Glass research of Sawyer et al. (2014) and He et al. (2015), as well as more general distraction research that has shown that increased visual-manual load increases lane keeping variation (Engstrom et al., 2005; Wilschut et al., 2008; Young et al., 2011). The manual load of scrolling through the text may have partly contributed to the degraded lane keeping performance (structural interference); however, drivers were required to make almost double the number of scrolling gestures on the Glass compared to the phone to move through each message, yet there were no significant differences found in lane keeping performance across the two devices. This suggests that some other mechanism of interference is also involved. Based on previous research with HMDs (e.g., Rash et al., 2009; Ververs and Wickens, 1998), it is believed that cognitive interference is also likely to play a role in the effects observed. Although Glass facilitates viewing of the road while looking at the display, drivers' ability to attend to both sources of information at once may have been limited. As such, drivers were not able to prevent the build-up of heading errors and maintain their baseline lane keeping performance. Support for the cognitive interference hypothesis comes from the findings of Sawyer et al. (2014), who also found that lane keeping performance was impaired by the use of Glass even though participants in their study used voice-activation, not manual gestures, to interact with Glass. Further research should explicitly examine the relative contribution of manual versus cognitive interference to the effects observed by directly comparing manual and voice-activated interaction with the Glass device.

Findings from the event detection measures suggest that using Glass while driving can also result in a failure of drivers to detect information presented on signs, even when this information is expected, but does not impact their response times (lane change initiation) if a sign is detected. Contrary to expectations, drivers missed a greater number of signs when using Glass compared to the phone, but the time taken to initiate a correct lane change did not differ significantly across either device or the dual and single task conditions. It is possible that the Glass device itself may have created a visual obstruction, either through the touchpad or the monocle located on the right arm, which may have obscured scanning of the signs. Given that the lane change signs were presented on both sides of the road, it is unlikely that these features would have completely obscured the signs; however, it may have impacted drivers' visual scanning patterns in a way that led them to miss a greater number of signs. The finding that drivers missed a greater number of signs when using Glass also suggests the influence of cognitive interference, in addition to any possible visual scanning failures. Despite the head-up design of the Glass facilitating greater viewing of the roadway than the phone, drivers may not have attended to the signs because their attention was focused on the text message; that is, drivers may have 'seen' a sign, but failed to attend to it properly, i.e., inattentional blindness (Mack and Rock, 1998). Lending support to the cognitive interference assumption, Beckers et al. (2014) also found that, compared to a voice-activated smartphone, drivers missed a higher number of detection targets when performing a voice-activated destination entry task on Glass. These authors attributed this result to the novel design of Glass creating higher levels of cognitive absorption. In the absence of eye-tracking, however, it is difficult to work out the relative contribution of visual versus cognitive failures to drivers missing a greater number of signs when using Glass. Further work should include eye-tracking to examine if drivers' visual scanning patterns differ when using a HMD versus a head-down display.

It is important to point out that the number of incorrect lane changes made was low across all conditions and this is probably due to the expected and highly predictable nature of the LCT. The nature of the LCT may also explain the lack of significant differences in lane change initiation results. This result was somewhat unexpected, as previous distraction research has found that drivers' ability to respond to events in a timely manner is degraded when performing secondary tasks (Greenberg et al., 2003; Strayer and Drews, 2004; Strayer et al., 2003). However, it is possible that drivers quickly learned to anticipate the lane change signs and regulate their behaviour with the text message task so that their reaction time to the lane change signs (when detected) was not impaired. Previous research with head-up displays has found that these display types can support and even improve the detection speed of *expected* events compared with head-down displays (Fadden et al., 1998; Rash et al., 2009). An important avenue for further research with Glass is to therefore examine the ability of drivers to detect and respond to events that are *unexpected* in nature while using the device.

The secondary task performance results suggest that participants were trading off performance on the reading task in order to maintain a desired level of performance on the driving task, with fewer words read in the dual-task conditions. Participants also read

17% more words and made fewer errors on Glass compared to the phone while driving. One explanation for the higher number of words read on Glass is the proximity of the Glass display to the participants' normal line of sight. This means drivers can shift their gaze from the road to the Glass display faster than they can to the phone and, thus, read a higher number of words over the same period of time. It is also possible that the layout of the text on Glass made it easier for participants to read the text and find their place again after they had glanced away from the display to the road, hence the reduced number of errors made. The text on Glass was more segmented than on the phone, with a smaller amount of text presented on each screen, and this may facilitate reading and place finding after glancing away from the display.

Although there was evidence that drivers attempted to regulate their interaction with the reading task, decrements in various driving performance measures were still observed, suggesting that participants were not able to share attention effectively across the driving and reading tasks without performance degrading on both. This was true for both Glass and the smartphone. It is also interesting to note that the drivers' self-regulation strategy in this study was likely facilitated by the expected and predictable nature of the lane changes, whereby drivers could easily time their interaction with the devices so that they were performed between the lane change signs. In reality, events occurring in the road environment are far less predictable, and the utility of such an interaction strategy may be less successful.

In line with expectations, drivers perceived that reading text on Glass was subjectively easier than on the phone. This finding is consistent with the work of Sawyer et al. (2014) who found that using a smartphone to text message induced a significantly higher level of physical demand on drivers than Glass. A number of reasons may explain why participants found the phone more demanding to use than Glass. First, the greater demand may derive from the fact that participants were required to take their eyes off the forward roadway to view the phone display, whereas drivers could shift their gaze more easily and quickly between the road and the Glass display. Second, the different layout of the text on the phone, whereby large amounts of text is presented on each screen, may have also played a role.

The observation that participants viewed Glass as less demanding than a dash-mounted phone to use while driving is of interest as the driving data revealed few benefits of Glass over the phone in terms of mitigating the impairments associated with reading text and Glass had an even more detrimental impact than the phone on failures to detect the lane change signs. This indicates that drivers may not be well calibrated as to how the use of a device affects their driving behaviour. Indeed, Horrey et al. (2008) found that distracted drivers in their study did not have good awareness of the magnitude of the effect of distraction on their driving performance. The greater perceived ease of use of Glass may also encourage drivers to use such a device more often when driving than they would a phone, which is of concern.

Participants in the current study were trained in use of the Glass and a subset of the sample had approximately 1.5 h prior experience under single-task conditions. Participants with prior Glass experience in this study showed no immunity to the impact of the text reading task on driving; suggesting that much more than 1.5 h of static experience with a device would be required if it is indeed even possible to offset its deleterious effects on driving. Research has found that practice with a task under dual-task conditions can diminish and, in some cases, eliminate the interference of a secondary task on driving performance (Shinar et al., 2005). It is possible that as drivers become more experienced with the use of Glass that its impact on driving may reduce and this is a topic worthy of further investigation. Future research with Glass should also examine the impact on driving of a greater range of the features and applications available on Glass and also under difference driving conditions, particularly in relation to unexpected roadway events.

4.1. Conclusions

The results of the project concur with previous head-mounted display research that, despite Glass device allowing users to maintain their visual attention on the forward scene, humans are fundamentally limited in their ability to divide their cognitive attention across two sources of information (the Glass display and the outside environment). This was evidenced by a range of performance decrements observed when reading text on Glass, including impaired lane keeping ability and a higher number of failures to detect expected lane change signs. Overall, our findings indicate that the head-up design of Glass does not render reading text while driving any safer than on a dash-mounted head-down display. Moreover, given that drivers perceived the Glass as less demanding than a traditional head-down display, it may even encourage technology use while driving.

Acknowledgements

We thank Adjunct Professor Michael Lenné for his assistance in the planning phases of this project and the participants who took part.

References

Beckers, N., Schreiner, S., Bertrand, P., Reimer, B., Mehler, B., Munger, D., Dobres, J., 2014. Comparing the demands of destination entry using Google Glass and the Samsung Galaxy S4. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 58, 2156–2160.

Bruyas, M.P., Brusque, C., Tattegrain, H., Auriault, A., Aillerie, I., Duraz, M., 2008. Consistency and sensitivity of lane change test according to driving simulator characteristics. IET Intell. Transp. Syst. 2, 306–314.

Byers, J.C., Bittner, A.C., Hill, S.G., 1989. Traditional and raw task load index (TLX) correlations: are paired comparisons necessary? Paper presented at the International Industrial Ergonomics and Safety Conference, Cincinnati, OH.

Capó-Aponte, J.E., Temme, L.A., Task, H.L., Pinkus, A.R., Kalich, M.E., Pantle, A.J., Rash, C.E., 2009. Visual perception and cognitive performance. In: Rash, C.E., Russo, M.B., Letowski, T.R., Schmeisser, E.T. (Eds.), Helmet-Mounted Displays: Sensation, Perception and Cognition Issues. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL.

Drews, F.A., Yazdani, H., Godfrey, C.N., Cooper, J.M., Strayer, D.L., 2009. Text messaging during simulated driving. Hum. Factors 51 (5), 762–770.

Edgar, G.K., Pope, J.C.D., Craig, I.R., 1994. Visual accommodation problems with head-up and helmet-mounted displays? Displays 15, 68–75.

Engstrom, J., Johansson, E., Ostlund, J., 2005. Effects of visual and cognitive load in real and simulated motorway driving. Transp. Res. F: Traffic Psychol. Behav. 8, 97–120.

Engström, J., Markkula, G., 2007. Effects of visual and cognitive distraction on lane change test performance. In: Fourth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Stevenson, WA.

Fadden, S., Ververs, P.M., Wickens, C.D., 1998. Costs and benefits of head-up display use: a meta-analytic approach. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 42, 16–20.

Fadden, S., Wickens, C., Ververs, P., 2000. Costs and Benefits of Head Up Displays: An Attention Perspective and A Meta Analysis. SAE Technical Paper, 2000-01-5542.

Greenberg, J., Tijerina, L., Curry, R., Artz, B., Cathey, L., Grant, P., Kochlar, D., Kozak, K., Blommer, M., 2003. Evaluation of driver distraction using an event detection paradigm. J. Transp. Res. Board (1843).

Harbluk, J.L., Burns, P.C., Lochner, M., Trbovich, P.L., 2007. Using the Lane-Change Test (LCT) to assess distraction: tests of visual-manual and speech-based operation of navigation system interfaces. In: Fourth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Stevenson, WA.

Harbluk, J.L., Mitroi, J.S., Burns, P.C., 2009. Three navigation systems with three tasks: using the Lane Change Test (LCT) to assess distraction demand. In: Fifth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Big Sky, Montana.

He, J., 2013. Head-up display for pilots and drivers. J. Ergon. 3, e120, http://dx.doi.org/10.4172/2165-7556.1000.

He, J., Ellis, J., Choi, W., Wang, P., 2015. Driving while reading using Google glass versus using a smart phone: which is more distracting to driving performance? In: Proceedings of the Eighth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, Snow Bird, UT, pp. 281–287.
Horrey, W.J., Lesch, M.F., Garabet, A., 2008. Assessing the awareness of performance decrements in distracted drivers. Accid. Anal. Prev. 40 (2), 675–682.
Hosking, S., Young, K.L., Regan, M., 2009. The effects of text messaging on young drivers. Hum. Factors 51 (4), 582–592.
ISO 26022:2010. Road Vehicles – Ergonomic Aspects of Transport Information and Control Systems – Simulated Lane Change Test to Assess In-vehicle Secondary Task Demand.
Klopott, F., Selway, W., 2014. Google Glass Faces Bans as States Move to Bar Use. http://www.bloomberg.com/news/articles/2014-02-25/google-glass-faces-driving-bans-as-states-move-to-bar-use.
MacArthur, K.R., Greenstein, S., Sawyer, B., Hancock, P.A., 2014. PSUM: Training in Google Glass and Android. Presented at the Annual Meeting of the American Psychological Association, Washington, DC.
Mack, A., Rock, I., 1998. Inattentional Blindness. MIT Press, Cambridge, MA.
Mattes, S., Hallén, A., 2009. Surrogate distraction measurement techniques: the Lane-Change Test. In: Regan, M.A., Lee, J.D., Young, K.L. (Eds.), Driver Distraction: Theory, Effects and Mitigation. CRC Press, Boca Raton, FL.
Owens, J.M., McLaughlin, S.B., Sudweeks, J., 2011. Driver performance while text messaging using handheld and in-vehicle systems. Accid. Anal. Prev. 43 (3), 939–947.
Patterson, R., Winterbottom, M.D., Pierce, B.J., 2006. Perceptual issues in the use of head-mounted visual displays. Hum. Factors 48 (3), 555–573.
Prinzel, L., Risser, M., 2004. Head-up displays and attention capture. NASA Technical Memorandum, 213000.
Rash, C.E., Russo, M.B., Letowski, T.R., Scheisser, E.T., 2009. Helmet-mounted Displays: Sensation, Perception and Cognition Issues. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL.
Sawyer, B.D., Finomore, V.S., Calvo, A.A., Hancock, P.A., 2014. Google Glass a driver distraction cause or cure? Hum. Factors 56 (7), 1307–1321.
Shinar, D., Tractinsky, N., Compton, R., 2005. Effects of practice, age, and task demands, on interference from a phone task while driving. Accid. Anal. Prev. 37 (2), 315–326.
Strayer, D.L., Drews, F.A., 2004. Profiles in driver distraction: effects of cell phone conversations on younger and older drivers. Hum. Factors 46, 640–649.
Strayer, D.L., Drews, F.A., Johnston, W.A., 2003. Cell phone-induced failures of visual attention during simulated driving. J. Appl. Psychol. 9, 23–32.
Stuart, G.W., McAnally, K.I., Meehan, J.W., 2001. Head-up displays and visual attention: integrating data and theory. In: Harris, D., Muir, H.C. (Eds.), Contemporary Issues in Human Factors and Aviation Safety. Ashgate, Aldershot.
Sullivan, J., 2008. Visual fatigue and the driver. UMTRI-2008-50. The University of Michigan, Transportation Research Institute, Ann Arbor, MI.
Tippey, K.G., Sivaraj, E., Ardoin, W.J., Roady, T., Ferris, T.K., 2014. Texting while driving using Google Glass Investigating the combined effect of heads-up display and hands-free input on driving safety and performance. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 58 (1), 2023–2027.
Ververs, P.M., Wickens, C.D., 1998. Conformal flight path symbology for head-up displays: defining the distribution of visual attention in three-dimensional space. Report No. ARL-98-5/NASA-98-1. Aviation Research Laboratory, Savoy, IL.
Wickens, C.D., Long, J., 1995. Object versus space-based models of visual attention: implication for the design of head-up displays. J. Exp. Psychol.: Appl. 1 (3), 179–193.
Wilschut, E.S., Rinkenauer, G., Brookhuis, K.A., Falkenstein, M., 2008. Effects of visual search task complexity on lane change task performance. In: Proceedings of the European Conference on Human Centred Design for Intelligent Transport Systems, Lyon, France.
Young, K.L., Lenné, M.G., Williamson, A., 2011. Sensitivity of the Lane Change Test as a measure of in-vehicle system demand. Appl. Ergon. 42 (4), 611–618.
Young, K.L., Rudin-Brown, C.M., Patten, C., Ceci, R., Lenné, M.G., 2014. Effects of phone interface type on driving and eye glance behaviour while text-messaging. Saf. Sci. 68, 47–54.