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Smartwatches are more distracting than mobile phones while driving: Results from an experimental study

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ABSTRACT

The use of smartwatches raises a number of questions about their potential for distraction in situations where sustained attention is paramount, like driving a motor vehicle. Our research examines distraction caused by smartwatch use in comparison to mobile phone use while driving. It also studies the difference in distractions caused by inbound text messages versus inbound voice messages, and outbound replies through text messages versus outbound voice replies. A within-subject experiment was conducted in a driving simulator where 31 participants received and answered text messages under four conditions: they received notifications (1) on a mobile phone, (2) on a smartwatch, and (3) on a speaker, and then responded orally to these messages. They also (4) received messages in a "texting" condition where they had to reply through text to the notifications. Eye tracking gaze distribution results show that participants were more distracted in the smartwatch condition than in the mobile phone condition, they were less distracted in the speaker condition than in the phone condition, and they were more distracted in the texting condition than in any of the others. The participants' driving performance remained the same in all conditions except in the texting condition, wherein it became worse. Eye tracking and pupillometry results suggest that participants' mental workload might be lower in the texting condition than in the other three conditions, although this result might be caused by a higher number of glances at the device in that condition. This study contributes to a better understanding of the distraction potential of smartwatches as well as identifying vocal assistants as the least distracting way of communicating while driving a vehicle. Industry leaders could become a key factor in informing the public of the smartwatch's potential for distraction.

1. Introduction

In 2017, 45.8 million Americans were using smart electronic devices that could either be worn as an accessory or simply as part of an item of clothing, with a projected 67 million users by 2022 (Statista, 2019). This emerging trend in the field of technology, called *wearables*, is quickly gaining in popularity. Experts foresee that the global wearable market will grow at a compound annual growth rate (CAGR) of 11.3 % from 2019 to 2025 (PR Newswire, 2019). Wearables include various items, with the most popular being the smartwatch. More than half the users of wearables use a smartwatch at least once a month (Wurmser, 2019). A recent report notes that one out of six Americans owns a smartwatch (Whitwam, 2019). Industry observers even project that the smartwatch will gain ground on other wearables by jumping from 58.2 % of all wearable technology sold in 2018 to 63.3 % in 2022 (Lamkin, 2018).

As smartwatches become more common, they also become a potential source of distraction. In certain contexts, like driving a motor vehicle, smartwatches could even become a threat to safety, much like when drivers send texts with their mobile phones, reducing their attention and ability to react quickly (Caird et al., 2014). While driving a motor vehicle, the act of engaging in any other activity that impairs driving and is not necessary for operating a vehicle, can be considered as distracted driving (FindLaw, 2016). In 2017, 3166 people died on U.S. roads as a result of distracted driving (National Highway Traffic Safety Administration (NHTSA, 2019).

In the United States, traffic laws differ from state to state. Most states do not have laws specifically prohibiting smartwatches, although they do have laws prohibiting distracted driving (FindLaw, 2020). Most states forbid talking on a mobile phone and texting while driving, but the use of a smartwatch is not specifically prohibited (FindLaw, 2016).

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Since distracted driving is such a broad term, the legality of using a smartwatch while driving is open to the suggestive interpretation of the law officer witnessing the act.

As the use of mobile phones while driving is prohibited by law because of the distraction it creates, other similar devices, like the smartwatch, should be investigated in the same context. More specifically, it is worth exploring how the use of a smartwatch differs from other sources of distraction, such as a mobile phone or a voice assistant, on the attentional state and driving behavior.

To address this, a within-subject experiment was conducted on the effect of various types of notifications on a smartwatch and a smartphone in a driving simulator. Notifications were sent to 31 participants assigned to four conditions. In three of the four conditions, participants received notifications on a device (mobile phone, smartwatch, or speaker), and they had to respond to these notifications vocally. In the fourth condition, they received written messages on either the mobile phone or the smartwatch, and they had to answer by texting on their phone.

2. Literature review

2.1. Prior research

People are distracted by a variety of things both inside and outside the vehicle. A study conducted on 16,556 drivers in Northern Virginia reported that 23.4 % were multitasking while driving (Kidd et al., 2016). Some distractions are perceived as harmless, but even seemingly innocuous actions like listening to music while driving caused more miscalculations and inaccuracies than when driving without music (Brodsky and Slor, 2013). Research shows that drivers who interact with passengers look at the road less frequently (Koppel et al., 2011) and that drivers feel a higher mental workload (or cognitive workload) when eating and/or drinking while driving than if they were only driving (Young et al., 2008). Although there is no universally accepted definition of mental workload (Cain, 2007), it can be defined as "the portion of operator information processing capacity or resources that is actually required to meet system demands", (Eggemeier et al., 1991).

Being distracted while driving is dangerous and can be fatal. In 2017, an estimated 9 % of all deaths involving car accidents in the country were caused by distracted driving (National Highway Traffic Safety Administration (NHTSA, 2019). Mobile phone use was the reason behind 14 % of such casualties. Moreover, 19 % of fatal accidents caused by distracted driving involved a mobile phone for people aged between 20 and 29, with that percentage rising to 23 % for people aged between 15 and 19 (National Highway Traffic Safety Administration (NHTSA, 2019).

Most literature on multitasking while driving revolves around the use of mobile phones. Strayer and Drews (2007) affirm that talking on the mobile phone disrupts attention from the driving task and that these drivers are not as aware of the environment around them. A meta-analysis of 33 studies concludes that the reaction time is slower when talking on the phone than when not (Caird et al., 2008). Caird et al. (2014) performed another meta-analysis focused on texting while driving, which finds that drivers who were texting kept glancing frequently and for lengthy periods of time away from the road, took longer to react to potential dangers than when driving without distraction, and were not as aware of external stimuli. Moreover, drivers were involved in more accidents and were not as comfortable staying in the middle of their lane. Young drivers are especially at risk of injuries related to cell phone distraction behind the wheel; a study showed that teenage drivers are likely to sustain more severe injuries when distracted by a cell phone or a passenger than any other source of distraction (Neyens and Boyle, 2008). Passengers are also more likely to sustain severe injuries if the driver is distracted by a cell phone or by passengers (Neyens and Boyle, 2008).

Although mobile phone usage is detrimental to a person's ability to drive safely, this practice still remains rampant. A study examined whether drivers texted while driving in the 30 days before answering the survey and whether they read a text during those same 30 days: 33 % of respondents wrote a text while 48 % of them recalled having read one (Gliklich et al., 2016). A different study on young drivers' self-reported behaviors shows that people will initiate a call on the cell phone if they believe it is important even though they realize it is dangerous (Nelson et al., 2009). Moreover, 45 % of 8505 American high school students admitted to texting while driving at least once in the month before answering a survey (Olsen et al., 2013). Another more recent study found that 90 % out of 469 respondents used their phone for something other than making a phone call at least once in the month prior to answering the survey (Meldrum et al., 2019), meaning that efforts to reduce use of distracting technology while driving has not eradicated the problem.

Smartwatches and smartphones share many similar features, so it is relevant to find out how distracting the former are in a driving environment, especially in comparison to mobile phones. A small number of studies have been conducted on the impact of smartwatch usage on driving. Giang et al. (2014) found, based on a small sample size ($n = 6$), that participants started engaging with a smartwatch faster than with a smartphone. They also took longer to read notifications and took more glances greater than 2 s at the smartwatch than at the mobile phone. Giang et al. (2015) also found, with a larger sample size ($n = 12$), that people glanced, on average, more often at the smartwatch than at the smartphone. The gaze distribution (i.e., the distribution of where one is looking during periods of time) of the drivers was focused for a longer amount of time on the smartwatch than on the mobile phone. Brake response time was longer when drivers received notifications on the smartwatch than on the smartphone, despite the perceived level of risk being similar for both devices.

Samost et al. (2015) studied how people initiated a phone call with a smartphone using a visual-manual method (VM) and an auditory-vocal method (AV), relative to a smartwatch using an auditory-vocal method (AV). Remote detection reaction time miss rate and reaction time were higher for the VM task than for other conditions. Driving behavior was more erratic for the VM task. The AV calling method for the phone and the smartwatch entailed lower cognitive workload than the VM task. Perlman et al. (2019) revisited the question a few years later, concluding that task time and number of glances were higher in the smartwatch condition than in the AV smartphone condition. The VM calling method measures were higher for self-reported workload ratings, mean single glance duration, percentage of long duration off-road glances, total off-road glance time, and percentage of time looking off-road.

He et al. (2014) compared speech-based text entry with handheld text entry on a mobile phone and concluded that, although both affect driving significantly compared to a drive-only condition, handheld text entry was more distracting than speech-based text entry. This study raises questions as to whether the same difference was found using different ways of receiving messages with speech-based text entry as the way to send messages. Handheld text entry using a smartwatch was not considered because of the small size of the device.

2.2. Hypotheses development

The goal of this research is to compare distraction caused by a mobile phone and a smartwatch in the way Giang et al. (2014; 2015) did: by sending notifications to both devices. The experiment also aims to replicate the results of Giang et al. (2014; 2015) using a larger sample size. The objective is also to extend their research by adding two other conditions to compare their levels of distraction: a condition simulating a vocal assistant where inbound messages are received through a speaker and a condition where outbound messages were sent manually. Samost et al.'s (2015) research on voice-activated command made us ponder on the level of distraction caused by inbound vocal messages inside a vehicle. Caird et al.'s (2014) meta-analysis on the distraction caused by texting and He et al.'s (2014) study on the distraction of speech-based and handheld text entry made us inquire about the level of distraction caused by outbound vocal and written messages. This experiment compares all the above conditions in order to determine if there is a safer way to stay connected inside a vehicle while driving and to see which condition is the most dangerous for drivers.

Giang et al.'s (2014; 2015) research on glances at both the smartwatch and the smartphone suggest that drivers glance longer at a smartwatch when they receive messages than at a mobile phone in the same context. Samost et al.'s (2015) research on glances at devices with voice-activated commands report that people glance more often at a smartwatch than at a mobile phone while initiating a phone call, although it is important to note that the scope of this study does not include the reception of messages on the devices. Caird et al.'s (2014) meta-analysis studying glances while texting and driving reported that drivers exhibited prolonged and more frequent glances off the road than when they were driving normally. Although a lot of research has been done on voice interaction inside a car while driving and its potential for distraction (McCallum et al., 2004; Baròn & Green, 2006), their studies aimed at measuring different tasks (destination entry, music selection, email processing, internet surfing, phone dialling) than those in this study (sending and receiving written and speech-based messages). All of this research enables us to posit the following hypotheses, the first of which is a replication hypothesis while the other two are new hypotheses:

H1a. Gaze distribution is less focused on the driving task while receiving written notifications on a smartwatch than while receiving them on a smartphone.

H1b. Gaze distribution is less focused on the driving task while receiving written notifications on a smartphone than when hearing them through a speaker.

H1c. Gaze distribution is less focused on the driving task when drivers have to respond to written notifications by text instead of responding to them vocally.

Giang et al.'s (2014; 2015) research on brake response time while receiving notifications on a smartwatch and a smartphone suggest that driving behavior is worse when the driver receives a message on a smartwatch than in the same context with a mobile phone. Perlman et al.'s (2019) research on driving behavior while interacting vocally with the devices reports that there was no difference between the auditory-vocal methods of initiating a phone call on a smartwatch and a mobile phone, but that they exhibited more erratic behavior when using the visual-manual method on the phone. However, that experiment only looked at the action of initiating a phone call and not the reception of notifications. He et al.'s (2014) study found that text entry with a speech-based cell phone was less harmful to driving performance than handheld text entry. These studies enable us to posit the following hypotheses, with the first and third ones being replication hypotheses and the second one being a new hypothesis:

H2a. Receiving written notifications on a smartwatch has more negative consequences on driving behavior than receiving them on a smartphone.

H2b. Receiving written notifications on a smartphone has more negative consequences on driving behavior than hearing them from a speaker.

H2c. Responding to written notifications by text has more negative consequences on driving behavior than responding to them vocally.

Perlman et al.'s (2019) use of heart rate and skin conductance measures made us wonder about the participant's mental workload during driving in different conditions. Since the scope of that study does not include notifications sent to devices, our first hypothesis is new. McCallum et al. (2004) studied cognitive workload on participants that were driving with a manual personal digital assistant and a vocal personal assistant and found that participants' cognitive workload was higher when they were interacting with a manual personal digital assistant. However, the reception of notifications was not part of the scope of the study, which means that our second hypothesis is considered a new hypothesis. The third hypothesis is also a new hypothesis since answering notifications is not the same interaction than what was experimented in McCallum et al. (2004). Studies show that eye tracking measures are a reliable way to estimate mental workload (Palinko et al., 2010; Marquart et al., 2015). Eye-tracking equipment was used to assess workload not only because many eye activity measures have been confirmed as good estimates of a driver's mental workload, but also because pupillometry shows reliability for real-time prediction and assessment of driver mental workload in recent studies (Marquart et al., 2015). This allows us to posit our final hypotheses:

H3a. Mental workload is higher while receiving written notifications on a smartwatch than on a smartphone inside a driving simulator.

H3b. Mental workload is higher while receiving written notifications on a smartphone than when receiving them vocally inside a driving simulator.

H3c. Mental workload is higher while responding to notifications by text than by responding orally to notifications inside a driving simulator.

An experimental research was set up to test these hypotheses.

3. Method

3.1. Experimental design

A within-subject experiment was conducted with the notification medium as the main independent variable. There were four conditions: (1) the *Phone* condition where participants received and read notifications on their phone while driving inside a driving simulator; (2) the *Watch* condition, where they received and read notifications on a smartwatch; (3) the *Speaker* condition, where they received notifications vocally on the phone's speaker. In these three conditions, the participant had to either read the notification out loud or hear it from the speaker (in the Speaker condition). When the notification contained a question, they had to answer orally. The fourth condition was (4) the *Texting* condition, where participants had to read out loud an incoming notification on the mobile phone or the smartwatch, and then had to respond by texting on their phone.

3.2. Sample and procedure

Thirty-one participants between the ages of 18 and 47 (Mean = 25.61. SD = 6.24) were recruited. Sixteen of them were men. Every participant received monetary compensation in the form of a $30 gift card. Participants were recruited through the research panel of our institution. When people enter the research panel's website, they can choose which study they want to participate in from a list of ongoing studies. Therefore, people registered voluntarily to participate in the experiment. Participants were screened before the experiment for skin allergies, cardiac pacemaker, epilepsy, neurological and psychiatric diagnoses, and other diagnosed health problems. Participants were also screened for appropriate driving footwear, a valid driver's license that respects provincial laws, and motion sickness. Only 4 participants had demerit points deducted, and only 6 of them were involved in one accident in the last three years. The project was approved by the Ethics Committee of our institution. After filling out a consent form to take part in the study, participants were installed in the driving simulator for the experiment (see 3.3 Experimental Setup and Apparatus). They were then asked to fill out a questionnaire before starting the driving tasks.

While seated in the driving simulator, participants were subjected to a simple baseline task, termed the "vanilla" baseline condition (Jennings et al., 1992). They were then requested to practice on the driving simulator before the experiment. They started by driving inside the simulator while receiving notifications for 15−20 min in order to understand the procedure during the upcoming experimental tasks. The order of the four tasks (or conditions) was randomized. In the Phone condition, participants received six notifications on the phone, which they had to read out loud. Two of those six notifications were statements and did not require answers (e.g., "Tom Hanks is an American actor"), two were questions requiring short answers (e.g., "What color are your eyes?"), and the last two were mathematical questions (e.g., "5 × 7 =?"). These notification formats were used to include all types of notifications identified in Giang et al. (2015).

The content of notifications was randomized across the four conditions to avoid any bias. In the Watch condition, participants received six notifications, organized in the same manner, but instead of receiving them on the mobile phone, they received them on the smartwatch. They also had to read the notifications out loud and give an answer orally when required. In the Speaker condition, participants received six notifications, again organized in the same manner as above, but were not required to repeat them out loud. The questions had to be answered verbally. In the Texting condition, participants received six notifications either on the phone or the watch. After reading them out loud, they were instructed to respond by text on the phone.

3.3. Experimental setup and apparatus

The experiment took place in a university laboratory. Lighting, humidity, and temperature were controlled inside the room. There were research assistants sitting on the other side of the room behind a one-way mirror with a microphone to communicate with the participants. Participants were sat in a Playseat Evolution Dirt Machine (Playseat, Doetinchem, Netherlands) gaming chair in front of three 28-inch ASUS (New Taipei, Taiwan) screens to give a more immersive experience. City Car Driving (Multisoft, Novosibirsk, Russia) (City Car Driving, 2020), a video game designed to help beginner by making them drive in a realistic open world environment with other drivers, pedestrians, and traffic regulations was used in this experiment. City Car Driving is a software with realistic physics and modern, high-quality graphics that has been used in previous research using a driving simulation (Tran et al., 2017; Balters et al., 2018; Widyanti and Sutanto, 2017). Participants started every task at the same location in the middle of a virtual city, whose surroundings resemble a real-life city environment. Fig. 1 below shows the three-screen setup, gaming chair, and driving simulation software.

The smartwatch used for the experiment was an Apple Watch Series 3 38 mm (Apple, Cupertino, California) and the smartphone was an iPhone 6 s Plus (Apple, Cupertino, California) attached to a car phone holder, a legal way of using a mobile phone inside a vehicle. Only 9 out of the 31 participants were smartwatch users with only one of them who used it for over two years, according to the questionnaire's results. The messages were sent and received using the message application (Apple's iMessage) inside both the smartwatch and the smartphone.

Fig. 1. Experimental setup.

Gaze distribution data was obtained using two cameras pointing at the participant's face for the duration of the experiment. Images were recorded using the Media Recorder Software (Noldus, Wageningen, Netherlands). These were then transferred to the Observer XT software (Noldus, Wageningen, Netherlands) in order to properly synchronize the video images with the other measures. The exact moment at which notifications were sent to the devices was captured using Observer XT, as was the exact moment when participants were done answering. It also captured the moment participants pressed the *Send* key after typing the answer to a notification for our analysis of the Texting condition.

The City Car Driving software records every road violation during a task. Road violation is a broad term that refers to a violation of traffic guidelines or normal standards of driving. This data was extracted directly from the software. The participant's driving speed was assessed in every condition throughout the entire experiment using a Python code, which took a screenshot of the participant's vehicle driving speed (in km/h) three to four times per second.

Eye tracking and pupillometry measures were recorded using SMI Eye Tracking Glasses 2 (SensoMotoric Instruments, Berlin, Germany), which the participants wore throughout the experiment.

3.4. Operationalization of research variables

Based on prior research (Giang et al., 2015; Perlman et al., 2019), a set of eye tracking data was used to assess participants' gaze distribution. For every variable, the average result of each task (condition) was calculated for each participant.

Total Task Engagement Time (*TTET*) (Giang et al., 2015) is the duration of the task, from the moment participants receive a notification to the moment they have processed or answered it. It was calculated using the video recordings of the sessions, from the moment the notification of the inbound message was heard to the moment the subject finished speaking or the moment they hit the *Send* key on the smartphone for the Texting condition. *Total Glance Duration per Notification* (*TGD*) (Giang et al., 2015) is the amount of time a participant looks at the device after receiving a notification. If the participant looks at the device after the end of the task, it also counts as being a part of *TGD* for that notification until the subsequent notification is received on the device. Again, this measure was calculated using video recordings, where a glance is recorded every time the eye is captured looking away from the road. *Number of Glances per Notification* (*NGN*) (Giang et al., 2015) is the number of times a participant looks at the device after a notification is sent. Again, this measure was calculated using video recordings. *Average Glance Duration per Notification* (*AGD*) (Giang et al., 2015) is the average amount of time a participant looks at his or her device per glance. *Percentage of Time Off Road* (*TOR*) (Perlman et al., 2019) calculates the percentage of time, from the moment the notification is sent to the device to the moment the participant stops speaking or presses the *Send* key for the texting condition, where the eyes of the participant are off the road. *Average Longest Single Glance* (*LSG*) (Perlman et al., 2019) is the single longest of every glance that a participant threw at the device for

Table 1
Gaze distribution variables and their acronyms.

Acronym	Variable
TTET	Total Task Engagement Time
TGD	Total Glance Duration Per Notification
NGN	Number of Glances Per Notification
AGD	Average Glance Duration Per Notification
TOR	Percentage of Time Off Road
LSG	Longest Single Glance

every notification received on the device. An average of every longest single glance was then calculated. Table 1 below summarizes each variable with its acronym:

Of the 6 gaze distribution variables, data showed that only one had a normal distribution (*TOR*). Data for 4 of the 5 remaining variables (*TTET, TGD, NGN, LSG*) was normalized by transforming the variables by the log of the variable + 1. For the last variable (*AGD*), it was transformed by the log of the variable*10 + 1. A repeated measures linear regression was then used to analyze pairwise comparison between each condition. Stata's *VCE Cluster* option was used to control for non-independence of observations.

Driving behavior was measured using various methods. Total road violation data (Average = 8.58; Standard Deviation = 8.64) was transformed before the analysis in order to normalize it. A value of 0 was attributed to a task with five or less road violations. A value of 1 was attributed to tasks with six or more road violations. A Wilcoxon signed rank test was then used to analyze pairwise comparison between each condition. P-values were adjusted for pair-wise comparisons between the four conditions using the Holm-Bonferroni method (Kerby, 2014).

Speed metrics are some of the most commonly used metrics in driver behavior studies (Östlund et al., 2005). Studies suggest that drivers decrease their speed in order to cope with visual distraction (Patten et al., 2004). Driving speed per participant per experimental condition was calculated by averaging the speed on every screenshot driving speed data captured. Measuring the average acceleration and the standard deviation of acceleration can also be used to indicate safe driving. Speed and acceleration profiles are known to affect fuel consumption (André and Pronello, 1996). Moreover, longitudinal acceleration can be used as a measure of an unsafe or aggressive driving style (Vaiana et al., 2014). The acceleration formula ($a = \Delta v / \Delta t$) was used in order to calculate acceleration. A numerical value for acceleration/deceleration was calculated every time a screenshot of the speed was taken, except for the first one. Average and standard deviation of acceleration were then calculated for each condition using a repeated measures linear regression to analyze pairwise comparison between each condition. Speed and acceleration were normally distributed.

Hard braking is one of the three most prevalent types of risky behavior among drivers (Klauer et al., 2009). It usually means that the driver had to react instinctively to something in the environment because they were distracted, not paying attention or going too fast. Hard braking events were calculated using g-force. A g-force is a measure of acceleration in which 1 G is equal to the acceleration humans feel due to the force of gravity (Deziel, 2018). On Earth, 1 G is equal to 9.80665 m/s^2. This measure can be used to quantify any acceleration, not just when it applies to gravity. Researchers usually set the threshold for hard braking over 0.5 G (Hill et al., 2019; Botzer et al., 2019). After converting acceleration from m/s to g-force, hard braking events were tallied in every task for every participant by counting how many times deceleration went over 0.5 G. Data from hard braking events was normalized by transforming the variable by the log of the variable*10 + 1. Speed, acceleration, and hard braking events were also calculated using a repeated measures linear regression to analyze pairwise comparison between each condition.

Three eye tracking measures were taken using the SMI Eye Tracking Glasses 2 (SensoMotoric Instruments, Berlin, Germany) in order to assess cognitive workload (Palinko et al., 2010). Studies show that eye tracking inside a driving simulator is a reliable indicator of the drivers' cognitive workload estimation. Many measures can be used in eye tracking to calculate cognitive workload. Of these measures, blink duration is one that has been proven to decrease with increases in mental workload (Marquart et al., 2015). According to researchers, people might try to blink for a shorter amount of time in order to lose as little information as possible in tasks with higher cognitive load. Fixation duration is another measure that increases with increased mental workload (Marquart et al., 2015). For the same reason blink duration decreases with higher workload, drivers seem to fixate longer during tasks demanding higher concentration. Pupil diameter is also often considered in order to estimate mental workload, especially in the driving simulator environment (Marquart et al., 2015). Similar to fixation duration, pupil diameter increases with increased mental workload. Average and standard deviation of blink duration, fixation duration and pupil diameter were calculated for every participant through all four conditions. Of these six measures, two were transformed for normalization. Standard deviation of blink duration was normalized by transforming the variables by the log of the variable + 1 and standard deviation of pupil diameter was normalized by transforming the variable by the log of the variable*100 + 1.

4. Results and analysis

4.1. Gaze distribution (H1)

Table 2 summarizes the results for the average of every gaze distribution measure for all four conditions. The last six columns show significance values for pairwise post hoc comparisons between each task. A repeated measures linear regression was used to analyze pairwise comparison between each condition.

For *TTET (Total Task Engagement Time)*, there is no statistically significant difference between the Phone and Speaker conditions. The Watch condition took significantly more time on average than the Phone and Speaker conditions ($p < 0.000$). Moreover, the texting condition was significantly higher than all three other conditions ($p < 0.000$).

TGD (Total Glance Duration per Notification) is the lowest on average in the Speaker condition ($p < 0.000$). The Phone condition has higher *TGD* than the Speaker condition followed by the Watch condition ($p = 0.030$), which is higher than both. The Texting condition has the highest *TGD* on average ($p < 0.000$). *TGD* is statistically different through all conditions.

NGN (Number of Glances per Notification) is lower in the Speaker condition than in the other conditions ($p < 0.000$). *NGN* is also higher in the Watch condition than in the Phone condition ($p = 0.035$). On average, participants understandably look at the device a lot more in the Texting condition ($p < 0.000$). Again, the difference between the averages of every condition is statistically significant.

AGD (Average Glance Duration per Notification) is lower in the Speaker condition than in the others ($p < 0.000$), followed by the Phone condition ($p < 0.000$). The Watch condition saw a slightly higher *AGD* than the Phone condition ($p = 0.034$), and the Texting condition had the highest ($p < 0.000$). The difference between the averages of every condition is statistically significant.

On average, *TOR (Percentage of Time Off Road)* is the lowest during the Speaker condition ($p < 0.000$). It is higher for the Watch condition than the Phone condition ($p = 0.015$). The Texting condition has the highest *TOR* ($p < 0.000$). The difference between the averages of every condition is statistically significant.

The Speaker condition has the lowest average for *LSG (Longest Single Glance)* ($p < 0.000$) followed by the Phone condition. The Watch condition is higher than the first two ($p < 0.000$) ($p = 0.019$) and, as usual, the Texting condition has the highest *LSG* ($p < 0.000$). The difference between the averages of every condition is, once again, statistically significant.

Taken together, gaze distribution was focused on the device more frequently and for the longest amount of time in the Texting condition. Participants also looked at the device for longer and more frequently in the Watch condition than in the Phone condition which provides support to H1a, although not as much and as long as in the Texting condition, which provides support to H1c. Participants looked less frequently and for shorter periods of time at their device in the Speaker condition than in the other three which provides support to H1b. Overall, these results provide support to H1a, H1b, and H1c.

Table 2
Gaze distribution results and pairwise comparisons.

Dependant variable	Phone (P)	Watch (W)	Speaker (S)	Texting (T)	P vs W p-value	P vs S p-value	P vs T p-value	W vs S p-value	W vs T p-value	S vs T p-value
(l)TTET[1]	2.05	2.30	2.07	3.08	***0.000***	0.748	***0.000***	***0.000***	***0.000***	***0.000***
(l)TGD[1]	0.99	1.23	0.42	2.39	***0.030***	***0.000***	***0.000***	***0.000***	***0.000***	***0.000***
(l) NGN[1]	0.98	1.19	0.45	2.06	***0.035***	***0.000***	***0.000***	***0.000***	***0.000***	***0.000***
(ld) AGD[2]	2.41	2.46	1.28	2.75	***0.034***	***0.000***	***0.000***	***0.000***	***0.000***	***0.000***
TOR	0.28	0.30	0.11	0.50	***0.015***	***0.000***	***0.000***	***0.000***	***0.000***	***0.000***
(l) LSG[1]	0.78	0.86	0.38	1.35	***0.019***	***0.000***	***0.000***	***0.000***	***0.000***	***0.000***

[1] (l): Data was normalized using *ln(DependantVariable + 1)* [2](ld): Data was normalized using *ln(10*DependantVariable + 1)*.

4.2. Driving behavior results (H2)

Results for the average number of road violations per condition are summarized in Table 3. The last six columns show significance values for pairwise post hoc comparisons between each task. A Wilcoxon signed rank test was then used for pairwise comparisons.

Results show statistical differences in the average number of violations between the Phone condition and the Texting condition ($p < 0.000$), between the Watch condition and the Texting condition ($p < 0.000$) and between the Speaker condition and the Texting condition ($p = 0.002$), with violations in the Texting condition being higher than in the three other conditions. Differences were not significant between the other conditions.

Table 4 summarizes the results for the five driving behavior measures (average and standard deviation of speed, average and standard deviation of acceleration, hard braking events) per condition. The last six columns show significance values for pairwise post hoc comparisons between conditions. A repeated measure linear regression was used to analyze pairwise comparison between each condition.

Results suggest that for average speed and standard deviation of speed there was no significant difference between conditions. Results also suggest that for average acceleration and its standard deviation, the only significant difference was between the standard deviation of the Watch and Speaker conditions: it was higher for the Speaker condition ($p = 0.019$).

For hard braking behaviors, Table 4 shows that there was a statistically significant difference between two pairs of conditions. The Texting condition has a higher average of hard braking events than both the Phone ($p = 0.017$) and the Watch conditions ($p = 0.037$), suggesting that participants drove more dangerously in the Texting condition than in the other two conditions.

Because of the statistically significant difference between the Texting condition and each of the other three conditions for road violations and the statistically significant difference between the Texting condition and both the Watch and the Phone conditions in hard braking events, H2c is supported. Participants' driving behavior was impeded while answering notifications through text. Since no statistically significant difference was found between any other conditions in almost every measure (except for standard deviation of acceleration between the Watch and Speaker conditions), H2a and H2b are not supported.

4.3. Cognitive workload (H3)

Table 5 summarizes the results for the six eye tracking measures (average and standard deviation of blink duration, average and standard deviation of fixation duration, average and standard deviation of pupil diameter) per condition. Predicted values for every variable through all four tasks were generated by subtracting results from the earlier baseline condition to those of the four conditions. The last six columns show significance values for pairwise post hoc comparisons between conditions. A repeated measure linear regression was used to analyze pairwise comparison between each condition.

Results show that average fixation duration is lower in the Texting condition than in the other three conditions. Since drivers fixated for shorter amounts of time during the Texting condition, it would mean that participants were exposed to lower mental workload in that condition than in the other three, although this might be a result of an increased number of glances at the device during the Texting condition. Results also show that standard deviation of pupil diameter is smaller in the Phone condition than in the other three, which means that the spread of the data is closer to the mean than in the other conditions. No other statistically significant results were found.

Standard deviation of pupil diameter is lower in the Phone condition than in the Watch Condition, but since no other statistical difference can be found, H3a cannot be supported. No difference can be found between the Phone and the Speaker condition either, other than standard deviation of pupil diameter, which means that H3b is not supported either. Average fixation duration is lower in the Texting condition than in the other three conditions. Since H3c posits higher mental workload in the Texting condition, H3c is not supported.

5. Discussion and conclusion

This study aims at comparing the effect of various types of notifications on a smartwatch, smartphone and vocal assistant in a driving context. Results focus on gaze distribution, driving behavior and cognitive workload. First of all, results support that gaze distribution is less focused on the driving task while receiving written notifications on a smartwatch than while receiving them on a smartphone, that it is less focused on the driving task while receiving written notifications on a smartphone than when hearing them through a speaker, and that it is less focused on the driving task when drivers have to respond to written notifications by text instead of responding to them vocally. Regardless of the mobile device (smartwatch, smartphone or vocal assistant), they might have an impact on the driving task, particularly for attention with eyes off the road scene.

However, results of the experiment do not support that receiving written notifications on a smartwatch has more negative consequences on driving behavior than receiving them on a smartphone and that receiving written notifications on a smartphone has more negative consequences on driving behavior than hearing them from a speaker. Moreover, results support that responding to written notifications by

Table 3
Road violations results and pairwise comparisons.

Dependant variable	Phone (P)	Watch (W)	Speaker (S)	Texting (T)	P vs W p-value	P vs S p-value	P vs T p-value	W vs S p-value	W vs T p-value	S vs T p-value
Total Road violations	6.97	6.71	7.13	13.52	0.751	0.933	***0.000***	0.637	***0.000***	***0.002***

Table 4
Telemetry data results and pairwise comparisons.

Dependant variable	Phone (P)	Watch (W)	Speaker (S)	Texting (T)	P vs W p-value	P vs S p-value	P vs T p-value	W vs S p-value	W vs T p-value	S vs T p-value
Average Speed	8.87	8.79	9.04	8.95	0.848	0.755	0.871	0.658	0.716	0.827
StdDev Speed	5.58	5.77	5.96	5.89	0.288	0.146	0.237	0.399	0.537	0.760
Average Acceleration	0.03	0.03	0.04	0.03	0.380	0.715	0.449	0.130	0.802	0.236
StdDev Acceleration	1.31	1.24	1.34	1.29	0.054	0.458	0.679	***0.019***	0.144	0.354
(ld)HardBraking Event[1]	1.42	1.43	1.46	1.69	0.868	0.722	***0.017***	0.838	***0.037***	0.058

[1] (ld): Data was normalized using *ln(10*DependantVariable + 1)*.

Table 5
Eye tracking/Pupillometry results and pairwise comparisons.

Dependant variable	Phone (P)	Watch (W)	Speaker (S)	Texting (T)	P vs W p-value	P vs S p-value	P vs T p-value	W vs S p-value	W vs T p-value	S vs T p-value
Average Blink Duration	−313.84	−309,33	−316,69	−312,64	0.487	0.700	0.874	0.409	0.720	0.600
(l) Std Dev Blink Duration[1]	4.29	4.21	4.23	4.35	0.329	0.388	0.276	0.873	0.123	0.109
Average Fixation Duration	−162.24	−160.61	−156.20	−181.25	0.785	0.343	***0.039***	0.526	***0.027***	***0.004***
Std Dev Fixation Duration	383.83	381.83	375.41	352.69	0.889	0.514	0.134	0.637	0.130	0.274
Average Pupil Diameter	0.61	0.58	0.59	0.75	0.192	0.440	0.165	0.751	0.080	0.105
(ld) Std Dev Pupil Diameter[2]	3.44	3.67	3.56	3.72	***0.007***	***0.038***	***0.013***	0.056	0.412	0.068

[1] (l): Data was normalized using ln(DependantVariable + 1) [2](ld): Data was normalized using ln(100*DependantVariable + 1).

text has more negative consequences on driving behavior than responding to them vocally. This suggests that receiving notifications on a smartwatch or smartphone may not lead to more hazardous driving behavior, but sending a text message does.

Results did not support that mental workload is higher while receiving written notifications on a smartwatch than on a smartphone inside a driving simulator, that mental workload is higher while receiving written notifications on a smartphone than when receiving them vocally inside a driving simulator and that mental workload is higher while responding to notifications by text than by responding orally to notifications inside a driving simulator. Our data suggest that mental workload was not affected during our experimentation by notifications on any of the conditions.

Although gaze distribution results suggest that drivers are more distracted by a smartwatch than a smartphone and that people are more distracted looking at a device for information than hearing it through a vocal assistant, driving behavior results do not suggest that people are worse drivers because of it. Cognitive workload results do not indicate a significant increase in workload. The difference between manual text entry and speech-based text entry suggests that drivers are more distracted and driving worse when texting answers than when saying them out loud, although mental workload was not significantly different. However, this does not mean that the smartwatch is not more dangerous than the smartphone or that a vocal assistant is not less risky than both. Distracted drivers do not get into accidents every day, but their behavior becomes more dangerous when something unexpected happens and they are too slow to react (Overton et al., 2015). The less distracted they are, the more likely they will react quickly to those unexpected events.

These results make three contributions to road safety research. To our knowledge, little research has been done on the impact of smartwatches while driving. Of those studies, only Giang et al.'s (2014; 2015) two experiments examined the impact of notifications on both smartwatches and smartphones, but with smaller sample size (n = 6 and n = 12). Samost et al. (2015) and Perlman et al. (2019) compared the two devices, but instead of examining notifications sent to the device, they looked at how people made calls from them. Our first contribution extends the work of Giang et al. (2014; 2015) by examining notifications on both devices, but with a larger sample size. This contribution is important in order to confirm the conclusions made in previous studies and to ensure that such conclusions can be applied to future experiments.

Comparisons between the two types of notifications mentioned above and the other two types in this study (notification import on a speaker and manual text entry as an answer to a notification) constitute our second contribution. The objective of this experiment was to see if those other types of communication inside a vehicle were as distracting as the notifications sent in Giang et al.'s research (2015). Giang et al. (2014; 2015) examined both types of notification exports in both their studies but did not compare them with one another. He et al. (2014) compared speech-based text entry with manual text entry, but they only used a mobile phone to make that comparison. It is interesting to see where the smartwatch falls in these comparisons that have already been made. Our study makes a very good contribution to road safety, not only by identifying the smartwatch's dangerous potential for distraction, but also by showing that a vocal assistant is a safe alternative for people to receive and answer notifications while driving.

Adding measures that are different from other studies on the impact of using a smartwatch while driving for driving behavior and mental workload constitute our third contribution. Driving behavior measures were different from other studies about smartwatches and distracted driving. Giang et al. (2014; 2015) measured brake response time. Samost et al. (2015) and Perlman et al. (2019) looked at lane position, steering wheel reversals and speed as well as a remote detection response task that was more about detecting environmental stimuli. This experiment was concentrated on speed, acceleration, hard braking events and number of road violations. Perlman et al. (2019) used heart rate and skin conductance measures, but no studies conducted on the impact of smartwatches measured mental workload using eye tracking or pupillometry. These measures were used in our study to give a more complete picture of the impact of the four conditions while driving. This contribution is useful since we can compare results from different measures through many studies in order to get as much information as possible on driving behavior and mental workload while using the different devices behind the wheel.

Many similarities can be observed between results from this experiment and previous studies on the same topic. In Giang et al.'s (2014) first experiment, participants took longer to read notifications with the smartwatch than with the smartphone, although they started looking at the watch faster. Giang et al's (2015) follow-up experiment found that people glanced more at the smartwatch than at the phone and that their brake response time was longer when a lead vehicle was slowing down in front of them in a watch condition than in a phone condition. The findings in both studies are similar to those in our experiment : The smartwatch is more distracting to the driving task than the smartphone.

Samost et al.'s (2015) study on the impact of initiating a call from either a smartwatch using an auditory-vocal method and from a phone using both the auditory-vocal method and a visual-manual method showed that participants driving behavior was more erratic and entailed higher mental workload when using the visual-manual method than the auditory-vocal method. Perlman et al. (2019) recreated the experiment and confirmed that the visual-manual method was more distracting than both auditory-vocal methods, but also added that task time and the number of glances were greater in the smartwatch condition than in the phone's auditory-vocal condition. Those two studies' conclusions coincide with those of our experiment, which found that communicating with an electronic device through voice activated commands is less distracting than communicating through manual entry.

Our results have implications for policy makers. Even if interacting with a smartwatch might be considered an act of distracted driving, which is illegal in most states (FindLaw, 2016), there is still enough left to interpretation. More clarity is needed regarding the use of a smartwatch while driving, and since research is a key point in evaluating technology and distraction level (Canadian Council of Motor Transport Administrators (CCMTA, 2018), we believe this study can be taken into consideration in regard to road safety regulation. Public and private insurance companies can also benefit from a clearer view of the smartwatch's impact on driving, and make use of the above conclusions to inform drivers of the risks involved in driving with a smartwatch, through education and enforcement, for instance with targeted advertising. The present research supports the importance of considering smartwatches as a distraction during driving.

Limitations of the study must be acknowledged. There was no control condition for driving in the study. This was mainly due to a technical limitation. Since the battery in the eye tracking glasses started to overheat after approximately 45 min, we made the decision not to have a control condition in order to have enough time to test our four conditions. Further research is needed to integrate a control condition without notifications in order to compare the conditions to normal driving without any distraction. To study all types of notifications seen in both Giang et al.'s studies (2014; 2015), we experimented with three different types of notifications, although we did not look at the differences between them. One of our measures of mental workload, fixation duration, saw a difference between the Texting condition and the other three conditions. Since fixation duration was lower in that condition, that would entail lower mental workload, although this does not account for the higher number of glances at the device in the Texting condition. Further research should be aware of this before using fixation duration as a measure. The experiment used a specific smartwatch and a specific smartphone. More research should be done using different devices in order to confirm or deny the results of this study. It would also have been interesting to find out if Apple users were more or less distracted during the experiment than other types of users (i.e., Microsoft, Google, Huawei) since this study was conducted using only Apple products. Moreover, hard braking events, speed, acceleration, and road violations were used as measures of driving behavior. More driving measures could be added in a future study for a better overall view of driving behavior such as lateral lane position. More information on this type of measure could provide insights about lane guidance in vehicles which provide warnings to drivers veering off course and minimize the risk of accidents if the drivers are distracted. Another avenue to explore in the future would be to conduct new experiments in a few years when people will be as familiar with smartwatches as they are with mobile phones today. Twenty-four (24) out of 31 participants were aged between 20 and 26 years old. Future studies on this topic should recruit people from different age groups to make sure there is no age bias. Participants were not screened for issues related to eyesight and vision, although they were required to have driven at least once in the past year and to have a valid driver's license, which means they needed to see well enough to be able to drive. Nonetheless, screening for issues related to eyesight and vision should be a part of subsequent research.

The smartwatch is a new potential source of distraction while driving. Participants look at their device more often while receiving messages on a smartwatch as compared to when they receive them on a mobile phone. Also, participants are less distracted by messages when they hear them than when they read them. Furthermore, answering messages while driving is forbidden, but answering vocally to messages is a better alternative than answering through text. Drivers can reduce distractions by having incoming messages read through speakers and outbound messages orally dictated, instead of reading them on their devices and texting back their reply. This will help make the roads safer for all.

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Hong Kong Journal of Occupational Therapy.

Authorship contribution

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Declaration of Competing Interest

The authors report no declarations of interest.

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