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Interacting with Android Auto and Apple CarPlay when driving: The effect on driver performance

A simulator study

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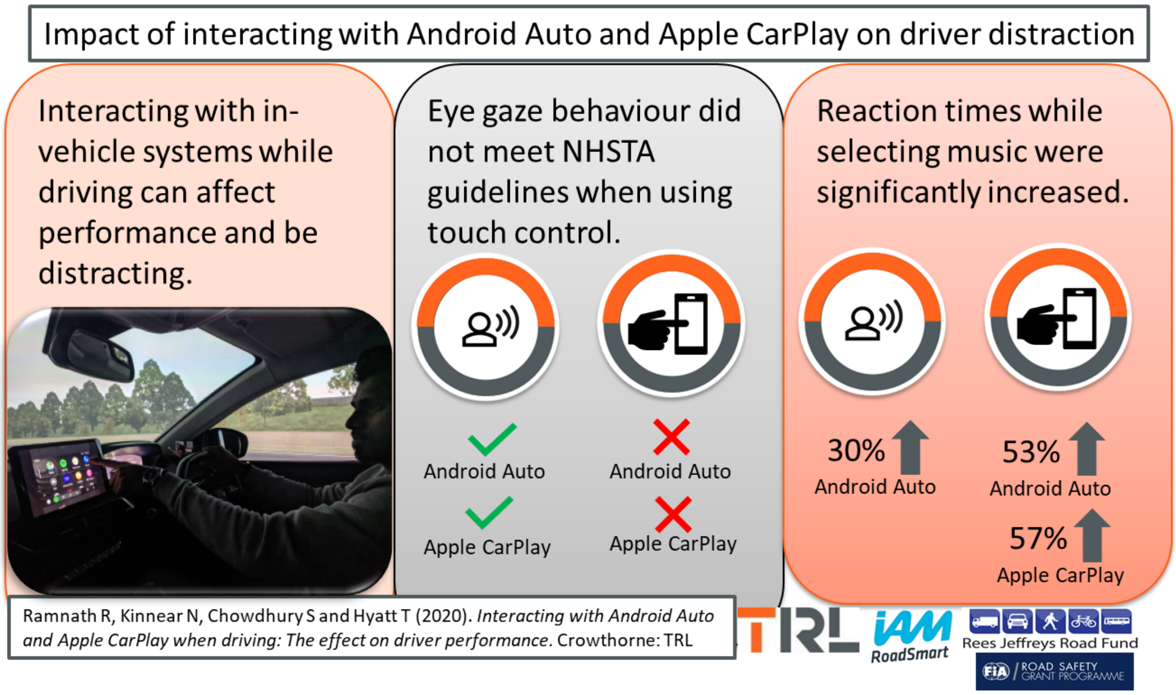
Graphical Abstract



Key findings

- Controlling the vehicle's position in the lane and keeping a consistent speed and headway to the vehicle in front suffered significantly when interacting with either Android Auto or Apple CarPlay, particularly when using touch control.
- Participants failed to react more often to a stimulus on the road ahead when engaging with either Android Auto or Apple CarPlay compared with a control drive.
- Reaction time to a stimulus on the road ahead was higher when selecting music through Spotify when using Android Auto and Apple CarPlay. The impact on reaction time when using touch control was worse than texting while driving (based on previous studies).
- Use of either system via touch control caused drivers to take their eyes off the road for longer than NHTSA recommended guidelines. When using voice control all measures were within NHTSA guidelines.
- Participants underestimated the time they thought they spent looking away from the road when engaging with Android Auto and Apple CarPlay via touch control.

Executive Summary

Background

The increasing use of in-vehicle infotainment systems while driving has led to concerns around driver distraction and the potential impact on road safety. A review for the European Commission estimated that driver distraction is likely to be a factor in 10 to 30% of all road collisions in Europe each year (TRL, TNO & RappTrans, 2015). Multiple studies have measured in-vehicle distraction when driving while performing secondary tasks such as hand-held and hands-free mobile phone use, text messaging and social media (Basacik et al., 2011; Parkes et al., 2007; Reed & Robbins, 2008). All studies concluded that there were various forms of distraction (cognitive, visual and physical) that negatively affected driving performance. Similar negative effects were also reported from use of modern in-vehicle manufacturer installed infotainment systems (Strayer et al., 2017). Subsequent research compared manufacturer systems to more recent applications, namely Google's Android Auto and Apple's CarPlay and found that these applications resulted in lower workload levels (Strayer et al., 2018). Nevertheless, little research has been conducted to understand the impact of these new popular mobile-based infotainment systems on driving performance.

IAM RoadSmart in partnership with the FIA Foundation and Rees Jeffreys Road Fund commissioned TRL to explore the impact of Android Auto and Apple CarPlay on driver performance using TRL's High Fidelity 300° DigiCar simulator. It also sought to compare the results to other forms of driver impairment from previous studies that used the same simulator 'impairment' route.

Method

The study comprised two experimental trials: one using Android Auto and another using Apple CarPlay. Twenty Android users participated in the Android Auto trial and twenty Apple users participates in the Apple CarPlay trial. In both trials, participants completed three drives on the same simulated test route: a control drive (where they did not interact with any system), a voice enabled drive (where they interacted with the respective system using voice control only) and a touch enabled drive (where they interacted with the respective system using touch control only).

The test route was divided into three sections:

1. Car following: two music-related tasks accessing music on Spotify and BBC radio
2. Erratic motorway traffic: two navigation tasks to a railway station and restaurant or petrol station
3. Figure eight loop: reading texts and making a call

Participants were also asked to react (by flashing their lights on the indicator stalk) when a red bar appeared on screen (to measure reaction time to an external event requiring attention). This appeared four times during each drive and coincided with engagement with the infotainment app.

There were four main measures of driving performance collected: reaction time to the red bar, driver behaviour measures such as speed, lane position and headway, eye gaze behaviour and self-reported performance.

Detailed findings

- Analysis of reaction times to the red bar showed that participants using Android Auto took significantly longer to react to the red bar during the touch and voice drive compared with the control drive while performing the music selection task.
- Participants using Apple CarPlay took significantly longer to react to the red bar during the touch drive compared with the control drive when performing the music task, and during the voice drive compared with the control drive when performing the navigation task.
- Participants failed to react to the red bar more often during the touch drive in both Android Auto and Apple CarPlay compared with control, with no significant differences between voice and control.
- Participants significantly reduced their average speeds while performing the music and navigation tasks using the touch feature, in both Android Auto and Apple CarPlay. Furthermore, participants using Android Auto showed a significant reduction in average speeds while performing the texting and calling tasks using both voice and touch features.
- During the first part of the drive, participants were asked to maintain a constant headway (distance) to the vehicle in front. Analysis of standard deviation of headway showed larger deviations during the touch drive compared with the control for both infotainment systems.
- Analysis of deviation in lane position showed large variations in lane position for the touch drive, compared with control, while performing the music, texting and calling tasks using both infotainment systems. There was also a significant increase in deviation of lane position for the voice drive while performing the texting and calling tasks using Apple CarPlay.
- Eye gaze behaviour for Android Auto showed that the sum of all fixations away from the road was over 12 seconds for all tasks apart from one reading text task. This does not meet the guidelines set out by NHTSA (the US National Highway Traffic Safety Administration).
- For Apple CarPlay, the sum of all fixations away from the road was over 12 seconds for the Spotify music selection task, navigation, and reading a text and making a call.
- For both systems, eye gaze behaviour was within the NHTSA guidelines when using the voice control feature.
- Participants underestimated the time they thought they spent looking away from the road during the touch drives with both infotainment systems.
- In both infotainment systems, participants reported better driving performance in the control drive than in the voice and touch conditions. Additionally, participants reported the touch drive to be more difficult and distracting than the voice drive for all music and navigation tasks, although no difference was reported in the texting and calling tasks.

Conclusions

The data measured in DigiCar clearly demonstrate that interacting with either Android Auto or Apple CarPlay when driving increases demand on the driver and requires attentional resources that impact driving performance. While drivers reduce their speed to manage this increase in demand, this is not sufficient to compensate for the impact on their driving performance. Controlling the vehicle's position in the lane and keeping a consistent headway to the vehicle in front suffered significantly when interacting with the systems, particularly when using touch control.

In general, driving performance was more negatively impacted when using touch control to interact with the systems compared with voice control. Participants were able to keep their eyes on the road more when using voice control than touch control, and were more likely to identify stimuli that required attention. Despite this, most participants reported using touch rather than voice control in their real-world driving.

Participants' ability to respond to the red bar stimuli (indicative of an external event requiring attention) was negatively affected when undertaking some tasks, like music selection and navigation, for both infotainment systems. Participants failed to respond to more red bar events, and when they did, the reaction time was longer than the control drive (particularly when selecting music). At motorway speeds (as simulated), the increase in mean reaction time would result in an increased stopping distance between 18.7m and 24.9m (between four and five car lengths).

The study sought to understand how these reaction time results compared with those seen in other forms of driver impairment. As the same simulator route was used in previous TRL studies, it was possible to compare reaction times with the control drive in each study. While some caution is necessary when making such comparisons (due to differences in time, samples and response method), the relative difference is indicative of the effect of engaging with features of both systems. Compared with the control drive, reaction times showed a mean increase of 57% and 53% when playing music through Spotify using the touch feature on Apple CarPlay and Android Auto, respectively. This is worse than the impairment associated with conducting a hand-held call while driving (45.9%). The effect of engaging with some features through voice control, with both systems, was similar to the impairment associated with texting (34.7%) and conducting a handsfree call (26.5%). For both touch and voice control with both systems, reaction times were greater than established benchmarks of the effect of alcohol consumption (at the legal limit) and cannabis use on reaction time when driving.

1 Introduction

Driver distraction is widely recognised as an important road safety issue; the more attention a driver diverts away from the main driving task, the more likely it is their driving behaviour will be negatively affected. Sources of distraction can be from outside the vehicle (e.g. other road users, road infrastructure, roadside advertising) or from inside the vehicle (e.g. smartphone use, eating and drinking, conversations). Analysis of accident data shows that driver distraction is a causal factor in 5% of road traffic accidents in Great Britain (DfT, 2018). However, these data are based on contributory factors assigned to injury collisions by police officers who may or may not have attended the scene, and therefore the figures may be an underestimate. A review for the European Commission by TRL, TNO and RappTrans (2015) estimated that distraction is likely to be a factor in 10-30% of all road collisions in Europe each year.

Previous research has highlighted the impact of in-vehicle distraction on driver performance and safety. This has included studies of telephone use, including hand-held and hands-free use while making a call, and the reading and writing of text messages (Parkes at al., 2007; Reed & Robbins, 2008). Such work built on a landmark TRL study, to benchmark mobile phone use while driving compared with driving at the legal alcohol limit (Burns, Parkes, Burton, Smith & Burch, 2002). Using the same simulated route used in these studies, a study commissioned by IAM RoadSmart further explored the effect of engaging with social media while driving (Basacik, Reed & Robbins, 2011). It found that impaired performance was the result of various forms of distraction: having to concentrate on the smartphone task (cognitive), holding the phone (physical), and the significant increase in time spent looking at the phone (visual) to interact with it. Although participants did reduce their speed, this was not enough to compensate for the poorer driving performance. For example, even though they were driving more slowly, they were still unable to control the vehicle as well as they did when they were not using their smartphone. The role of various forms of distraction was explained in more detail in the IAM think piece "The battle for attention: Driver distraction–a review of recent research and knowledge" (Kinnear & Stevens, 2015).

As a result of studies such as these, it is possible to consider how other forms of new in-car technology might lead to distraction and pose a risk to road safety. Recently, music streaming apps and in-car infotainment systems have become common and integrated in vehicles, replacing traditional modes of in-car entertainment. For example, Google's Android Auto and Apple's CarPlay are two popular applications which connect to a vehicle's infotainment display. These allow drivers to interact with their phone through that display, eliminating the need for them to directly interact with their phone. Both apps offer simplified layouts, with large icons to make them easy to use. These apps are becoming a popular feature on many new cars and some evidence exists to suggest they are less distracting than traditional OEM (original equipment manufacturer) infotainment systems (Strayer et al., 2018). Young et al. (2012) noted that secondary task interactions with more than two steps while driving have been associated with increases in perceptual response time to critical events, frequency of collisions and the number and duration of glances away from the road. Strayer et al. (2018) compared Apple CarPlay and Android Auto with OEM in-vehicle infotainment systems as part of an on-road trial with a 25mph speed limit and found that both Apple CarPlay and Android Auto provided more functionality than the OEM in-vehicle entertainment system and resulted in lower workload levels and lower interaction time. When drivers engaged the systems vocally instead of manually the workload levels were reported to be even lower. Additionally, there was no difference in overall workload levels between Android Auto and Apple CarPlay. Nevertheless, little is understood about how interaction with either Apple CarPlay or Android Auto compares to other common sources of impairment and distraction, such as mobile phone use.

The aim of the study was to understand whether commonly available infotainment systems affect driving performance, and how this compares with other forms of driver impairment. The research investigated the distraction caused by infotainment systems using a similar method to previous studies (e.g. Reed & Robbins, 2008; Basacik et al., 2011) to allow for comparison.

2 Method

2.1 Design

Two repeated-measures experiments were conducted to measure driver performance when using either Android Auto or Apple CarPlay while driving. Participant's reaction time, eye gaze behaviour and vehicle control measures were analysed for evidence of the effect of using these in-vehicle infotainment systems on driver performance.

Participants drove the simulator vehicle through a defined test route three times, taking breaks between drives:

1. **Control drive**: where participants did not interact with any in-car infotainment system.
2. **Voice enabled drive**: where participants performed various tasks using the voice control feature on the infotainment system.
3. **Touch enabled drive**: where participants performed various tasks using the touch screen on the system.

The order of the three drives was counterbalanced across the sample to control for order effect.

2.1.1 Test route

Participants drove through a 15-minute test route which included motorway driving and a figure of eight curve. The simulator route consisted of three sections with smooth naturalistic transitions between each section. These are shown in Table 1.

Table 1: The road sections used for the simulator trial

Section	Description	Length	Configuration	Speed Limit
1	Car following	2.4 miles	3 lane motorway plus hard shoulder in each direction. One vehicle present that the driver is required to follow at a steady distance	70mph
2	Erratic motorway traffic	5.6 miles	3 lane motorway plus hard shoulder in each direction. Light traffic present that the driver is required to interact with (e.g. changing lane and overtaking)	70mph
3	Loop	2.0 miles	A loop in a two-lane 'figure of 8' with a long left turn and long right turn separated by a short straight	40mph
	Total	**10.0 miles**		

In the car following section, participants were instructed to follow the lead vehicle at a safe and constant distance (as they would have experienced in the familiarisation drive). The lead vehicle stayed in the inside lane at all times and smoothly increased and decreased its speed between 43.8mph (70kph) and 68.8mph (110kph) during this section of the drive. In the erratic traffic section, participants were asked to drive as they normally would. They were asked to change lanes or overtake as necessary. Finally, in the loop section, participants were instructed to try to stay in the centre of their lane and to drive at 40mph.

Participants were asked to perform different tasks on the infotainment system at various points during the drive. Each task was assigned to a specific section of the drive to ensure that there were no confounding factors and driver behaviour could be compared across the three drives. A summary is presented in Table 2.

Table 2: Tasks in each section by drive

Section	Description	Control	Voice	Touch
1	Car following	No tasks	Play song on Spotify	
			Play BBC Radio	
2	Erratic motorway traffic	No tasks	Navigate to a train station	
			Navigate to a restaurant/petrol station	
3	Loop	No tasks	Receive texts	
			Make a call	

Figure 1 shows a timeline of the test route with the system tasks and presentation of the red bars to record reaction time. Across all drives (including control), participants were required to respond to the red bars at four timepoints in order to test their reaction times.

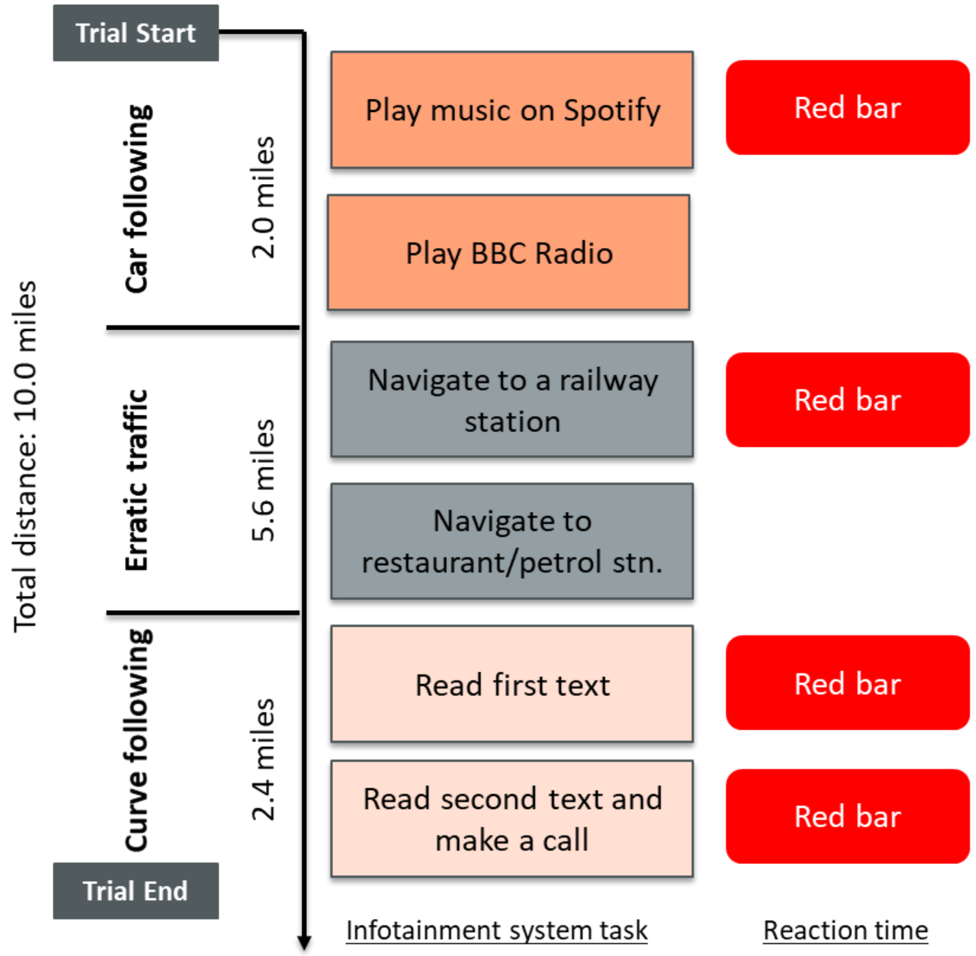


Figure 1: Schematic timeline of events in the drive

The trigger was the presentation of a red bar stimulus above the carriageway and ahead of the driven vehicles across all motorway lanes. This is shown in Figure 2. Participants were instructed to respond by pulling back the right-hand indicator stalk as quickly as possible. If drivers failed to respond within 10 seconds, this was treated as a missed event.

Figure 2: Red bar stimulus

2.1.2 Infotainment tasks

The research brief was to measure driver performance across a range of tasks. These tasks included playing music on Spotify, playing a radio station on the BBC iPlayer Radio app, navigating, receiving text messages, and making a call. The participants had to perform all these tasks in both the voice-enabled and touch-enabled drive.

While care was taken to ensure that all tasks could be performed by voice or touch, there were some cases where participants had to touch the microphone button in the voice drive to initially engage the system. For example, 'Okay Siri' or 'Okay Google' did not work in some cases, and participants had to use the touch button to enable voice commands.

2.1.2.1 *Spotify*

Participants were instructed to play music on the Spotify app in both the voice-enabled and touch-enabled drives. Participants were familiarised with how to use the app for both scenarios. In the voice-enabled drive, participants were instructed to play "Shape Of You by Ed Sheeran", whilst in the touch-enabled drive, participants were instructed to play "Summer by Calvin Harris". The first red bar corresponded with the participant attempting to complete this task.

2.1.2.2 *BBC iPlayer Radio*

Participants were instructed to play a specific radio station using the BBC iPlayer Radio app in both the voice-enabled and touch-enabled drives. Participants were familiarised with how to use the app for both scenarios. In the voice-enabled drive, participants were instructed to play the main local radio station “BBC Radio Berkshire”, whilst in the touch-enabled drive, participants were instructed to play “BBC Radio 2”.

2.1.2.3 *Navigation*

Participants were instructed to complete two navigation tasks per drive on the Maps app. Participants were familiarised with how to use the app for both scenarios. In the voice-enabled drive, participants were instructed to navigate to “Reading Station”, and to “the nearest restaurant”. In the touch-enabled drive, participants were instructed to navigate to “Wokingham Station”, and to “the nearest petrol station”. The second red bar corresponded with the participant navigating to Reading station and Wokingham station in the voice and touch drive respectively.

2.1.2.4 *Receiving text messages*

Participants were sent two texts during the loop section of the drive. They were familiarised with how to get the infotainment system to read out the text messages they received. In the voice-enabled drive, the first text sent to participants was “Hi. It’s Rosie. Looking forward to seeing you later. Can you please bring with you some apples, stamps, a thank you card, sun cream, onions, coffee, and hair gel?” The second text sent to the participant was “Hi. Rosie here again, something has come up, can you call me?”, which corresponded with the next task (see section 2.1.2.5).

In the touch-enabled drive, the first text sent to participants was “Hi. It’s Rosie. Looking forward to seeing you later. Can you please bring with you some bananas, playing cards, a birthday card, deodorant, tomatoes, teabags, and toothpaste?” The second text sent to the participant was “Hi. Rosie here again, something has come up, can you call me?”, which corresponded with the next task (see section 2.1.2.5).

The third and fourth red bars corresponded with the first and second text respectively.

2.1.2.5 *Making a call*

The second text sent prompted the participant to make a phone call. If the participant did not make the call, they were prompted by the researcher to do so. Once the call was made, the participant was asked to recall as many items as they could from the shopping list in the earlier text messages. The lists in both drives contained seven items to correspond with the known capacity limits of short-term memory (Miller, 1956).

2.2 Participants

Participants were recruited from TRL's participant database [1] and through social media advertising to take part in the trials. Participants had to meet the following criteria in order to be included in the study:

- Be regular users of a touchscreen smartphone (Android or iOS).
- Have a full UK driving licence.
- Be regular car drivers (i.e. drive more than once per week) and have over three years of driving experience.

Participants were assigned to the relevant trial based on whether they used Android or Apple devices.

Forty-six participants were recruited using an opportunistic sampling approach; there were six cases of simulator sickness (5 females and 1 male). For the 20 participants who completed the Android Auto trial, the average age was 45 years (range 20 to 77; sd=18); 15 were male and 5 were female. The 20 participants who completed Apple CarPlay trial had a mean age of 37 years (range 20 to 57; sd=9); 13 were male and 7 were female.

Thirteen participants in the Android Auto trial and 11 in the Apple CarPlay trial indicated that they currently used their mobile phones as in-vehicle infotainment devices.

2.3 Materials and data

2.3.1 DigiCar

TRL's advanced driving simulator, DigiCar, was used for this study. DigiCar comprises a full vehicle (Peugeot 3008) with fully operational controls surrounded by curved screens for a 300˚ field of view (as shown in Figure 3). It recreates high fidelity test environments that accurately reflect real-world driving conditions. Motion cues were supplied by an unobtrusive motion system linked to the graphics engine. Driver interaction with the vehicle controls was captured directly from the vehicle CAN BUS at a frequency of 20Hz. Bi-directional video cameras also captured the driver and the route being driven.

[1] TRL's participant database contains the details of over 2,000 local volunteers whom are willing to take part in simulator research. It contains details of a broad range of drivers, enabling TRL to recruit samples of drivers' representative of most driving populations.

Figure 3: DigiCar, TRL's advanced driving simulator

Android Auto and Apple CarPlay were presented to participants on a 10" Samsung Galaxy Tab A6 (SM-T580) tablet (running Android version 8.1.0) affixed to the interior of the DigiCar over the vehicle's existing in-car infotainment screen. For the Android Auto study, a Motorola Moto G6 enabled with Android version 9 was used and connected to the tablet like a user would in their own car. The same set-up was implemented for the Apple CarPlay study using an Apple iPhone7 enabled with iOS 12.2, connected to the tablet. The phones were set up with dummy accounts with complete access to all relevant apps – Spotify premium, BBC iPlayer Radio App, and Maps. Participants only interacted with the tablet and did not have to interact with the phones during the study.

2.3.2 Simulator data

Driver performance was measured by analysis of several vehicle control variables. These were mean and standard deviation of speed (in mph), headway (in metres) to the lead vehicle, standard deviation in lane position (in metres) and reaction time to the red bars (in seconds).

Driver behaviour was analysed during periods where participants were interacting with the in-vehicle devices. These periods of interest were defined based on the location of the participant's vehicle while they were performing each task. The period of interest for each task started when the automated voice instruction began and ended at a constant location prior to the start of the next task. For the control drive, driver behaviour data were extracted from the equivalent locations obtained from the voice and the touch drives. The length of the period of interest differed depending on the task and section of the drive, although was constant across the three drives. For example, tasks performed in the erratic traffic section had a longer period of interest than the tasks performed in the car following section, but the time window was the same in the control, voice and touch drives.

At the end of the simulator drive, participants were asked to call the researcher (using voice or touch) and recall as many items as they could that were sent to them via text messages. The items were the same for Android and Apple but differed for the voice and touch drives. The number of items recalled in each was recorded.

2.3.3 Eye Gaze Behaviour

In addition to the simulator data, a video of drivers' faces was recorded during the drive, in order to analyse visual behaviour. Coders watched the video during each of the task-defined time windows at half speed, using a stopwatch to record:

- Total time spent looking at the infotainment system
- Number of glances directly at the infotainment system

Driver visual distraction can be objectively measured using this method and compared against guidelines, such as those published by the US National Highway Traffic Safety Administration (NHTSA), to contextualise those results. The NHTSA "Driver Distraction Guidelines for In-Vehicle Electronic Devices" (2013) are primarily developed for evaluating the distraction potential from in-car devices and, therefore, provide relevant guidance to determine driver distraction caused by infotainment systems. These guidelines specify three acceptance criteria:

1. At least 85% of fixations away from the road are less than 2 seconds in duration
2. The mean duration of all fixations away from the road is less than 2 seconds duration
3. The sum of all fixations away from the road should be less than 12 seconds

These criteria are deemed met if they hold true for a minimum of 87.5% of the sample population tested.

2.3.4 Questionnaire

Driver 'perceived' performance was measured by a subjective post-trial questionnaire, administered immediately after completion of each drive. Measures included self-reported driving performance, perceived difficulty and distraction in performing tasks such as playing music or navigating to a destination, and estimated time that eyes were directed away from the road ahead to engage in an HMI (Human Machine Interface) task. Non-task specific measures such as self-reported driving speed, perceptual awareness, and overall ability to react to the dynamic environment were also recorded. All responses were in the form of Likert Scales ranging from 1-7 (as seen below) except for those that asked the participant to estimate the number of seconds their eyes were taken off the road:

Easy						Difficult
1	2	3	4	5	6	7

Participant responses were collected on their general driving habits including how often they use a mobile phone whilst driving; what features of a cars' infotainment system they use/ have used in the past (such as music selection, social media, phone calls and satellite navigation through voice or touch); and their opinions of what activities are legal and/or illegal to engage in whilst in control of a motor vehicle.

2.4 Procedure

Participants completed a comprehensive familiarisation process. A standard familiarisation route was used, and participants drove it for at least five minutes, or until they were judged to be fully comfortable with the simulator and the driving task. This was to help participants to become comfortable with controlling the simulator vehicle and driving in the virtual environment. Following this, participants were made familiar with operating the infotainment system. Here, participants were given the opportunity to interact with either Apple CarPlay or Android Auto (depending on the device they would be using for the trial). Participants were shown how to use Spotify, BBC iPlayer Radio, Maps, text messaging, and calling features and were asked to try running all of these apps independently. Participants only undertook their first drive once they were confident with using the infotainment system. Participants proceeded to undertake another familiarisation drive that included a car following task (driving at a safe and constant distance behind a lead vehicle) and a driving through traffic task. During this drive, participants were asked to interact with the infotainment system to get familiar with using the system whilst driving. Participants were also introduced to the occurrence of the red bar stimulus.

Once participants had been familiarised with the simulator and the infotainment system, they started their first drive. Following this drive, they took a break and completed a short questionnaire to obtain feedback about the drive they had just completed. Participants then undertook the second drive, and on completion took a break and completed another short questionnaire. Participants then completed the final drive and again completed a short questionnaire at the end of the trial.

3 Results

This section presents the results of driving performance using two in-vehicle infotainment systems, Android Auto and Apple CarPlay. As mentioned in Section 2.1, each participant completed three drives: a control drive (participants do not interact with the infotainment system); a voice drive (participants interact using a voice enabled system); and a touch drive (participants interact using a touch enabled system).

Section 3.2 presents the results of using the Android Auto in-vehicle device and Section 3.3 presents results of using the Apple CarPlay in-vehicle device. Comparison of the three drives have been split by sections of the drive (car following, erratic traffic and loop) and driver behaviour has been analysed only for the periods of interest where participants were interacting with the system. This provides greater understanding of driver behaviour when interacting with Android Auto or Apple CarPlay using voice and touch.

While the design of the trial was the same for Android Auto and Apple CarPlay, it is not possible to draw direct meaningful comparisons between the results obtained from the two trials. Both pieces of software have different operating systems that result in slightly different ways of using the applications. In addition, there may be inherent differences and biases between users of Apple compared with Android that could not be measured or controlled for in this study. To truly test for differences between the two user types would require a significantly larger sample that controlled for such biases. Finally, there were some differences in age distribution between the participants recruited for the two trials, although any effect of this is unknown.

3.1 Statistical tests

Appropriate statistical tests were used to test for significant differences in driver behaviour measures between the three drives (control, voice and touch). Linear mixed effects models were used to test for significant differences in driver behaviour measures between the three drives. This test is particularly useful in settings with missing data and repeated measures (where every participant does multiple drives). If the results were significant (voice/touch was significantly different to the control drive), these have been marked by an asterisk in the respective charts.

Results were classified as 'statistically significant' if the p-value was less than 0.05 (a common standard in behavioural sciences). The p-value is a measure of probability, and a value of less than 0.05 implies that any differences between the groups being tested has a less than 5% chance that the difference occurred at random.

While p-values obtained from statistical tests are used to inform whether an effect exists, they do not give much information about the size of the effect. In such cases, an effect size is calculated to measure the magnitude of the phenomenon or the degree of association between two variables. Generally, an effect size of less than 0.09 denotes a small effect, between 0.1 and 0.25 is a medium effect and over 0.26 denotes a large effect (Gravetter & Wallnau, 2013). Throughout the report, the effect size has been reported if any result is statistically significant to understand the magnitude of the relationship between two variables.

3.2 Android Auto

This section presents the results for the 20 participants who interacted with the Android Auto infotainment system during their drives. Any statistically significant result has been marked with an asterisk in the charts presented.

3.2.1 Reaction time

In total there were 80 reaction time events (red bars) (20 participants with four responses each). Participants failed to respond to the red bar 14 times in the touch drive, five times in the voice drive and three times in the control drive. McNemar's test showed a significant difference in the number of missed reactions between the control and touch drive (p=0.01). This suggests that interacting with Android Auto using touch interfered with participants' ability to respond to the red bars.

Figure 4 shows the mean reaction times for the first task (playing a song on Spotify) using Android Auto.

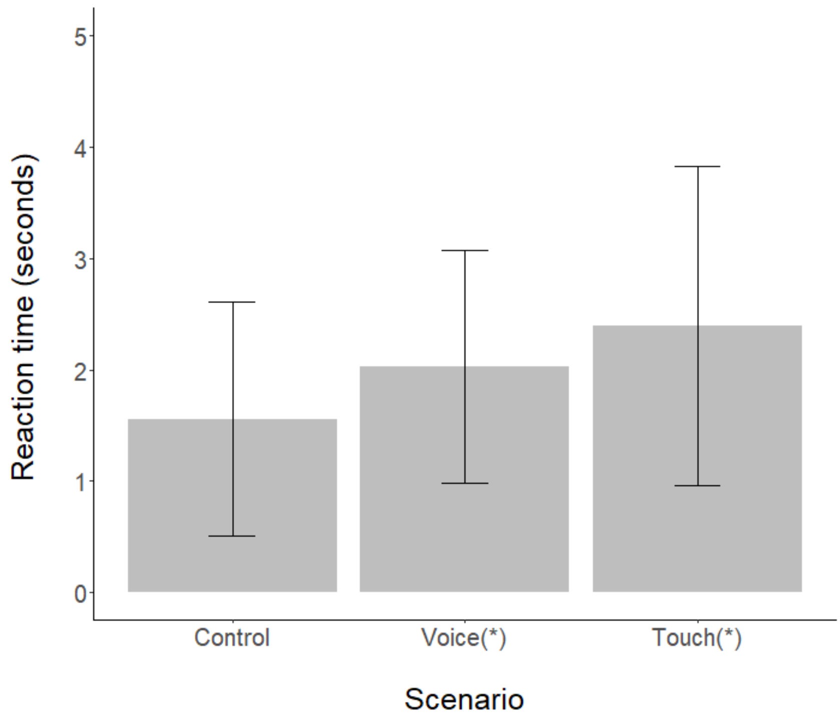


Figure 4: Reaction time for playing a song on Spotify using Android Auto (with standard deviation)

On average, the reaction time to the red bar during the touch drive was the highest (2.3 seconds), followed by the voice drive (2 seconds) and control drive (1.5 seconds). Statistical tests showed a significant difference in reaction times between the three drives ($p<0.05$) with a medium effect size (0.1). Post hoc comparisons showed a significant difference between control and touch ($p<0.05$) and control and voice drives ($p<0.05$). This suggests that interaction with the Android Auto infotainment system led to a slower reaction time in both voice and touch drives compared with the control drive.

The average reaction time for the second red bar (during the task of navigating to the nearest train station) was about 1.5 seconds for all three scenarios. Statistical tests showed no significant difference in reaction times between the three scenarios ($p=0.14$).

The average reaction time for the third red bar (during the reading of the first text) was similar (roughly 1.5 seconds) across all three scenarios. Statistical tests showed no significant difference between the three scenarios ($p=0.12$).

The average reaction time for the fourth red bar (during the reading of the second text and making a call) was around 1.3 seconds for all three scenarios. Statistical tests showed these results were not significantly different ($p=0.54$).

It is possible that participants became familiar to the appearance of a red bar after the first occurrence and started anticipating it during the remainder of the drive. It was also noteworthy that the duration of interaction with the system in the first task (playing music) was longer than for the following tasks, particularly reading the text messages, and results may demonstrate that it was easier to manage these tasks.

3.2.2 Car following

This section presents results from the first section of the drive where participants were asked to perform two music related tasks using Android Auto (play a song on Spotify and a BBC iPlayer Radio station) while following a white car ahead of them.

3.2.2.1 *Speed*

Figure 5 presents average speed while performing the music related tasks, where the black points are the average speeds for individual participants and the red point shows the sample mean for the three drives (control, voice and touch). It must be noted that to highlight the variability in average speed, the y-axis begins at 40mph.

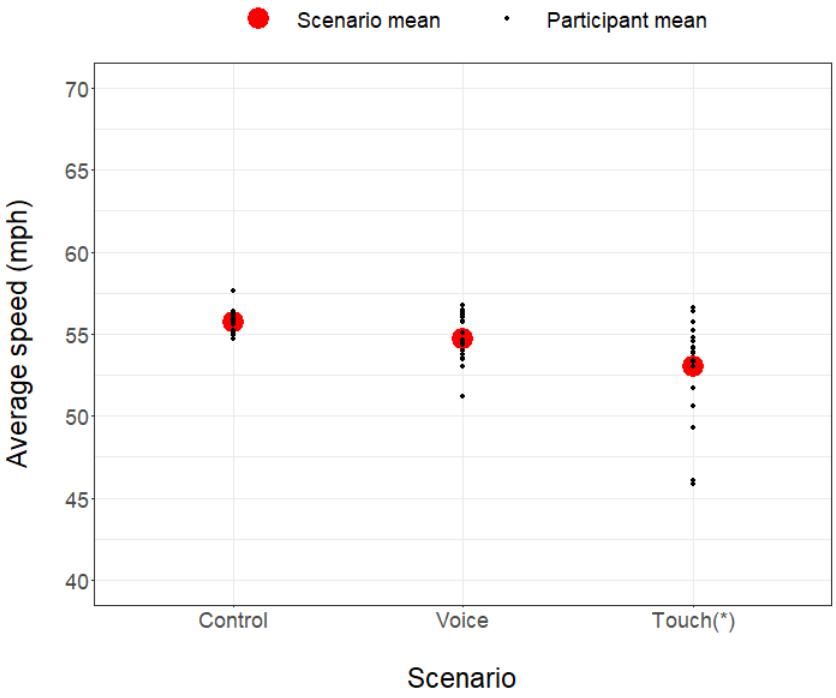


Figure 5: Average speed (mph) while performing music related tasks

Overall, the average speed during the control drive was the highest (55.7mph) followed by voice (54.7mph) and touch (53mph). Statistical tests found a significant difference in average speeds between the three scenarios ($p<0.05$) with a medium effect size of 0.25. There was a significant difference in average speed between the control and touch drives ($p<0.05$).

Average speeds for participants in the control drive show the least amount of variation compared with voice and touch. The average speed of individual participants in the touch drive varied from 46mph to 57mph. This may suggest that drivers needed to reduce their speeds while interacting with the in-vehicle device using touch in order to compensate for the additional task of playing music.

3.2.2.2 *Headway*

During the car following sections, participants were asked to maintain a constant distance between their vehicle and the car in front. Figure 6 presents the sample mean headway across the three scenarios (in red) and for individual participants (black points).

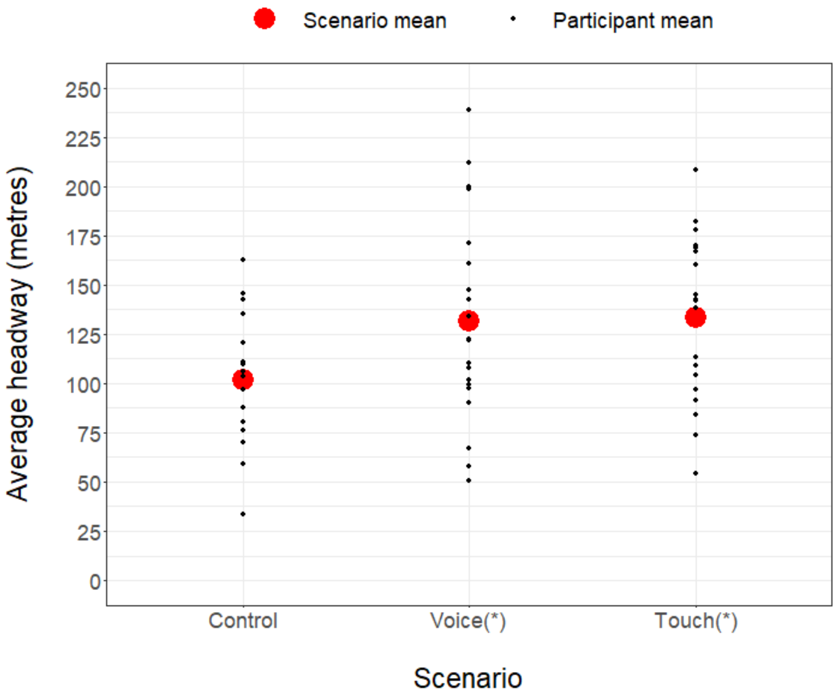


Figure 6: Average headway (m) while performing music related tasks

The average headway was the lowest for the control drive (101m), followed by voice (131m) and the highest for the touch drive (133m). Statistical tests showed that the average headway for both voice and touch drives was significantly ($p<0.05$) different to the control drive with a medium effect size of 0.12.

Figure 7 shows the standard deviation of headway within each drive. This metric helps understand whether participants were able to maintain a constant distance to the car in front; a higher value suggests participants were unable to maintain a constant distance.

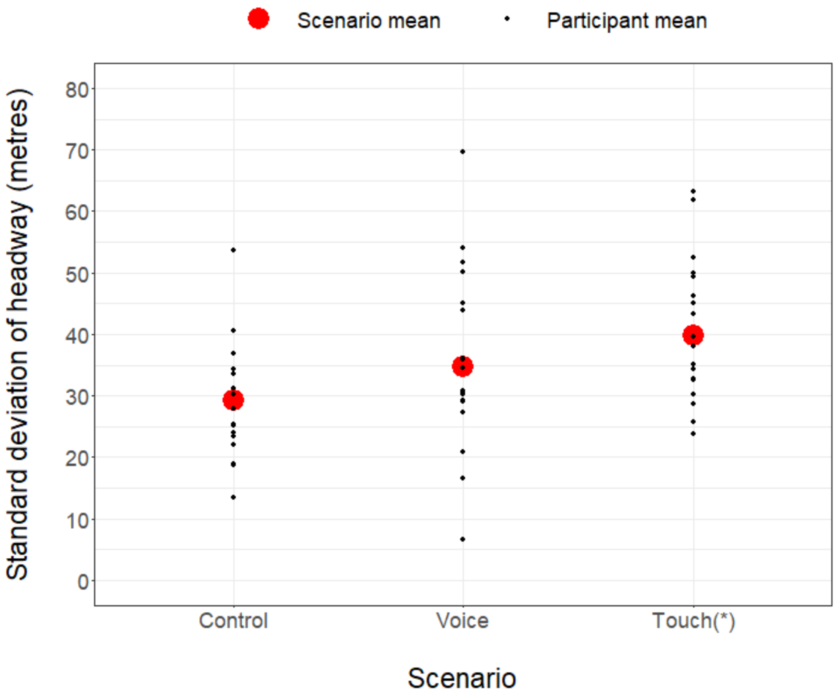


Figure 7: Standard deviation of headway (m) while performing music related tasks

The standard deviation in headway was highest for the touch drive (39m), followed by the voice drive (34m) and the lowest for the control drive (29m). This suggests that while interacting with Android Auto using touch to play Spotify or BBC iPlayer Radio, participants were unable to maintain a constant distance to the vehicle ahead of them.

Statistical tests showed that the standard deviation in headway was significantly different between scenarios ($p<0.05$) with a medium effect size of 0.11. Post hoc comparison showed that the touch drive was significantly different to the control drive ($p<0.05$).

3.2.2.3 *Lane position*

Lane position is a critical measure to understand variation in participants' vehicle position within a lane while performing tasks using voice or touch commands. The standard deviation in lane position shows whether participants were able to maintain a constant position within a given lane. A higher standard deviation suggests greater movements in the lane.

Figure 8 shows the standard deviation of lane position within each drive for every participant and every lane (blue points) and the sample mean for the three drives (red points).

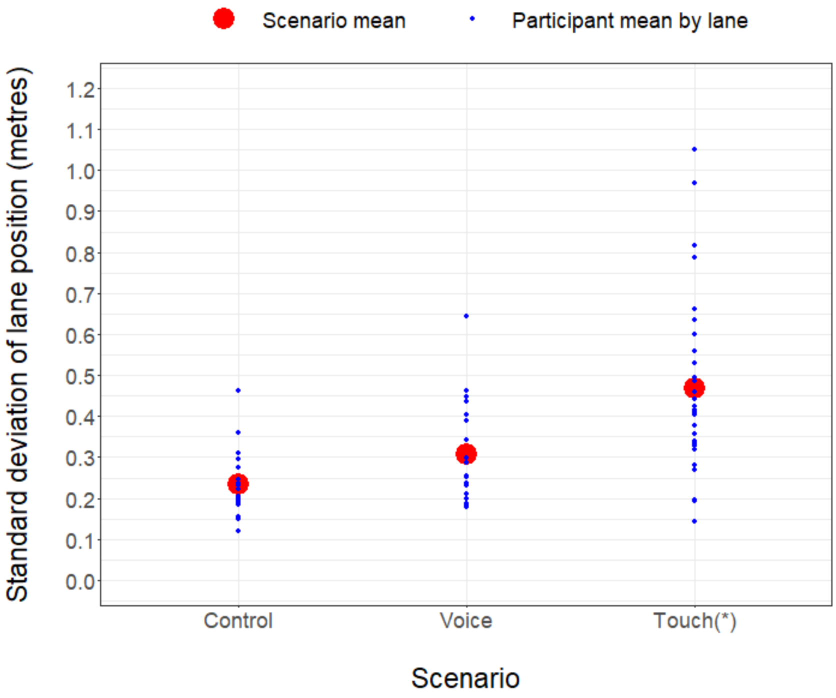


Figure 8: Standard deviation of lane position while performing music related tasks

The standard deviation of lane position was higher for the touch drive (0.46m) compared with the voice (0.3m) and control drives (0.23m). The standard deviation in lane position for individual participants (shown by the blue points) varied more in the touch drive, compared with the voice and control drives. This difference was statistically significant ($p<0.05$) with a large effect size of 0.26. Statistical tests showed that standard deviation in lane position for the touch drive was significantly different to the control ($p<0.05$) whereas there was no difference between voice and control ($p=0.24$).

This suggests that participants found it difficult to maintain a constant lane position while interacting with Android Auto using the touch feature, although no difference was found when using voice controls.

3.2.2.4 *Self-reported performance*

Participants were asked to subjectively rate (from 1=not well to 7=extremely well) how well they drove in the car following scenario. On average, participants gave the highest rating for the control drive (mean=5.5, sd=1.1), followed by voice (mean=4.3, sd=1.5) and touch (mean=3.5, sd=1.6). Statistical tests showed that self-reported scores for both voice and touch drives were significantly different to the control drive ($p<0.05$) with a large effect size of 0.42.

When asked to rate how easy or difficult they found each music-related task to be (from 1=easy to 7=difficult), participants found playing music using touch (mean=4.9, sd=1.4) to be more difficult than voice (mean=3.8, sd=1.7). This difference was statistically significant ($p<0.05$).

When asked to subjectively rate how distracting they found each task to be (from 1=not at all distracted to 7=completely distracted), participants reported interacting with Android Auto using touch (mean=5.7, sd=0.8) to be more distracting than voice (mean=4.1, sd=1.5). This difference was statistically significant ($p<0.05$).

Participants' self-reported rating of their driving performance for the three drives aligned with the driver behaviour metrics recorded from the simulator. This suggests that drivers have some awareness of the effect that the interaction with the system has on their driving performance.

3.2.3 Erratic traffic

This section focuses on the second part of the drive where participants drove through erratic motorway traffic. During this section of the drive, participants were asked to perform two navigation related tasks (navigate to a train station and to the nearest petrol station/restaurant). As stated in Section 3, results presented below focus on timing windows during the drive where the tasks were being performed, rather than the whole section.

3.2.3.1 *Speed*

Figure 9 presents the average speed for each participant (black points) and the sample mean for the three scenarios (control, voice and touch) (red points). It must be noted that to highlight the variability in average speed the y-axis begins at 40mph.

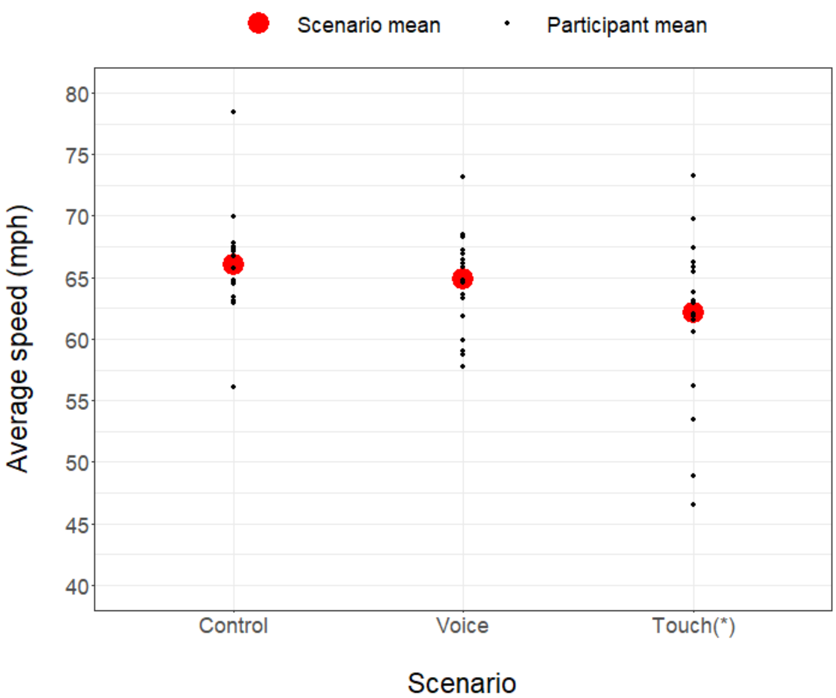


Figure 9: Average speed (mph) while performing navigation related tasks

The average speed for the control drive was the highest (66mph) followed by voice (64mph) and touch (62mph). Participants' average speeds (shown by the black points) showed the highest variation in the touch drive compared with the voice and control drives. This suggests that participants drove slower while interacting with Android Auto using touch as compared with voice or the control drive.

This result was statistically significant ($p<0.05$) with an effect size of 0.12. Statistical tests showed that average speed in touch was significantly different to the control drive ($p<0.05$).

The standard deviation of speed was about 3.5mph for the control drive, 4.7mph for voice and 5.5ph for the touch drive. Statistical tests showed that the result was significant with a very small effect size of 0.06, and the deviation in speed for the touch drive was significantly different to the control ($p<0.05$).

3.2.3.2 *Lane position*

The standard deviation of lane position was around 0.5 metres for all three scenarios. Statistical tests showed that the differences were not significant ($p=0.57$).

These results suggest that there was no difference in lane position between the three drives, however, the nature of this section of the drive required multiple lane changes that may mask variations in this metric.

3.2.3.3 *Self-reported performance*

Participants were asked to subjectively rate (from 1=not well to 7=extremely well) how well they drove in the erratic driving scenario. Participants reported better driving performance in the control drive (mean=5.2, sd=1.5), followed by voice (mean=3.9, sd=1.4) and touch (mean=2.9, sd=1.5). Statistical tests showed that both voice and touch were significantly different to control ($p<0.05$) with a large effect size of 0.6.

Participants' self-reported level of difficulty while performing the navigation related tasks was higher when using touch (mean=5.0, sd=1.7) compared with voice (mean=2.8, sd=1.6). This difference between voice and touch was statistically significant ($p<0.05$).

When asked about their level of distraction while performing each navigation related task, participants reported higher levels of distraction when using touch (mean=5.7, sd=1.5) than voice (mean=3.5, sd=1.5). This difference between voice and touch was statistically significant ($p<0.05$).

3.2.4 Loop

This section presents the results from the third part of the drive where participants received a series of texts and were asked to make a call, while driving on a highway in a figure of eight loop. During the call, participants were asked to recall items akin to a shopping list sent in the first text.

3.2.4.1 *Speed*

In this section of the drive, the posted speed limit was 40mph. The average speeds while reading texts and making a call are presented in Figure 10.

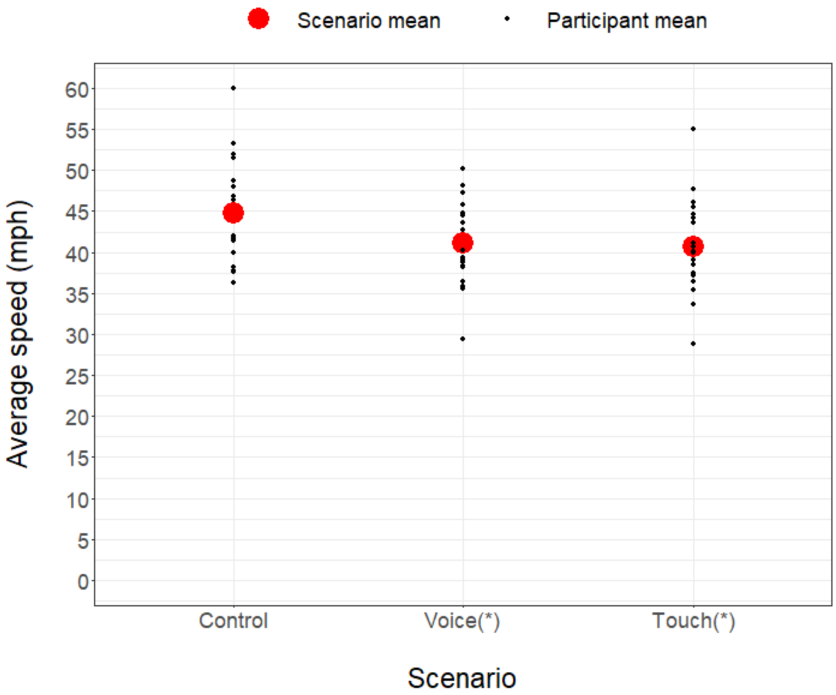


Figure 10: Average speed while reading texts and making a call

While interacting with the infotainment system during this section, the average speed was the highest for the control drive (44mph), followed by voice (41mph) and the touch drive (40mph). This difference was statistically significant with a small effect size of 0.06. Post hoc comparisons showed that both voice and touch were significantly different to the control drive ($p<0.05$).

This suggests that participants slowed down while interacting with Android Auto using the touch-enabled system.

The standard deviation of speed while reading texts and making a call is shown in Figure 11.

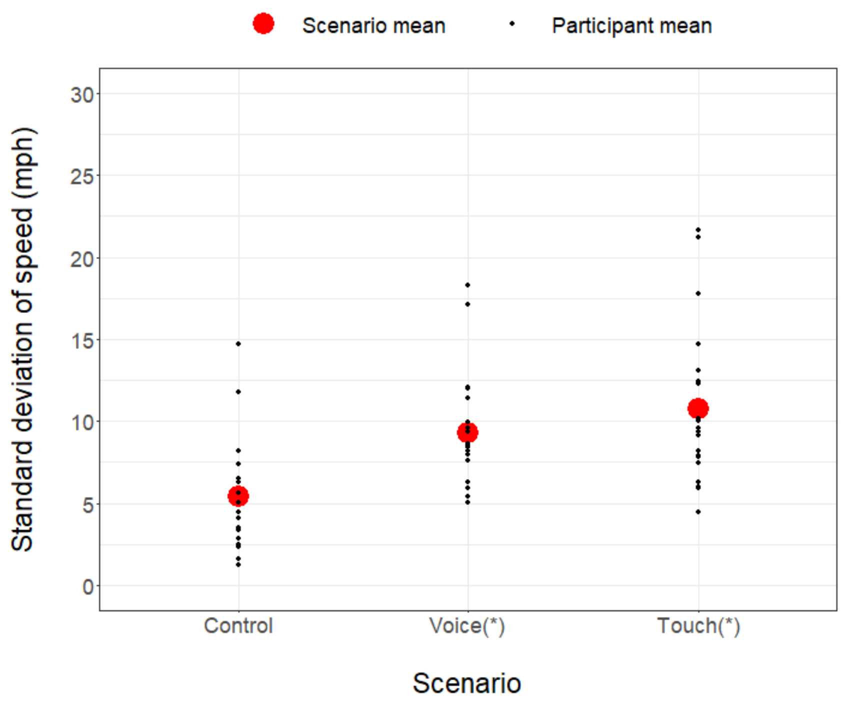


Figure 11: Standard deviation of speed while reading texts and making a call

The standard deviation of speed was similar between the three scenarios: touch (5.9mph), voice (5.5mph) and control (5.3mph). This difference was not statistically significant (p=0.68).

3.2.4.2 *Lane position*

The standard deviation of lane position is shown in Figure 12.

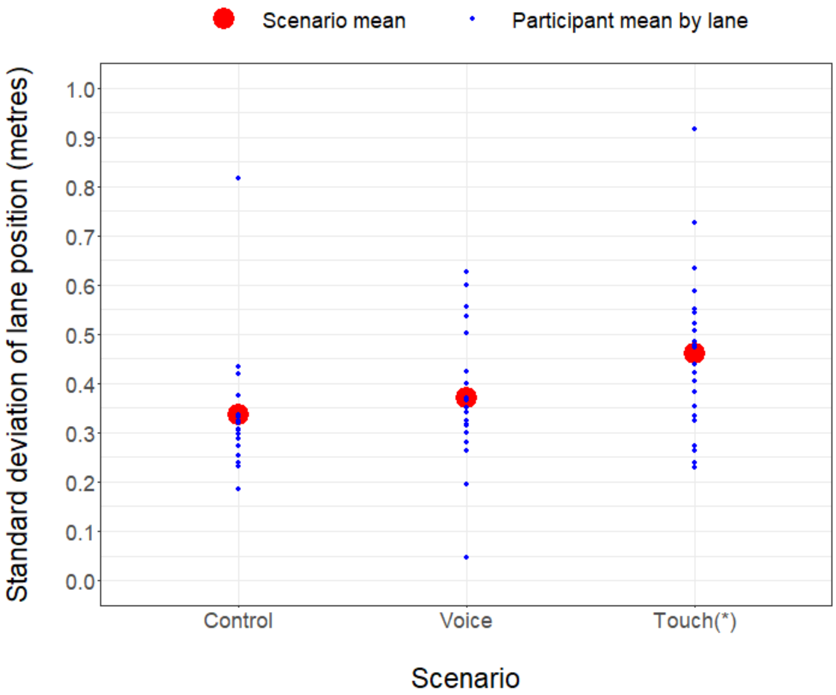


Figure 12: Standard deviation of lane position while reading texts and making a call

The touch drive showed the largest standard deviation of 0.46m, followed by voice (0.37m) and control (0.33m). This difference was statistically significant ($p<0.05$) with a medium effect size of 0.12. Post hoc comparison showed that standard deviation of lane position during the touch drive was significantly different to the control ($p<0.05$).

3.2.4.3 *Self-reported performance*

Participants reported better driving performance for the control drive (mean=5.3, sd=1.1) followed by voice (mean=4.4, sd=1.1) and touch (mean=3.4, sd=1.8). Statistical tests showed this difference to be significant ($p<0.05$) with an effect size of 0.4. Post hoc comparisons showed that both touch and voice were significantly different (and lower) than the control drive.

Self-reported level of difficulty to perform text and call related tasks was not found to be statistically significant between the touch and voice control drives.

In addition, participants were asked to subjectively rate their perceived level of distraction as they interacted with Android Auto to perform the tasks of reading texts and making a call. There was no significant difference in level of distraction between voice and touch.

3.2.4.4 *Number of items recalled*

During the third section of the drive, participants received a series of texts asking them to pick-up a number of items from the grocery store (items mentioned in section 2.3.2). The participants were then asked to call the researcher and recall the items that were mentioned in the texts. A summary of the number of items recalled is shown in Figure 13.

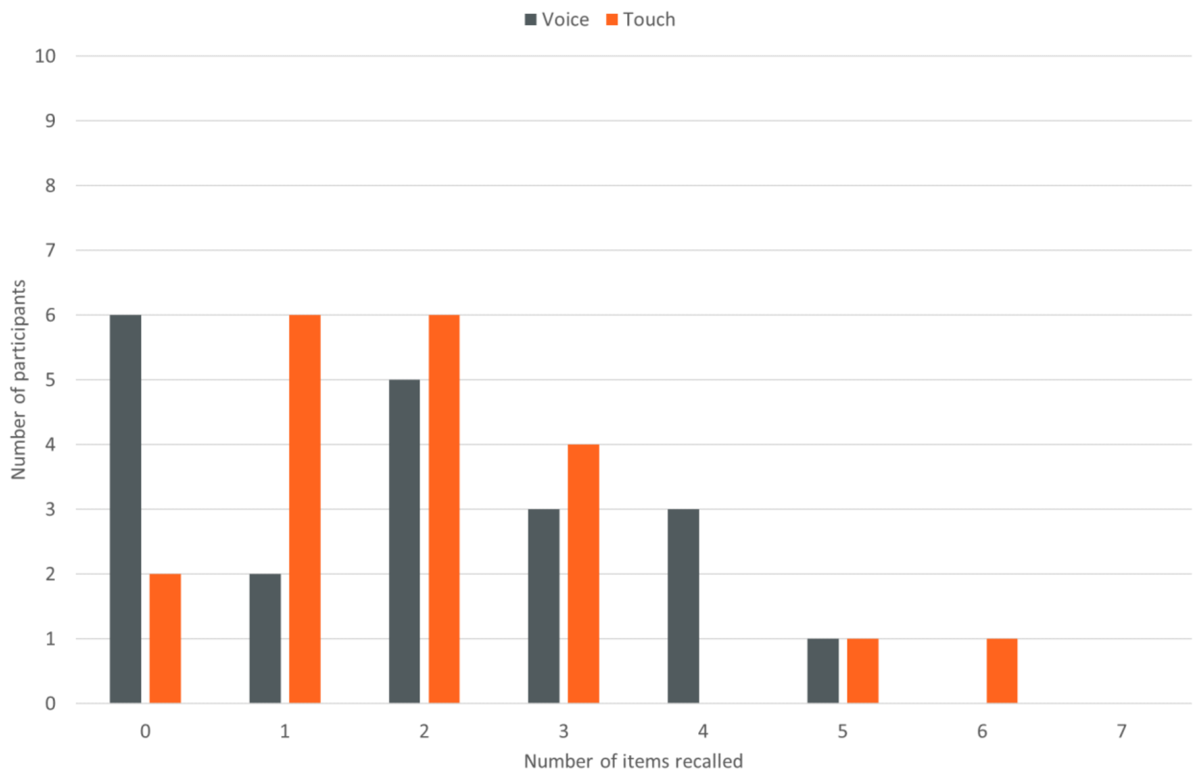


Figure 13: Number of items recalled

Twelve participants could recall one or two items in the touch drive. About 11 participants recalled between two to four items in the voice drive. For the voice drive, six participants could not recall any of the items and one recalled six items. On the other hand, for the touch drive, one participant recalled six items whereas two could not recall any items.

Participants were asked to report how easy or difficult (1=easy, 7=difficult) they found it to recall items after both voice and touch drives. In both drives, participants found it difficult to recall items: touch (mean=6.0, sd=1.1) and voice (mean=5.2, sd=1.66). This difference was not statistically significant (p=0.16). Additionally, when asked about the level of distraction associated with recalling items (1= not at all distracted, 7= completely distracted), participants reported similar levels of distraction for both touch (mean=5.1, sd=1.5) and voice (mean=4.5, sd=1.6) drives. The differences were not statistically significant.

3.2.5 Self-reported performance

Participants were asked some general questions about their driving at the end of each drive (control, voice and touch). Participants were asked to rank each of the following statements:

- Overall: I drove much worse than usual (1) to I drove much better than usual (7)
- Speed: I drove much slower than usual (1) to I drove much faster than usual (7)

- Distraction: I was much more distracted than usual (1) to I was much less distracted than usual (7)[2]
- Eyes on road: I kept my eyes on the road much less than usual (1) to I kept my eyes on the road much more than usual (7)
- Reaction to surroundings: I reacted to my surroundings much slower than usual (1) to I reacted to my surroundings much faster than usual (7)

Figure 14 presents the results for the three drives.

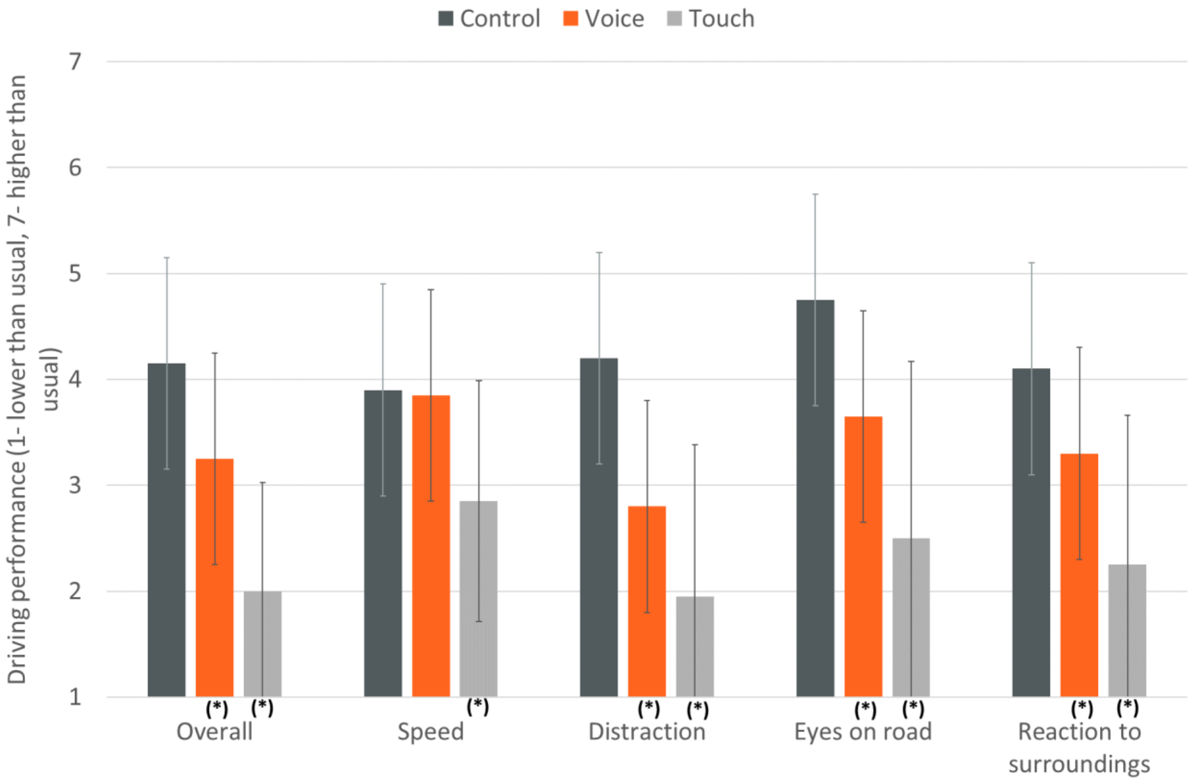


Figure 14: Overall driving performance (with standard deviation)

Across all performance measures, the participants' response for the control drive averaged at a score of 4 or 5 – this is to be expected and suggests drivers felt they drove no better or worse than usual during the control drive. However, participants' responses to all performance measures for the voice and touch drives were much lower than the control drive, apart from speed where there was no difference between voice and control drives. For instance, for the touch drive, participants thought they drove much worse, overall, than usual. Additionally, they thought they were more distracted than usual, had lower speeds, kept their eyes on the road less and reacted more slowly to their surroundings.

[2] This scale has been reversed for analysis and reporting and was worded as "I was much less distracted than usual (1) to I was much more distracted than usual (7)" to be consistent with the other questions in the questionnaire.

3.2.6 *Eye tracking analysis*

The amount of time drivers diverted their attention from the road ahead when undertaking a task was calculated by observing recording of their eye gaze direction. Table 3 shows the average time spent looking at the infotainment system for each task in the touch and voice drives for Android Auto.

Table 3: Mean time (seconds) spent looking at the infotainment system (measured and self-reported)

	Task	Android Auto (recorded)	Android Auto (self-reported)
Touch	Spotify task	**20**	11
	Radio task	**16**	12
	Navigation to railway station	**16**	13
	Navigation to restaurant/petrol station	**21**	13
	Reading first text	5	6
	Reading second text and making a call	**29**	7
Voice	Spotify task	4	4
	Radio task	6	5
	Navigation to railway station	4	5
	Navigation to restaurant/petrol station	4	4
	Reading first text	5	5
	Reading second text and making a call	9	4

Note: Bold red text denotes those that do not meet NHTSA guidelines

The recorded results were assessed against the NHTSA guidelines mentioned in section 2.3.3.

As total duration of eyes off the road and number of glances off the road have been recorded, average duration per glance could be calculated. However, the actual duration of each fixation was not calculated. Therefore, it cannot be judged if the first NHTSA criterion was met.

The second criterion states that the average duration of all fixations away from the road must be less than two seconds. This was met for all tasks across touch and voice drives. The last criterion states that the sum of all fixations away from the road should be less than 12 seconds. As seen from the text in bold and red in Table 3, this has not been met for almost all tasks completed by touch for Android Auto.

Participants were also asked to estimate the amount of time spent looking away from the road whilst performing each task. The results are also presented in Table 3 alongside the observed results. When it comes to interacting with the device using touch screen, participants underestimated the amount of time they thought they spent looking away from the road. Furthermore, some of the estimates made by the participants using Android Auto with touch screen did not meet the NHTSA criteria (for instance, both the navigation-related tasks).

When using the voice activation feature, participants were fairly accurate in their estimation, and participants met the NHTSA criteria.

3.3 Apple CarPlay

This section presents the results for the 19 participants[3] who completed the two drives while interacting with Apple CarPlay infotainment system and the control drive.

As mentioned in Section 3, the analysis only focuses on the defined period of interest around tasks where participants were directly interacting with the system rather than the entire drive or section.

3.3.1 Reaction time

In total there were 76 reaction time events (red bars) (19 participants with four responses each). Participants failed to respond to the red bar 14 times in the touch drive, eight times in the voice drive and twice in the control drive. McNemar's test showed a significant difference in the number of missed reactions between the control and touch drive ($p<0.05$). This suggests that interacting with Apple CarPlay using touch interfered with participants' ability to respond to the red bars.

Figure 15 presents the reaction times for the first task (playing a song on Spotify) using Apple CarPlay.

[3] One participant had to be excluded from the analysis due to missing data.

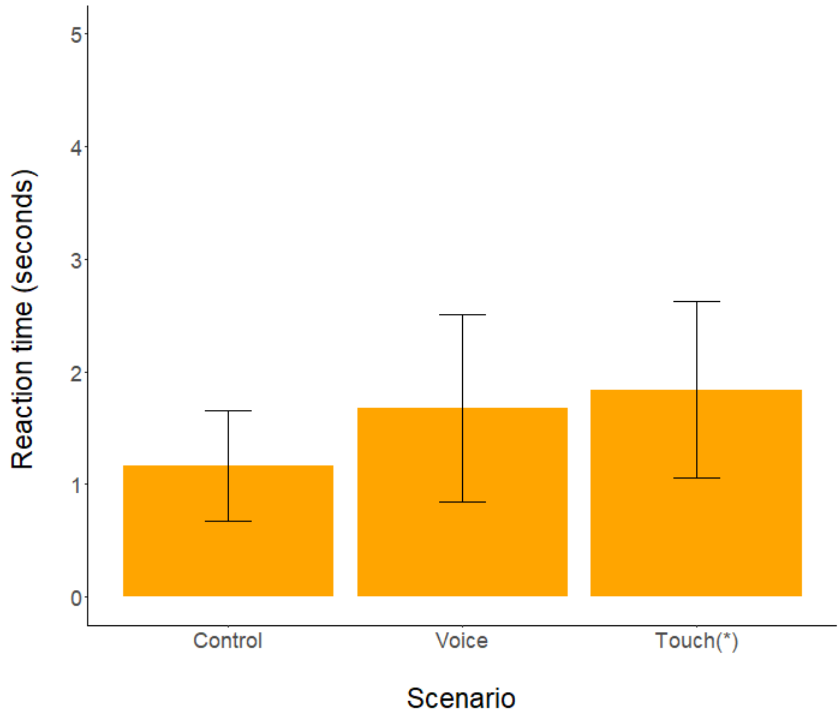


Figure 15: Reaction time for playing a song on Spotify using Apple CarPlay (with standard deviation)

On average, the reaction time to the red bar during the touch drive was the highest (1.8 seconds), followed by the voice drive (1.7 seconds) and control drive (1.2 seconds). Statistical tests showed a significant difference in reaction times ($p<0.05$) with a medium effect size of 0.14. Post hoc comparison showed that reaction times for the touch drive were significantly different to the control drive ($p<0.05$). This suggests that interaction with the infotainment system led to a slower reaction time for the touch drive compared with the control drive.

Figure 16 shows the reaction time to the red bar during the task of navigating to the nearest train station.

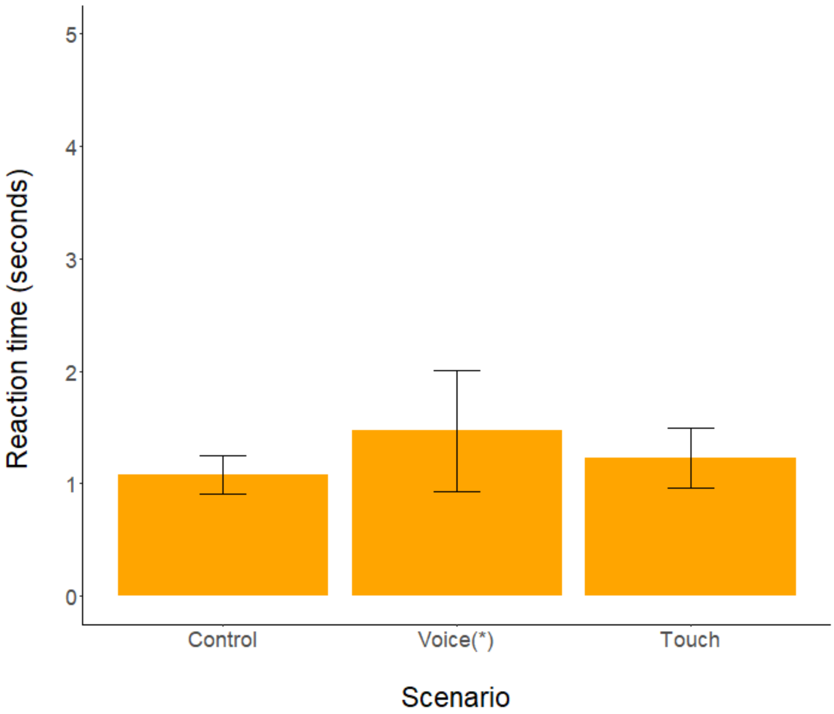


Figure 16: Reaction time for the navigation task (with standard deviation)

The average reaction time for the voice drive was the highest at 1.5 seconds, 1.2 for touch and the lowest for control drive at 1.0 seconds. Statistical tests showed that this difference was statistically significant ($p<0.05$) with an effect size of 0.16. Post hoc comparison showed that the difference between control and voice was significant ($p<0.05$).

The average reaction time for the third red bar (during the reading of the first text) was similar (roughly 1.3 seconds) across all three scenarios. Statistical tests showed no significant difference between the three scenarios ($p=0.36$).

The average reaction time for the fourth red bar (during the reading of the second text and making a call) was around 1.2 seconds for all three scenarios. Statistical tests showed these results were not significantly different ($p=0.08$).

As with Android Auto, results may represent both a learning and task related effect.

3.3.2 Car following

This section presents results from the first section of the drive where participants were asked to perform two music related tasks using Apple CarPlay (play a song on Spotify and a BBC iPlayer Radio station) while following a white car ahead of them.

3.3.2.1 *Speed*

Figure 17 presents average speed while performing the music related tasks, where the black points are the average speeds for individual participants and the red point shows the sample mean for the three drives (control, voice and touch). It must be noted that to highlight the variability in average speed, the y-axis begins at 40mph.

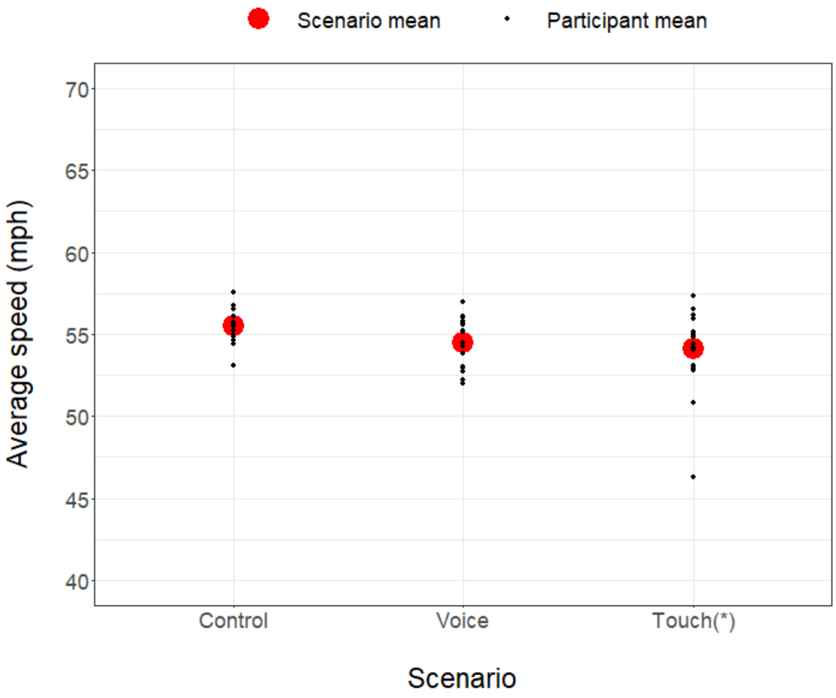


Figure 17: Average speed (mph) while performing music related tasks

Overall, the average speed during the control drive was slightly higher at 55mph compared with the voice and touch drives at 54mph. Statistical tests showed that this difference was significant ($p<0.05$) with a small effect size of 0.07. Post hoc comparison showed that touch was significantly different to control ($p<0.05$). This is due to the greater amount of variation in average speed between participants in the touch drive (as shown by the black points).

The standard deviation of average speed was about 7mph for all three drives and the difference was not significant ($p=0.32$).

3.3.2.2 *Headway*

The average headway was highest at 135m for the touch drive, 131m for the voice drive and the lowest at 114m for the control drive. However, these differences were not statistically significant ($p=0.17$).

The standard deviation in headway (shown in Figure 18) helps understand if participants were able to maintain headway while interacting with Apple CarPlay. The black points present the average headway for each participant, whereas the red points present the scenario mean.

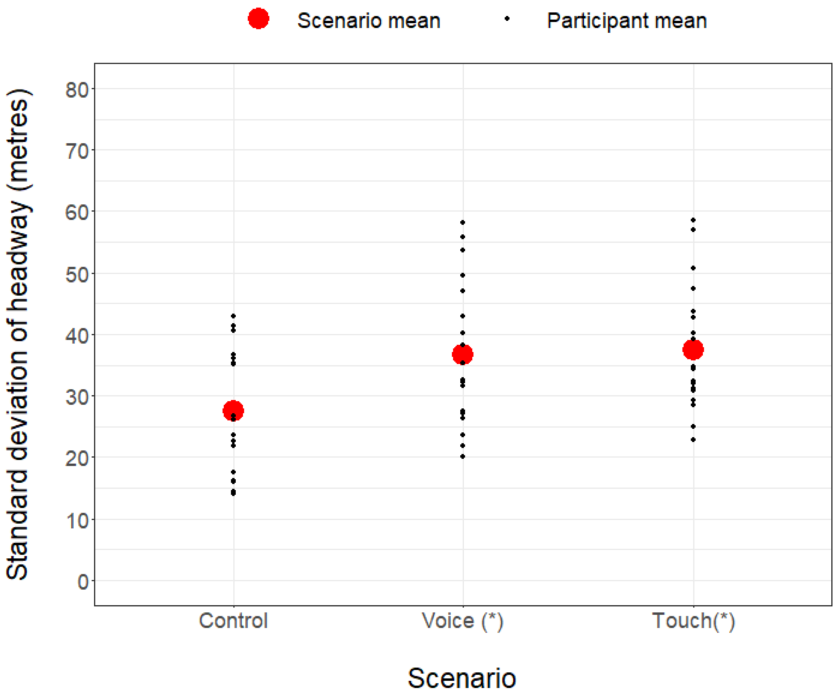


Figure 18: Standard deviation of headway (m) while performing music related tasks

The standard deviation in headway was comparatively higher for touch and voice (37m) compared with the control drive with a standard deviation of 27m.

Statistical tests showed that the standard deviation in headway was significantly different between scenarios ($p<0.05$) with an effect size of 0.15. Post hoc comparison showed that both voice and touch drives were significantly different to the control drive ($p<0.05$). This indicates that participants were unable to maintain a constant distance to the vehicle in front of them while interacting with Apple CarPlay to play music or the radio.

3.3.2.3 *Lane position*

Figure 19 shows the standard deviation of lane position within each drive for every participant and every lane (blue points) and the sample mean for the three drives (red points).

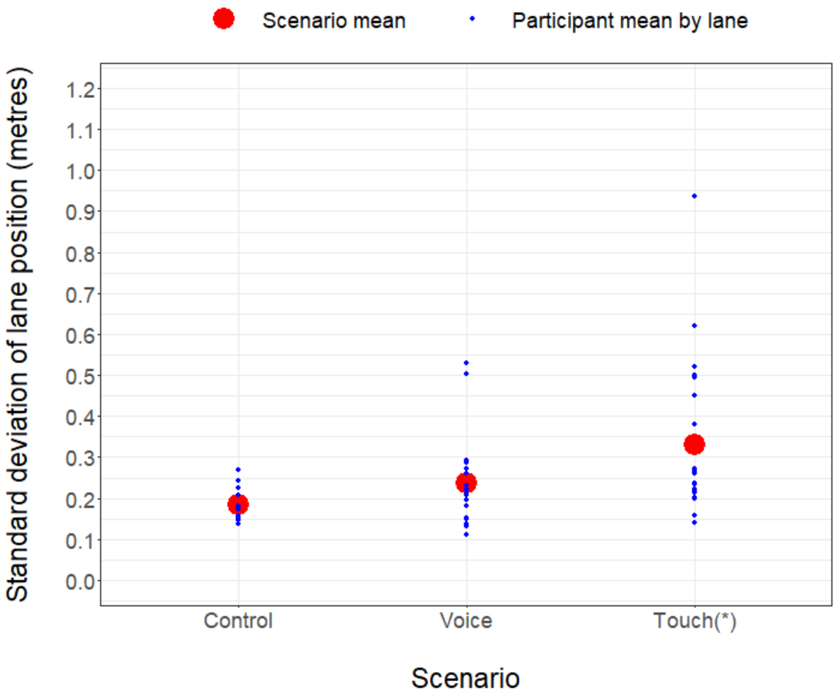


Figure 19: Standard deviation of lane position while performing music related tasks

The standard deviation in lane position was higher for the touch drive (0.3m) compared with voice and control at approximately 0.2m. These differences were significant (p<0.05) with an effect size of 0.16. Statistical tests showed that the standard deviation in lane position for the touch drive was significantly different to the control drive (p<0.05), however, there was no difference between the voice and the control drive (p=0.28). The data suggest that participants showed greater variation in lane position within their drives.

While drivers reduced their speed while interacting with Apple CarPlay using touch, they were unable to maintain a constant headway and position within their lane during this section of the drive.

3.3.2.4 *Self-reported performance*

Participants reported slightly better driving performance for the control drive (mean=5.2, sd=1.3) followed by voice (mean=4.7, sd=1.3) and touch (mean=4.6, sd=1.3). Statistical tests and post hoc comparisons showed that both voice and touch were significantly different to control drive (p<0.05) with an effect size of 0.11.

When asked about the level of difficulty, participants found touch (mean=3.7, sd=1.8) to be more difficult than voice (mean=2.8, sd=1.6), however the differences were not significant (p=0.09).

In addition, participants were asked to subjectively rate their perceived level of distraction as they interacted with Apple CarPlay to perform music related tasks. Participants reported touch (mean=4.5, sd=1.3) to be more distracting than voice (mean=3.2, sd=4.5), and these differences were significant (p<0.05).

3.3.3 Erratic traffic

This section focuses on the second part of the drive where participants drove through erratic motorway traffic. In this section, they performed two navigation related tasks (navigating to the nearest railway station and to the nearest restaurant/petrol station).

Results presented below focus on timing windows during the drive where the tasks were being performed, rather than the whole section.

3.3.3.1 Speed

While using Apple CarPlay to navigate to different destinations, the average speed was the highest for control at 66mph, followed by voice (64mph) and touch (62mph). However, statistical tests showed that these differences were not significant (p=0.06). The standard deviation of speeds was about 4mph for voice and control, and 6mph for touch. These differences were not significant (p=0.08).

3.3.3.2 Lane position

The standard deviation of lane position was around 0.5 metres for all three scenarios. Statistical tests showed that the differences were not significant (p=0.26).

These results suggest that there was no difference in lane position between the three drives, however, the nature of this section of the drive required multiple lane changes that may mask variations in this metric.

3.3.3.3 Self-reported performance

Similar to the results from the previous section, participants reported better driving performance in the control drive (mean=5.3, sd=1.3), followed by voice (mean=4.5, sd=1.3) and touch (mean=3.4, sd=1.8). Statistical tests showed that both voice and touch were significantly different to the control drive (p<0.05) with a large effect size of 0.5.

Participants' self-reported level of difficultly while performing the navigation related tasks was significantly (p=0.05) higher when using touch (mean=3.8, sd=2.1) compared with voice (mean=2.5, sd=1.4).

When asked about their level of distraction while performing each navigation related task, participants reported significantly higher (p<0.05) levels of distraction when using touch (mean=4.5, sd=1.6) than voice (mean=3.2, sd=1.5).

3.3.4 Loop

The third, and final, section of the drive required participants to drive through a figure of eight loop. In this section, participants received a series of texts and made a phone call during the drive. During the call, participants were asked to recall items akin to a shopping list sent in the first text.

3.3.4.1 *Speed*

In this section of the drive, the posted speed limit was 40mph. The average speed was around 38mph for the control drive, 40mph for the voice drive and 38mph for the touch drive. These differences were not statistically significant (p=0.64).

Standard deviation of speed was, on average, 4mph for all three drives. There was no significant difference between the three drives (p=0.8).

3.3.4.2 *Lane position*

Figure 20 presents the standard deviation of lane position while interacting with Apple CarPlay to read texts and make calls.

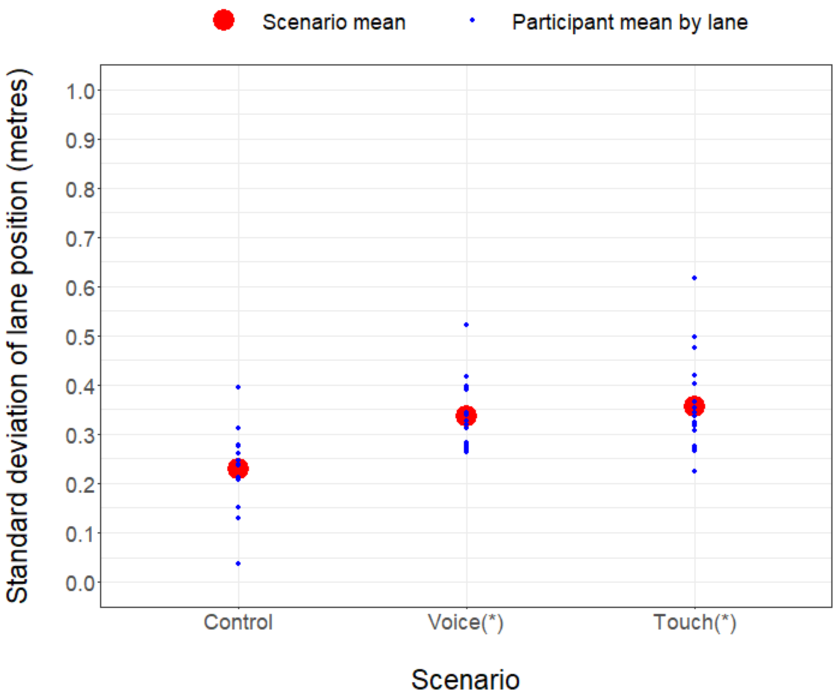


Figure 20: Standard deviation of lane position while reading texts and making calls

Overall, the standard deviation of lane position was higher for the touch (0.35 metres) and voice drives (0.33 metres) compared with the control drive (0.23 metres). These results were statistically significant (p<0.05) with a medium effect size of 0.20. Post hoc analysis showed that both voice and touch were significantly different to control (p<0.05).

These results suggest that while interacting with Apple CarPlay to read texts and make a call, participants were unable to maintain lane position in both voice and touch drives compared with the control drive.

3.3.4.3 *Self-reported performance*

Participants reported better driving performance in the control drive (mean=5.5, sd=1.0), followed by voice (mean=4.5, sd=1.3) and touch (mean=4.3, sd=1.7). Statistical tests showed that both touch and voice were significantly different to the control drive ($p<0.05$) with a large effect size of 0.27.

Self-reported level of difficulty to perform text and call related tasks was not found to be statistically significant between the touch and voice control drives. When asked about their level of distraction, participants reported no statistically significant differences between voice and touch drives ($p=0.3$).

3.3.4.4 *Number of items recalled*

During the third section of the drive, participants received a series of texts asking them to pick-up a number of items from the grocery store (items mentioned in Section 2.3.2). The participants were then asked to call the researcher and recall the number of items that were mentioned in the texts. Figure 21 shows summary statistics of the number of items recalled.

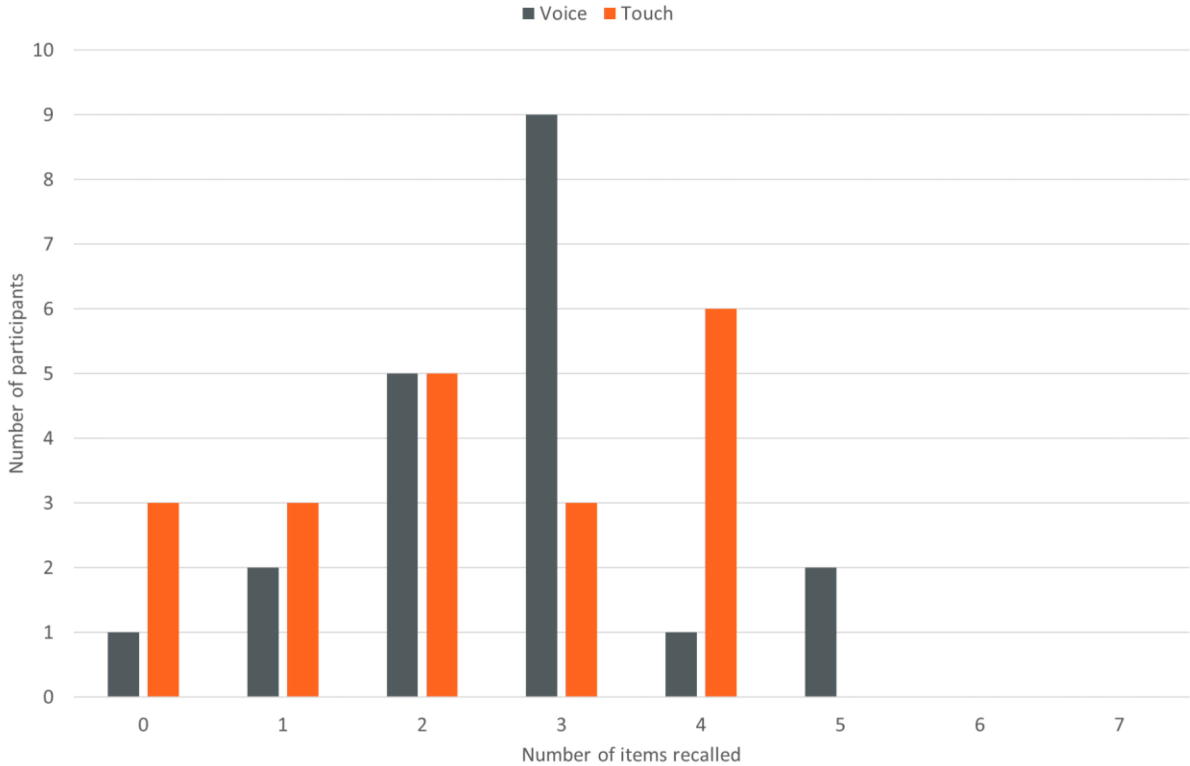


Figure 21: Number of items recalled

Nine of the participants recalled 3 items in the voice drive and six recalled 4 items in the touch drives. There was one participant who recalled none of the items and two who recalled 5 items in the voice drive. On the other hand, three participants could not recall any of the items in the touch drive and six recalled four items.

When asked about the level of difficulty, participants provided similar scores for both drives and the differences were not significant ($p=0.8$). Similarly, the level of distraction was not significantly different between voice and touch drives ($p=0.9$).

3.3.5 *Self-reported performance*

Participants were asked to compare their driving performance during the three drives to their normal day-to-day driving. Participants were asked to rank each of the statements provided in Section 3.2.5.

Figure 22 presents the results for the three drives.

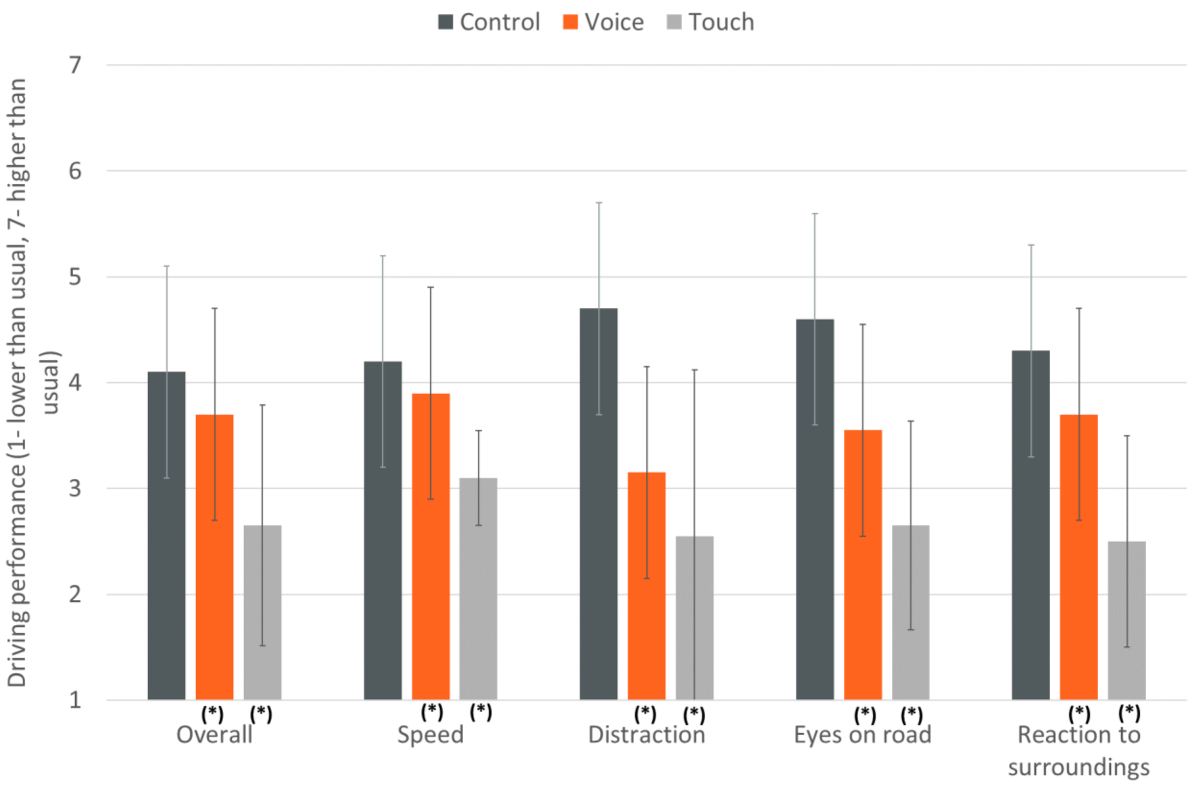


Figure 22. Self-reported driving behaviour (with standard deviation)

Overall, participants thought they drove better and were less distracted for the control drive compared with voice and touch. Additionally, participants thought they had their eyes on the road more often and were much more reactive to their surroundings for the control drive compared with the voice and touch drives. Statistical tests showed that their responses for the voice and touch drives were statistically significantly different ($p<0.05$) to the control drive on each measure, as shown by the asterisks in Figure 22.

3.3.6 *Eye tracking analysis*

The amount of time drivers diverted their attention from the road ahead when undertaking a task was calculated by observing recordings of their eye gaze direction. Table 4 shows the average time spent looking at the infotainment system for each task in the touch and voice drives for both Android Auto and Apple CarPlay.

Table 4: Mean time (seconds) spent looking at the infotainment system (measured and self-reported)

	Task	Apple CarPlay (recorded)	Apple CarPlay (self-reported)
Touch	Spotify task	**14**	5
	Radio task	11	5
	Navigation to railway station	10	5
	Navigation to restaurant/petrol station	**16**	6
	Reading first text	4	6
	Reading second text and making a call	**12**	5
Voice	Spotify task	7	3
	Radio task	6	3
	Navigation to railway station	5	3
	Navigation to restaurant/petrol station	3	3
	Reading first text	4	2
	Reading second text and making a call	6	3

Note: Bold and red text denotes those that do not meet NHTSA guidelines

The recorded results were assessed against the NHTSA guidelines mentioned in section 2.3.3.

The second criterion states that mean duration of all fixations away from the road must be less than two seconds duration. This was met for all tasks across touch and voice drives. The last criterion states that the sum of all fixations away from the road should be less than 12 seconds. As seen from the text in bold and red in Table 5, this has not been met for three tasks completed by touch for Apple CarPlay.

Participants were also asked to estimate the amount of time spent looking away from the road whilst performing each task and presented alongside the observed results. When it comes to interacting with the device using touch screen, participants underestimated the amount of time they thought they spent looking away from the road

When using the voice activation feature, participants underestimated their self-reported time compared with their actual time.

3.4 General opinions

At the end of the trial, participants were asked some questions regarding general driving behaviour and their opinion on certain regulations.

Of the 40 participants who took part in the two trials, 12 (30%) said they used their mobile phones whilst driving either once or twice per journey or more frequently. Ten participants (25%) said they used their phones for some journeys but not all journeys. The remaining 17 (43%) said they never use their phones while driving or only in emergency situations.

Participants were asked to select features of the infotainment system that they have used during their everyday driving. They were asked to select all features that applied to them and results are presented in Table 5.

Table 5: Number of participants that use different features of infotainment systems or a mobile phone by touch and voice control

	Via touch screen	Via voice activation	Not used
Sat Nav	35	17	2
Select music	34	13	3
Receive/respond to text	18	19	14
Make/receive phone calls	29	23	3
Social media activity	6	3	34
Other	3	1	36

NB participants chose all options that applied to them

In general, interacting with the infotainment system or mobile phones via touch screen was more common than via voice activation. The majority (87%) of the participants said they had used sat nav or music features using touch screen, whereas less than half (43%) of the participants has used sat nav using voice activation. A similar number of participants used voice activation or touch screen for texting and calling purposes. Other activities like social media, connecting to Bluetooth, vehicle settings etc. were used by a very small number of participants.

Participants were asked to rate, using a 7-point Likert scale, the extent to which they agreed (1) or disagreed (7) with some statements. The results are presented in Table 6.

Table 6: Level of agreement with general statements

To what extent do you agree or disagree with the following statements?	Average response 1 (strongly agree) to 7 (strongly disagree)
Some people can drive safely even when they are using a hand-held mobile phone at the same time	5.7
Taking chances and breaking a few rules does not necessarily make bad drivers	4.7
People stopped by the police for speaking on a hand-held mobile phone whilst driving are unlucky because lots of people do it	4.5
I never take risks whilst driving	2.6
I would be happier if the regulation around using mobile phones while driving was more strictly applied	1.9

On average, participants tended to disagree with statements ‘Some people can drive safely even when they are using a hand-held mobile phone at the same time’ and ‘Taking chances and breaking a few rules does not necessarily make bad drivers’. On the other hand, there was a greater level of agreement with statements ‘I never take risks whilst driving’ and ‘I would be happier if the regulation around using mobile phones while driving was more strictly applied’.

Participants were also asked how risky it would feel to perform certain tasks when compared with driving with full concentration. Using a 7-point Likert scale, participants were asked to provide a rating between 1 (not at all risky) and 7 (extremely risky). The average scores are presented in Table 7 below.

Table 7: Average risk rating whilst performing certain tasks

Compared with driving with full concentration, how risky would it feel to do the following whilst driving in free-flowing traffic?	Average risk rating 1 (not at all risky) to 7 (extremely risky)
Send a short text message on a hand-held phone	6.6
Read a text message on a hand-held phone	6.3
Send a short text message on a hands-free phone/infotainment system (via touch screen)	5.9
Input new destination details into sat nav on a hand-held phone	5.9
Read a text message on a hands-free phone/infotainment system	5.0
Input new destination details into sat nav on a hands-free phone/infotainment system	4.9
Look at a traffic accident that you are passing	4.8
Send a short text message on a hands-free phone/infotainment system (via voice activation)	4.6
Eat a packet of crisps	4.3
Open a bottle of water	4.2
Make or receive a phone call on a hands-free phone/infotainment system (via touch screen)	4.1
Select a different radio station on the car radio/infotainment system	3.5
Make or receive a phone call on a hands-free phone/infotainment system (via voice activation)	3.5
Talk to passengers in the vehicle	2.5

Participants gave sending or reading text messages on hand-held devices the highest average risk rating. It is interesting to note that talking to passengers in the vehicle had the lowest risk rating; interacting with an infotainment system to send a text via voice activation received a higher risk rating.

Participants were also presented with some statements and asked to identify whether those statements were legal or illegal. The results are summarised in Table 8.

Table 8: Views on illegal or legal statements

Do you think the following are legal or illegal?	Illegal	Legal	Answer
Making a call using a hand-held phone while driving	39	1	Illegal
Reading a text message on a hand-held phone whilst queuing in stationary traffic	38	2	Illegal
Using a hand-held phone as a passenger whilst supervising a learner driver	32	8	Illegal
Following a map on a hand-held phone whilst driving	22	18	Illegal
Receiving a call whilst driving without touching the phone	5	35	Legal

Almost all the participants said making a call using hand-held phones while driving or reading a text message on a hand-held phone whilst queuing in stationary traffic was illegal. On the other hand, most of the participants said that receiving a call hands-free while driving was legal.

3.5 Comparison with previous impairment studies

Earlier studies at TRL[4] have used the same impairment drive simulator route and a similar method to that applied in the current study to:

- Benchmark the relative performance impairment of mobile phone conversations while driving against that caused by alcohol consumption to the legal limit.
- Investigate the influence of cannabis on driving performance.
- Compare the effects of a range of everyday life driving conditions (e.g. music, children in the car) on driver performance.
- Investigate the effect of text messaging on driver performance.
- Investigate the effect of social media on driver performance.

All the previous studies used reaction time events to assess relative impairment to a control group, although the trigger stimuli and response mechanisms have differed slightly over time. While some caution is therefore necessary (also due to differences in time and samples), it allowed for some comparison of the relative impairment (experimental v control in each study). For example, Burns et al. (2002) found that reaction times were significantly higher in each of their three test conditions than in the control condition (12.4% higher when at the legal alcohol limit; 26.5% higher whilst talking on a handsfree phone; 45.9% higher whilst talking on a handheld phone). Sexton et al. (2000) found reaction times were 21% higher when drivers were under the influence of cannabis. Reed and Robbins (2008) found a mean increase of 34.7% to the visual stimulus when sending a text compared with the control drive.

[4] See Basacik et al. (2011); Parkes, Luke, Burns & Lansdown (2007); Reed & Robbins (2008); Sexton et al. (2000).

Figure 23 below shows the percentage change in reaction time for various driver impairment compared with the reaction time for the respective control drives. All the tasks that have statistically significantly higher reaction times in the current study have been added for comparison.

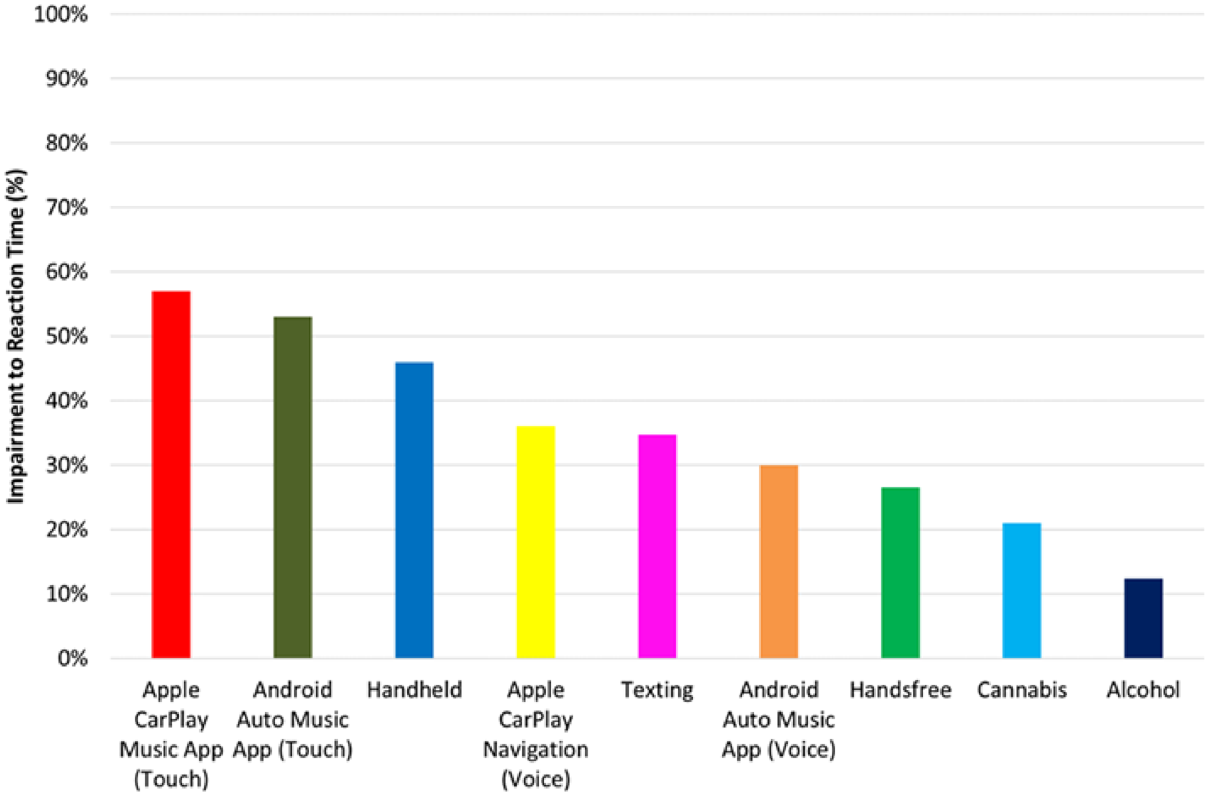


Figure 23: A comparison of the changes in reaction time caused by engaging in a range of activities while driving

In the current study, there was a mean increase of 53% and 30% in playing music on Spotify using touch and voice respectively on Android Auto. There was a mean increase of 57% for the same task using Apple CarPlay using touch. There was also a mean increase of 36% whilst interacting with Apple CarPlay using voice to navigate.

These results suggest that using touch control to select a song has a bigger impact on reaction time compared with all previous distraction measures studied. Furthermore, using voice control to complete the music related task with Android Auto is worse than alcohol and cannabis impairment, and handsfree conversations, but less detrimental than using a phone for handheld conversations and for texting. Using voice control on Apple CarPlay to navigate was also detrimental to reaction time and similar to the impairment caused by texting.

4 Discussion

The main purpose of this study was to investigate if using Google's Android Auto and Apple's CarPlay infotainment systems while driving affected driving performance in TRL's DigiCar simulator. Previous research suggests that these infotainment systems are easier to use when compared with native OEM in-car systems and reduce driver workload (Strayer et al., 2018). However, little is known about how these devices might affect driver performance and potentially cause driver distraction, that could subsequently impact road safety. To test this, two experimental trials were conducted in TRL's DigiCar following an established 'impairment route' during which drivers in each trial interacted with the infotainment systems.

4.1 Reaction Time

The main purpose of the red bar was to measure reaction time to an external stimulus whilst interacting with the infotainment system. Results showed that, for both infotainment systems, participants failed to react to red bars more often during the touch drive compared with the control drive. This presumably reflects the greater eyes-off-road time required when interacting with the system via touch control.

For both Android Auto and Apple CarPlay, there was a significant difference in reaction time between the three drives when participants were prompted to play music using the infotainment system. Reaction times for both voice and touch drives were significantly higher than the control when interacting with Android Auto. Reaction time for the touch drive was significantly higher than the control drive when interacting with Apple CarPlay (no difference was found for voice control). Participants using Apple CarPlay also showed a significant increase in reaction time during the voice drive when performing the navigation task.

The increased response time to red bar events, and increased failure to detect them at all, has clear implications for safety if considered to be indicative of external events requiring a driver's attention in the real world. At motorway speeds (as simulated), the increase in mean reaction time would result in an increased stopping distance between 18.7m and 24.9m (between four and five car lengths).

4.2 Driving performance

Key driver behaviour metrics such as speed, headway and lane position were analysed to compare when participants were interacting with the infotainment systems compared with the control drive. This provided a deeper understanding of the impact on driver performance when completing tasks.

When using either infotainment system, drivers tended to reduce their speed significantly in the touch drive while completing music and navigation related tasks. When using Android Auto, there was also a significant reduction in speed using either voice or touch control while performing the texting and calling tasks. This corresponds with the results of previous research (e.g. Reed & Robbins, 2008) which has established that participants tend to reduce their speed when distracted. The reduction in speed is indicative of drivers having taken on a secondary task causing additional demand. Humans have limited capacity to process information and driving generally requires a lot of attentional resources. When taking on an additional task while driving, drivers have to adapt their behaviour to manage the demand on their cognitive resources so that they do not become overloaded and lose control of the vehicle. Driver behaviour theory has noted how the primary mechanism for drivers to manage sensory demand when driving is speed. By slowing down, drivers open up some resource for undertaking a secondary task, while attempting to maintain a safety margin (Fuller, 2009). The data from the questionnaire supports that drivers were aware that their driving was impaired to some degree whilst engaged in the various tasks and chose to reduce their speed as a result. However, while drivers slow down to take on a secondary task, drivers' performance can often be found to deteriorate regardless. Both maintenance of the distance to the vehicle in front and lane position were affected when interacting with the infotainment systems, despite drivers having reduced speed when interacting with them.

Participants were asked to maintain a constant distance to the vehicle in front during the car following sections. Results showed that when interacting with Android Auto and Apple CarPlay using the touch feature, participants showed a significantly higher deviation of headway compared with the control drive. The lack of any other traffic in that part of the task meant that participants could afford to leave large safety margins whilst interacting with the infotainment system. However, in a real-world traffic situation, vehicles following may create pressure for a distracted driver to maintain progress relative to vehicles ahead, which in turn could decelerate more rapidly than was experienced in the simulator scenario.

Another change in driving performance was the standard deviation of lane position while interacting with the system. The music, texting and calling tasks revealed large increases in variability of lane position when interacting with both infotainment systems using the touch feature compared with the control drive. Furthermore, when using Apple CarPlay for texting and calling tasks, there was a significant increase in deviation of lane position for the voice feature compared with the control drive.

Taken as a whole, the findings indicate that interacting with either infotainment system results in a deterioration in driving performance. A reduction in speed was not enough of a mitigation for participants to maintain a constant headway or lane position. It should be noted, however, that voice control did not result in deterioration of driving performance to the same extent as touch control and suggests that performance is not as badly affected when the requirement to take eyes off the road is reduced.

4.3 Eye Gaze behaviour

Video data of drivers' faces were analysed to calculate the amount of time drivers diverted their gaze from the road ahead when completing a task. Additionally, participants were also asked to estimate the amount of time they thought they spent looking away from the road. The results were assessed against the NHTSA guidelines.

When interacting with Android Auto using the touch feature, the sum of all fixations away from the road did not meet the NHTSA guidelines of being less than 12 seconds for the two music-related tasks, the two navigation tasks and the reading a text and making a call task. However, all tasks met the NHTSA guidelines when using the voice control feature. Participants' estimation of time spent looking away from the road was higher for touch compared with voice but was nevertheless an underestimation of their actual time.

When interacting with Apple CarPlay using the touch feature, the sum of all fixations away from the road did not meet the NHTSA criteria of being less than 12 seconds for the Spotify music selection task, navigating to a restaurant or petrol station task and reading a text and making a call task. However, their self-reported measure for touch underestimated the time they spent looking away from the road. All guidelines were met when using the voice enabled feature.

The findings suggest that while drivers are aware of the distracting effects of interacting with the systems via touch control, they still underestimate the impact it has on the time they are looking away from the road. Voice control is clearly beneficial in comparison to touch with respect to driver maintaining their eyes on the road.

4.4 Self-reported performance

Participants completed a questionnaire at the end of each drive providing self-assessed ratings of their performance. The data indicated that for both infotainment systems, participants reported better driving performance during the control drive compared with both voice and touch drives. For all music and navigation tasks using Android Auto and Apple CarPlay, participants found the touch drive to be more difficult and distracting than the voice drive.

In general, participants in the sample were familiar with the use of infotainment systems or mobile phones while driving. Ninety-five percent of participants used their mobile phones or in-vehicle infotainment systems for navigation or music selection during everyday driving. The vast majority of this interaction is via touch control rather than voice. This result is particularly interesting as both self-reported surveys and the results from the simulator drives indicated that participants found interacting with the in-vehicle systems using touch screen to be more difficult, distracting and resulted in a change in driver behaviour. Participants also had a clear idea about the legality of mobile phone use whilst driving. The vast majority of participants appeared to understand what was legal and illegal with regards to interacting with a mobile phone. Supporting previous surveys of car drivers, this suggests that drivers continue to interact with mobile devices despite being aware that they are distracting and that some behaviours are illegal.

4.5 Conclusion

This study sought to understand the impact of interacting with mobile-based infotainment systems on driver performance. It also sought to understand how the results from this study compared with other forms of driver impairment. Two repeated measures studies were conducted, with Android Auto and Apple CarPlay, to gather evidence on driver performance.

Participants' took longer to react to external stimuli (the red bar) when interacting with both infotainment systems using the touch feature followed by the voice feature in order to play music. Furthermore, participants failed to react to a larger number of stimuli when having to interact with either systems using the touch feature compared with the control drive.

Compared with the control drive, reaction times showed a mean increase of 57% and 53% when playing music through Spotify using the touch feature on Apple CarPlay and Android Auto, respectively. While the same impairment route was used, comparison with previous studies needs to be caveated due to differences in time, samples and response method. Nevertheless, it suggests that the level of impairment found here is in line with use of a mobile phone for a hand-held call. Further, the effect of engaging with some features through voice control, with both systems, was akin to the impairment associated with conducting a handsfree call. All of these produce longer reaction times when benchmarked against alcohol consumption (at the legal limit) and cannabis use.

Participants showed a significant reduction in their average speeds when completing the music and navigation tasks use the touch feature in both infotainment systems. This reduction in speed is a clear indication that drivers were responding to an increase in mental demand; something that drivers acknowledged in their self-reported ratings. However, this compensatory reduction in speed was not enough to maintain their driving performance. Despite reducing speed, participants were unable to maintain a consistent gap to the vehicle in front and unable to maintain their lane position to the same standard as their control drive. Overall, these vehicle control measures were better when using voice control compared with touch control (for both systems), presumably because voice control allowed participants to maintain their eyes on the road more than touch control.

Eye gaze measures showed that participants interacting with Android Auto or Apple CarPlay using the touch feature did not meet US NHTSA guidelines for many of the tasks. They did meet the guidelines for eyes off the road time using voice control with both systems. However, in both cases, participants underestimated the amount of time spent looking away from the road, which could be an area for concern.

Results from this study generally indicate that interacting with both systems (Android Auto and Apple CarPlay) using the touch feature had a more negative impact on driver performance compared with not interacting with a device at all. Despite having to reduce speeds to be able to complete the additional tasks provided, participants were unable to maintain a constant lane position, headway, and spent much longer with their eyes off road. Interacting with the infotainment systems using the voice feature showed better driving performance than the touch feature, however, still significantly different to the control drive in some measures (such as reaction time and lane position).

Previous research has indicated that Android Auto and Apple CarPlay are improvements on infotainment systems that had been brought to market by vehicle manufacturers. Nevertheless, the data from this study highlight that both systems increase demand for drivers' attentional resources, which has a detrimental impact on their driving performance. How that impact translates into safety outcomes on the road is unknown, although with driver distraction estimated to be a factor in 10-30% of collisions in Europe it is important that systems like these are thoroughly tested. This is particularly pertinent given that the biggest detriment was caused by touch control, the form of control most used by participants in their real-world driving.

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Interacting with Android Auto and Apple CarPlay when driving: The effect on driver performance

This study aimed to assess the impact of interacting with two infotainment systems, Android Auto and Apple CarPlay, on four driver performance measures: reaction time, driving behaviour, eyes-off road and self-reported performance. It also compared the results with other forms of driver impairment studied previously.

Twenty regular Android users took part in the Android Auto trial and 20 regular Apple users took part in the Apple CarPlay trial. Each participant completed three 20 minute drives in TRL's DigiCar simulator: control (no interaction with infotainment system), voice enabled and touch enabled. The route was divided into sections and participants performed music, navigation, texting and calling tasks at specific times during the drive.

Compared with the control drive, participants in both trials showed a reduction in average speed, increase in deviation of headway and larger deviation of lane position for most tasks; this effect was greater when using touch features than voice features. Eye gaze measures indicated that participants did not meet the NHTSA criteria for most of the tasks when using touch controls for both systems, but they met the criteria when using voice control. Self-reported data suggested that participants found interacting through touch to be more difficult and distracting than voice. Most critically, reaction time to a stimulus on the road ahead was significantly higher when selecting music through Spotify when using Android Auto and Apple CarPlay. Participants also failed to react more to the stimulus on the road ahead when engaging with either Android Auto or Apple CarPlay compared with a control drive. Comparison with previous driver impairment studies showed that the increase in reaction time when interacting with either system using touch was higher than previously measured forms of impairment, including texting and hand-held calls.

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