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Cognitive load, working memory capacity and driving performance: A preliminary fNIRS and eye tracking study

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ABSTRACT

A common cause of road traffic incidents is driver distraction, which can occur when the driver's attention is engaged in a concurrent secondary task. However, the relationship between cognitive demands, individual differences in working memory capacity and driving performance has received little research attention. Using a fixed-base driving simulator, the aim of this study was to use a combination of self-report, functional near infrared spectroscopy (fNIRS) and mobile eye tracking data to investigate the impact of cognitive load on drivers' gaze behaviour and driving performance, as well as explore the relationship between working memory capacity and driving performance under increased cognitive load. Twenty-one participants with a range of driving experiences (e.g., 0–14 h per week) completed a simulated driving task in a simple environment (i.e., country highway) under single-task (driving only) and dual-task (driving + modified 2-back task) conditions. Cognitive load was assessed via fNIRS data that manifested as changes in regional oxygen saturation (rSO_2) in prefrontal cortex as well as self-report data of perceived mental effort. Participants' working memory capacity was assessed using the Operation Span Task. Findings showed that prefrontal rSO_2 and perceived mental effort was significantly greater under dual-task conditions compared to the single-task condition. In the dual-task condition, participants' gaze dwelled for longer on the road and they made fewer fixations, of longer durations. Participants were able to maintain driving performance in this condition, although this was at the expense of secondary task performance. Interestingly, driving infractions under dual-task conditions were negatively correlated with participants' working memory capacity. The findings suggest that engaging with distracting secondary tasks while driving may increase drivers' cognitive load and change their gaze behaviour. Driving performance can seemingly be maintained under such conditions, but this may be partly determined by the driver's working memory capacity.

1. Introduction

Road injuries are among the 10 leading causes of death in the world (Mathers et al., 2017). Driving is a complex and attentionally

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demanding task that entails many distractions which divert the driver's attention away from critical events and place increased demands on working memory (WM; Lee et al., 2008; Kircher & Ahlstrom, 2017). WM is a cognitive mechanism which enables us to actively retain small chunks of information for use in ongoing tasks (Baddeley & Hitch, 1974) and individuals vary in their WM capacity (Unsworth & Engle, 2007). In the present work, using a fixed-base driving simulator, we used a novel combination of self-report, functional near-infrared spectroscopy (fNIRS) and eye tracking technology to examine the effects of a cognitively demanding secondary task on drivers' performance in a relatively simple environment, including associated changes in their allocation of visual attention and experienced cognitive load. Furthermore, we undertook an explorative analysis of the relationship between WM capacity and driving performance under both single-task and dual-task conditions.

To drive safely, drivers must simultaneously attend to a variety of stimuli including in-vehicle audio prompts, changes in road surfaces, fluctuating traffic conditions, other road users' behaviour, and unexpected hazards – while concurrently performing motor tasks such as braking, changing gear, and steering. Consequently, effective management and allocation of attention is crucial to driver safety (Gugerty, 2011; Kircher & Ahlstrom, 2017), and eye movements are fundamental to this (Alberti et al., 2014). Research has shown that drivers will typically fixate straight ahead when driving, typically looking at proximal features of the environment (e.g., the vehicle in front; Underwood et al., 2003). However, this is dependent on the complexity of the environment and the experience levels of the driver. Complex environments, such as urban or motorway roads, place greater demands on the attentional systems which is suggested to limit scanning behaviours compared to less complex environments, such as country highways (Mackenzie & Harris, 2017). Furthermore, experienced drivers tend to exhibit more horizontally dispersed gaze patterns than less experienced drivers, scanning left and right of a central fixation point (Alberti et al., 2014; Chapman et al., 2002; Underwood et al., 2002; Konstantopoulos et al., 2010). This gaze behaviour may enable more rapid detection of peripheral hazards, such as a cyclist undertaking. Differences in gaze behaviour between experienced and less experienced drivers may be because the former have implicitly learned where to look (Underwood, 2007; Underwood et al., 2002). Alternatively, it may be because some driving-related process such as steering have become largely automated through practice (Mackenzie & Harris, 2015; 2017), consequently freeing up attentional resources for the experienced drivers to scan the environment more extensively. It is more likely a combination of both of these factors, because experienced drivers can still be distracted by task-irrelevant information, which often affects driving performance (Regan et al., 2011; Young et al., 2007).

Driver distraction has been defined as "the diversion of attention away from activities critical for safe driving toward a competing activity" (Lee et al., 2008, p.34). Previous research has shown that conversations with passengers (e.g., Drews et al., 2008) or via telephone (e.g., Strayer & Johnston, 2001; Strayer et al., 2003), and listening to music (e.g., Brodsky & Slor, 2013), are distracting and compromise driver safety. Specifically, it has been shown that increased cognitive load from engagement in a secondary task reduces drivers' horizontal visual scanning and use of mirrors (e.g., Engström et al., 2005; Recarte & Nunes, 2003). Changes in gaze behaviour under cognitive load are often a strategy to free up attentional resources in WM in an attempt to maintain performance on the primary task (Ellmers et al., 2016).

WM is central to our executive functions, the three most prototypical of which are *updating,* our ability to monitor and update representations in working memory; *shifting,* our ability to shift attention between different tasks; and *inhibition,* our ability to control our innate responses to environmental stimuli (Mäntylä et al., 2009; Miyake et al., 2000). Moreover, WM function is inextricably linked to attention, not least because both are limited resources (Oberauer, 2019). Specifically, it has been proposed that high task demands impair the shifting and inhibition functions, which results in stimulus-driven, rather than goal-directed, attention; for example, the individual may find it harder to inhibit their attention to task-irrelevant but salient distractions (Eysenck et al., 2007; Eysenck & Derakshan, 2011). This can manifest as more erratic and less efficient attention allocation, with a detrimental impact on primary task performance (e.g., Nieuwenhuys et al., 2008). However, if task demands are low then an individual can increase their effort to maintain their goal-directed attention, and their performance in the primary task (Eysenck & Calvo, 1992). Importantly, the ability to resist distraction and cognitive interference has been linked to individual differences in WM capacity. Specifically, individuals with high WM capacity are generally better able to maintain cognitive control and remain task-focused (Engle, 2002; Engle & Kane, 2004). Therefore, it is suggested that participants with high WM capacity should exhibit fewer performance decrements in a primary task when concurrently performing a demanding secondary task (Szameitat et al., 2022).

The Operation Span task (OSPAN; Unsworth et al., 2005) is a measure of WM capacity (McCabe et al., 2010). Driving research using the OSPAN has shown that individuals with high WM capacity exhibit fewer decrements in driving performance under dual-task conditions than those with low WM capacity, in terms of braking, lane changing behaviour (Watson & Strayer, 2010; Ross et al., 2014) and hazard perception (Wood et al., 2016). Wood et al. (2016) monitored participants' gaze behaviour during a hazard perception driving task and observed that, when performing an auditory secondary task, individuals with low WM capacity fixated less frequently on developing hazards, which impaired their ability to predict and react to them. However, although Wood et al. manipulated participants' cognitive load, their hazard perception task only required button press responses and did not require any interaction between the driver and other road users. Therefore, this task did not pose the same complex visuomotor control challenges as driving. Furthermore, an online measure of cognitive load during the task was not captured; to include such a measure will provide greater insight into the relationship between cognitive load and gaze behaviour when driving in complex and dynamic naturalistic environments.

To measure cognitive load, the vast majority of previous research has used retrospective self-report measures, such as the Rating Scale of Mental Effort (RSME; Zijlstra, 1993) or the National Aeronautics and Space Administration-Task Load Index (NASA-TLX; Hart & Staveland, 1988). Self-report approaches are often adopted as they afford quick and non-invasive assessment of mental effort. However, such methods may not provide a valid measure of cognitive load or capture the temporal fluctuations in load that occur during performance of complex tasks (Gredin et al., 2020). As technology has advanced, researchers have used neuroimaging techniques to measure brain activation, specifically in the prefrontal cortex, to provide a more sensitive and objective index of cognitive load (Antonenko et al., 2010). Functional near-infrared spectroscopy (fNIRS) provides an online measure of cognitive load via changes in prefrontal oxygen saturation (rSO_2) (Ciftçi et al., 2008; Sassaroli et al., 2008) and overcomes many of the issues associated with other neuroimaging techniques, such as lack of portability and high sensitivity to motion artefacts (Pinti et al., 2018; Pinti et al., 2020). This means fNIRS can be used in naturalistic environments without posing any additional risk or restriction to the participant or the quality of data collected (e.g., Balardin et al., 2017; Metzger et al., 2017; Pinti et al., 2015). Research conducted using simple computer-based experimental tasks (e.g., Herff et al., 2014; Sassaroli et al., 2008) and complex naturalistic ones such as driving (e.g., Foy & Chapman, 2018; Tomioka et al., 2009; Tsunashima & Yanagisawa, 2009) typically show that increases in cognitive load are reflected in increases in oxygenated haemoglobin, with accompanying decreases in deoxygenated haemoglobin (Lohani et al., 2019; Liu et al., 2016).

Foy and Chapman (2018) combined fNIRS and eye tracking to investigate the effect of changes in the road environment on driver behaviour, gaze behaviour and cognitive load. Prefrontal rSO2 increased when driving on demanding suburban routes comprising many junctions and pedestrians, relative to straight multi-lane roads with no pedestrians. The increases in cognitive load on the suburban roads also corresponded with reductions in driving speed and changes in gaze behaviour. As cognitive load increased, average fixation duration decreased and horizontal dispersion of participants' visual scanning increased, somewhat contrary to previous findings (e.g., Recarte & Nunes, 2000) – although the greater traffic, pedestrian and parked car densities might have increased the need for such scanning behaviour, to detect potential hazards. Whilst Foy and Chapman's study captured changes in cognitive load due to changing environmental conditions, the effect of a cognitively demanding, secondary task on gaze behaviour and driving performance, and the mitigating effects of individual differences in WM capacity, were not assessed.

The aim of the current preliminary study is to examine the effects of a cognitively demanding secondary task on performance of a simulated driving task; we collected a combination of self-report, fNIRS and eye tracking data to do so. Given the preliminary nature of this study, we conducted an exploratory analysis to see whether individual differences in WM capacity relates to driving performance under both single-task and dual-task conditions. The simulated driving task was relatively basic, but still required the driver to engage in naturalistic visuomotor behaviours; for example, frequent use of mirrors, steering to avoid collisions, braking as appropriate, and changing gear. We predicted that cognitive load, as manifested in changes in prefrontal rSO_2 and self-reported perceived mental effort, would be greater in a dual-task condition comprising a secondary task that is irrelevant to driving, when compared to driving only (single-task condition; Sassaroli et al., 2008; Tsunashima & Yanagisawa, 2009). In accordance with previous research (Wood et al., 2016), we predicted that greater cognitive load would manifest in changes in gaze behaviour, albeit potentially with maintenance of performance on the primary driving task (cf. Eysenck & Calvo, 1992). We also predicted that individuals with lower WM capacity would perform inferiorly on the simulated driving task, particularly under dual-task conditions (Watson & Strayer, 2010; Wood et al., 2016).

2. Methods

2.1. Participants

Twenty-one participants (10 females, 11 males) with an age range of 18–32 years ($M = 23.86$ yrs, $SD = 4.58$ yrs) took part in the study. A power analysis was performed for sample size estimation using G*Power 3.1. Based on a previous study which used fNIRS to investigate changes in rSO_2, and eye tracking to examine changes in gaze behaviour, during a driving simulation task involving different levels of task load (Foy & Chapman, 2018), a required sample size of 18 was estimated, for a large effect size ($\eta_p^2 = 0.12$) with an alpha of 0.05 and a power of 0.95. We recruited an additional three participants to mitigate for potential attrition.

All participants had held a driver's license for at least 1 year ($M = 5.35$ yrs, $SD = 4.08$ yrs), and drove 0–14 h per week at the time of the study ($M = 4.74$ hrs, $SD = 3.92$ hrs; two participants reported 0 h of driving per week). All participants reported normal or corrected-to-normal vision and were right-handed according to their Edinburgh Handedness Inventory (Oldfield, 1971) responses. The study was approved by the research ethics committee of the lead institution.

2.2. Stimuli and apparatus

All testing was conducted in the SIM Lab at the Brunel University London LEAP Lab (https://www.brunel.ac.uk/research/Networks-and-Labs/LEAP-Lab).

2.2.1. Driving simulation task

City Car Driving 1.5 driving simulator software (https://citycardriving.com) was used (cf. Mackenzie & Harris, 2017). The image was projected on to a wall (200 cm × 112 cm) using an Optoma GT1080E HD short throw projector (Optoma, New Taipei City, Taiwan). The participants were positioned 170 cm from the wall such that the simulated field of view was 60.9° x 36.5°, which is comparable to previous research (Mackenzie & Harris, 2017) and close to that in a real car (cf. Huisingh et al., 2015). A steering wheel, gear stick and pedals (Logitech Driving Force GT, Lausanne, Switzerland) were used to mimic real-world driving, including the vehicle's inertia, brake torque, and steering wheel torque. Wing mirrors, a rear-view mirror and speedometer were visible on screen.

The virtual environment was a country highway with single and dual lane carriageways and no pedestrians. The traffic level was set as high and the traffic behaviour was set as highly aggressive (100 %), moderately dangerous (70 %) and with moderate amounts of emergency braking (70 %). These settings were chosen to create demanding road conditions in which the driver was required to attend to other vehicles, some of which would behave erratically (e.g., suddenly switching lanes) 1–2 times per condition; the nature and timing of the behaviours were randomised. The software tracked driving performance using a points system (see Measures section for more details). If the participant drove the car off the road such that it became stuck, then they restarted the task from the beginning; this occurred in < 5 % of conditions. Total driving time was 4 min per condition. Several steps were taken to provide consistency across experimental conditions: Participants were instructed to drive along the highway as they normally would, ignoring exits and respecting all traffic rules; no verbal or visual guidance was provided by the researcher; and prior to completing the driving task, each participant underwent a familiarization condition which included three 2-minute tasks.

2.2.2. *Secondary cognitive task*

An auditory modified 2-back task was used to increase cognitive load in the dual-task condition. The *n*-back task is a sequential letter memory task that increases WM load and activation of dorsolateral and inferior frontal regions of prefrontal cortex (Braver et al., 1997; Manoach et al., 1997; Ragland et al., 2002). In the 4-minute dual-task driving condition, the participant responded to 12 modified 2-back trials – one every 19 s, on average. Each trial comprised auditory presentation of 5, 6 or 7 pre-recorded letters played at a rate of 2 s per letter in a randomised order. At the end of each trial, the spoken phrase "2-back" prompted the participant to state the letter they had heard two letters prior to the current one. The participant was given 8 s to give their response. To promote secondary task engagement, participants were instructed that their performance on this task was equally important to that of the primary driving task. Each participant performed the modified 2-back task by itself at the beginning of the experiment to determine their individual baseline performance.

2.2.3. *Functional near infrared spectroscopy*

Cerebral oxygenation of the prefrontal cortex was measured using Functional Near-Infrared Spectroscopy (fNIRS) (INVOS 5100C Near-infrared Cerebral Oximeter, Somanetics, Troy, MI). A disposable alcohol wipe was used to degrease the skin on the participant's forehead, and a dry gauze pad was used to ensure that the area was completely dry before placing the sensors. Two adhesive fNIRS pads that emitted NIR signals at 730- and 810-nm wavelengths were placed over the left and right side of the forehead above the eyebrows. Each pad comprised two optodes located at a distance of 3 and 4 cm from the sensor. Each pad was securely taped to the skin to ensure that daylight interference was minimised. The oximeter calculated regional blood oxygenation saturation (rSO_2) values by measuring the portion of NIR light reflected back to the scalp, which depends on the differential concentrations of oxygenated and deoxygenated haemoglobin present in the neuronal tissue; an average rSO_2 value was determined every-five seconds.

2.2.4. *Rating scale of mental effort*

The RSME requires participants to indicate their perceived mental effort in relation to a recently completed the task, on a scale ranging 0 to 150 (Zijlstra, 1993). Nine descriptors lie along the scale, ranging from "absolutely no effort" (a score of 2 on the scale) to "extreme effort" (1 1 3). The participants were shown the scale and then verbalised their score.

2.2.5. *Eye tracking glasses*

Eye movements were recorded using mobile eye-tracking glasses (Applied Science Laboratories [ASL], Bedford, MA, USA), which recorded momentary point of gaze at 30 Hz. The glasses were connected to a recording device that was positioned unobtrusively near the participant, and was connected wirelessly to a laptop that the researcher monitored throughout data collection. Prior to each condition, the glasses were calibrated using a 9-point grid that spanned the display screen used for the experimental tasks. For the driving conditions, the parsed recording files started at the frame in which the car started to leave its parking bay and ended in the frame prior to the end of the condition. In the event of collisions that interrupted the driver's progress through the virtual environment,

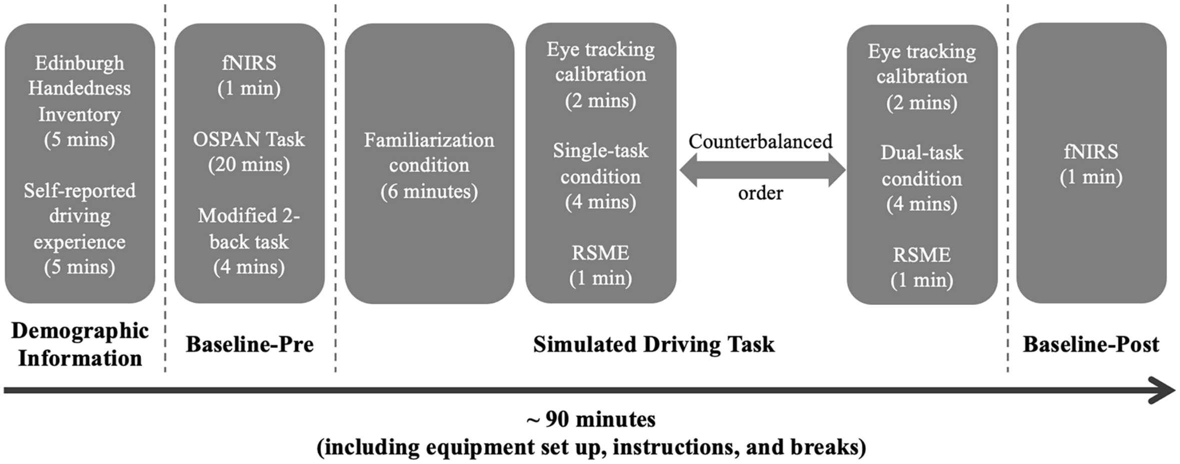

Fig. 1. Overview of the procedure including the demographic information, baseline measures and simulated driving task conditions.

sections of the recordings were excised from the frame at which the car collided to when the car was moving at approximately 30 km/h. At this speed, participants' gaze behaviour had normalized – specifically, they were looking through the windscreen rather than at the vehicle controls or the researcher.

2.2.6. *Operation Span task*

The automated version of the OSPAN task (Unsworth et a., 2005) provided a measure of participants' WM capacity. In this task participants were required to solve math problems presented on a laptop computer (e.g., $(8/2) - 1 = 1$? true/false?) and then remember an unrelated letter that was presented on the screen after each problem. After each trial, participants had to recall as many letters as possible, and to type them on the keyboard in the same order in which they had been presented. The task comprised 17 trials (2 familiarization trials with 2 letters to remember followed by 3 trials each with 3, 4, 5, 6, and 7 letters to remember), presented in a random order. The score was calculated as the total number of letters recalled across all error-free trials (Unsworth et al., 2005). The task took approximately 20 min to complete.

2.3. *Procedure*

Fig. 1 provides an overview of the procedure. We employed a repeated measures design. Upon arrival in the lab, participants completed the informed consent form, the Edinburgh Handedness Inventory (Oldfield, 1971), and a demographics questionnaire that included questions about their driving experience, before the fNIRS sensors were applied to their forehead. Following this, participants were asked to count down from 30 to zero for one minute, to allow the establishment of baseline rSO_2 levels (Baseline-Pre). Participants then completed the OSPAN task and the baseline assessment of the modified 2-back task performance. Upon completion of these initial tasks, the researcher helped the participant to don the eye tracking glasses.

Participants then completed the simulated driving task, under single-task and dual-task conditions; the order of these conditions was counterbalanced across participants. Each condition lasted four minutes, with a rest interval of one minute between each, to allow rSO_2 to return to baseline levels. After completing each condition, participants completed the RSME. Before the experimental conditions, participants completed a familiarization condition to ensure they were comfortable with the driving task. Upon completion of the simulated driving conditions, participants counted down from 30 to zero for one minute as the researcher acquired an additional baseline measure of rSO_2 levels (Baseline-Post), to act as a comparator for the original baseline measurements. The total testing time was approximately 90 min.

2.4. *Measures*

2.4.1. *Cognitive load*

To examine changes in cognitive load in the simulated driving task in both single-task and dual-task conditions, fNIRS and RSME data were collected.

2.4.1.1. *Percentage change of rSO_2 from baseline.* Raw rSO_2 levels were automatically recorded from the left and right prefrontal cortex (PFC) using fNIRS. Left and right PFC scores were averaged to provide an overall score, which was subsequently transformed into a percentage of rSO_2 change from baseline for analysis. There were no differences between baseline rSO_2 values obtained at the beginning and end of the experimental protocol, in either left PFC, $t(19) = 1.61$, $p = .12$, or right PFC, $t(19) = 1.54$, $p = .14$. Therefore, baseline scores obtained at the beginning of the experimental protocol were used to calculate task-related changes in rSO_2 values.

2.4.1.2. *Perceived mental effort.* Self-reported RSME scores were used as a measure of participants perceived mental effort in each condition.

2.4.2. *Driving task performance*

Driving performance was evaluated using the total number of infractions and the total number of infraction points accumulated based on a demerit-based point system, as per previous research using the same simulation software (e.g., Mackenzie & Harris, 2017). The software recorded a number of infractions, which we classified into four categories: *major infractions*, such as crashes with other vehicles; *vehicle control infractions* such as the wheels moving off the road or on to the wrong side of the road; *speed infractions*, wherein the stated limit was exceeded; and *signal infractions* such as indicator disuse when changing lanes. Five demerit points were awarded for a major infraction, four for a vehicle control infraction, three for a speed infraction, and two for a signal infraction. Hence, a higher number of points indicated poorer performance.

2.4.3. *Secondary task performance*

The total number of letters correctly reported in the modified 2-back task was divided by 12 (number of trials) and multiplied by 100 to yield a percentage accuracy score, for each condition.

2.4.4. *Gaze behaviour*

To examine gaze behaviour in the simulated driving task under single-task and dual-task conditions, three measures were determined; total number of fixations, mean duration of fixations, and percentage dwell time on five areas of interest (AOIs): the *road ahead*, the *rear-view mirror*, the *left wing mirror*, the *right wing mirror*, and the *speedometer* (cf. Mackenzie & Harris, 2017). Due to calibration issues, eye tracking data from four participants were not recorded, resulting in analysis of 17 participants' gaze data.

2.4.4.1. Total number of fixations. The total number of fixations were recorded. Fixations were defined as a point-of-gaze that remained on a location for a minimum of 100 ms and a maximum fixation radius of 1° (Wood et al., 2016; Franklin et al., 2018). The number of fixations was automatically calculated using proprietary software (ASL, Bedford, MA, USA).

2.4.4.2. Duration and number of fixations. Average fixation duration and total number of fixations were recorded and calculated automatically, for each condition.

2.4.4.3. Percentage dwell time on AOIs. The percentage dwell time – the percentage of each driving condition time for which participants fixated on each AOI was determined via frame-by-frame analysis using video editing software (Adobe Premiere Pro, Version CS 5; Adobe Inc., San Jose, CA).

2.4.5. Working memory capacity

For the OSPAN task, the total number of letters recalled across all error-free trials was calculated for each participant and used as an index of WM capacity (Unsworth et al., 2005).

2.5. Data analysis

All data were screened for outliers and non-normality prior to analysis. Paired-samples t-tests were used to compare the percentage change in rSO_2 from baseline and perceived mental effort, for both single-task and dual-task conditions. Driving task performance, characterized as total number of infractions and total number of infraction points, was also analyzed using paired-samples t-tests, again for both conditions. Performance on the secondary cognitive task (i.e., modified 2-back task) was analyzed using a paired-samples t-test to compare the number of correct responses at baseline and in the dual-task condition. Paired-samples t-tests were conducted to assess differences between total number of fixations, mean duration of fixations, and percentage dwell time on AOIs across conditions. To explore the relationship between WM capacity and driving performance under single and dual-task conditions, Pearson's correlation coefficient was calculated for OSPAN scores and driving performance scores for each condition. For t-tests, Cohen's d was used as a measure of effect size. The alpha level for significance was set at $p < .05$.

3. Results

3.1. Cognitive load

To compare cognitive load in the single-task and dual-task driving conditions, percentage change in prefrontal rSO_2 from baseline and RSME scores were analyzed.

3.1.1. Percentage change of prefrontal rSO_2 from baseline

Screening of the fNIRS data revealed no outliers and the data were normally distributed, and so parametric analyses were performed. Fig. 2 shows the mean percentage change in prefrontal rSO_2 from baseline in the single-task and dual-task conditions. A

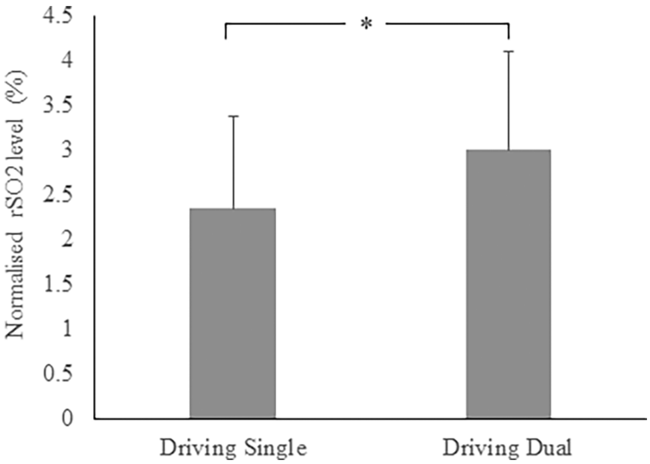

Fig. 2. Mean Percentage Change in Prefrontal Regional Blood Oxygenation Saturation (rSO_2) from Baseline in the Single-task and Dual-task Conditions. Error bars represent standard error. *p <.01.

paired-samples *t*-test revealed that the percentage change in prefrontal rSO_2 from baseline was significantly higher in the dual-task condition (*M* = 3.00, *SE* = 1.11) than in the single-task condition (*M* = 2.35, *SE* = 1.03), *t*(20) = 3.61, *p* =.002, d = 0.13, 95 % CI = 0.27 – 1.03.

3.1.2. Perceived mental effort

Data screening revealed no outliers and normally distributed data; hence, parametric analyses were conducted on the RSME scores. Paired-samples *t*-test revealed that perceived mental effort was significantly greater in the dual-task condition (*M* = 84.10, *SE* = 5.83) than in the single-task condition (*M* = 50.00, *SE* = 5.48), *t*(20) = 5.89, *p* <.001, d = 1.32, 95 % CI = 22.02 – 46.17. Consistent with the changes in prefrontal rSO_2, self-reported mental effort increased in the dual-task condition.

3.2. Driving task performance

To compare driving performance in the single-task and dual-task conditions, the total number of infractions and the total infraction demerit points were analyzed. Data screening revealed no outliers, and the data were normally distributed, and so parametric analyses were applied. A paired-samples *t*-test revealed no significant difference between the total number of infractions in the single-task condition (*M* = 1.33, *SE* = 0.39) and the dual-task condition (*M* = 1.52, *SE* = 0.31), t(20) = 0.44, p =.666, d = 0.12, 95 % CI = -1.10 – 0.72. Similarly, there was no significant difference in infraction points between conditions (single-task: *M* = 4.48, *SE* = 1.24; dual-task: *M* = 5.38, *SE* = 1.10), t(20) = 0.62, p =.541, d = 0.17, 95 % CI = -3.94 – 2.13. This suggests that although dual task performance increased cognitive load, driving performance was maintained.

3.3. Secondary task performance

Performance on the secondary task was analyzed to compare the number of correct responses in the modified 2-back task at baseline and in the dual-task condition. Data screening revealed no outliers, and the data were normally distributed, and so parametric analyses were conducted. A paired-samples *t*-test revealed a significant difference in accuracy between the 2-back task performance at baseline (*M* = 70.63, *SE* = 5.32) and that in the dual-task condition (*M* = 57.94, *SE* = 5.06), t(20) = 2.19, p =.041, d = 0.53, 95 % CI = 0.60 – 24.79. This suggests that, while performance on the primary task was maintained in the dual-task condition, performance on the secondary task was compromised.

3.4. Gaze behaviour

To assess the influence of cognitive load on visual attention in the single-task and dual-task driving conditions, the total number of fixations, the mean duration of fixations, and the percentage dwell time on AOIs were analyzed.

3.4.1. Total number of fixations

Data screening revealed no outliers and normally distributed data, and so parametric analyses were performed. A paired-samples *t*-test revealed that the total number of fixations in the single-task condition (*M* = 435.34, *SE* = 20.30) was significantly greater than in the dual-task condition (*M* = 393.82, *SE* = 18.77), t(16) = 2.20, p =.043, d = 0.51, 95 % CI = 1.57 – 81.25.

3.4.2. Mean duration of fixations

Data screening revealed no outliers, but data were positively skewed and leptokurtic in both the single-task (Skewness: 4.12; Kurtosis: 6.42) and dual-task (Skewness: 3.20; Kurtosis: 4.52) conditions; hence, nonparametric analyses were applied. A Wilcoxon Signed-Rank test showed a significance difference in mean duration of fixations in the single-task condition (*M* = 0.42 s, *SE* = 0.03) and in the dual-task condition (*M* = 0.47 s, *SE* = 0.03), *z* = -2.77, *p* =.006, *d* = 0.58. The gaze data collectively suggest that the addition of a cognitively demanding secondary task reduced the number of fixations and increased their mean duration.

Table 1
Mean (%) and Standard Error for Percentage Dwell Time on the Areas of Interest (AOI) in the Single and Dual Conditions of the Driving Task.

AOI	Condition	Mean (%)	Standard Error
Road	Single	82.19	1.69
	Dual	86.24	1.53
Rear-view mirror	Single	4.09	1.06
	Dual	2.78	0.69
Left wing mirror	Single	1.91	0.31
	Dual	1.51	0.33
Right wing mirror	Single	7.10	0.77
	Dual	5.61	0.88
Speedometer	Single	4.71	0.87
	Dual	3.85	1.03

3.4.3. *Percentage dwell time on AOIs*

Data screening revealed no outliers, but data were positively skewed and leptokurtic for three AOIs: The *Road* (Single-task: Skewness = -2.89, Kurtosis = 3.06; Dual-task: Skewness = -2.68, Kurtosis 4.08), the *Left Mirror* (Single-task: Skewness = 3.11, Kurtosis = 3.77; Dual-task: Skewness = 3.57, Kurtosis = 4.79), and the *Speedometer* (Single-task: Skewness = 1.58, Kurtosis = 0.20; Dual-task: Skewness = 4.40, Kurtosis = 6.68) and so nonparametric analyses were applied to these data. Descriptive statistics for the percentage dwell time on the AOIs in the different conditions is presented in Table 1. A Wilcoxon Signed-Rank test revealed a significant difference in percentage dwell time on the road between conditions, $z = 2.86$, $p = .004$, $d = 0.61$. Paired-Samples t-tests revealed a significant difference in percentage dwell time between conditions on the right wing mirror, t(16) = 2.14, p =.048, d = 0.44, CI = 0.02 – 2.96, and approached significance for the rear-view mirror, t(16) = 2.10, p =.052, d = 0.28, CI = -0.02 – 2.64. Similarly, for percentage dwell time on the left wing mirror, a Wilcoxon Signed Rank test suggested the difference between the single and dual task conditions only approached significance, $z = -1.87$, $p = .061$, $d = 0.29$. No significant difference was found for percentage dwell time on the speedometer between the single-task and dual-task conditions, $z = -1.30$, $p = .193$, $d = 0.22$. This suggests that with increased cognitive load from a secondary task, individuals spent a greater percentage of time fixating on the road compared to the mirrors, especially the right wing mirror.

3.5. *Working memory capacity*

To examine the relationship between WM capacity and performance in the driving task under single and dual-task conditions, Pearson's correlations were calculated for the OSPAN scores and performance scores based on the a priori predictions outlined at the end of the introduction. An analysis of Cook's distance and centred leverage value was carried out on the data to identify any outliers, which indicated that cases 3, 16 and 17 needed to be removed. Pearson's correlations revealed that the OSPAN score exhibited significant negative relationships with driving performance in the dual-task condition, for both total number of infractions, $r = -0.567$, $p = .014$, and total number of infraction points, $r = -0.536$, $p = .022$. However, no relationship was found for either performance metric in the single-task condition (total number of infractions, $r = -0.291$, $p = .242$; total number of infraction points, $r = -0.240$, $p = .337$), suggesting WM capacity only had a relationship with driving performance under dual-task conditions (see Fig. 3).

4. Discussion

In the current study, we used a unique combination of fNIRS, self-report and eye tracking data to examine the effect of additional cognitive load imposed by a secondary task on performance and gaze behaviour during a simulated driving task. In line with our predictions, the secondary task increased participants' prefrontal rSO_2 and self-reported mental effort, which suggests that cognitive load in the dual-task condition exceeded that of the single-task condition. Participants were able to maintain their driving performance despite the additional cognitive demand and supports the suggestion that drivers can divide their attention to multiple unrelated tasks, such as listening to music and talking to other passengers while driving (Brodsky & Slor, 2013; Drews et al., 2008). The findings may also show support for the Multiple Resource Theory (Wickens, 2008), which suggests that there are separate resources for different modalities. In the current study, the driving task, which is a visuo-motor task, may not have been impacted by the secondary cognitive task, which was an auditory task, as the resources are not shared by these tasks as the modalities are different. However, although driving performance was maintained, this seemingly came at increased physiological cost and self-reported effort – consistent with the predictions of Eysenck and colleagues' (Eysenck & Calvo, 1992; Eysenck et al., 2007; Eysenck & Derakshan, 2011). The increased attention to the driving task meant the participants had less attentional resource to maintain secondary task performance. Drivers must often prioritise amongst several attentionally and cognitively demanding tasks, and so our findings reinforce the notion that effective management and allocation of attention is key to driver safety (Gugerty, 2011; Kircher & Ahlstrom, 2017).

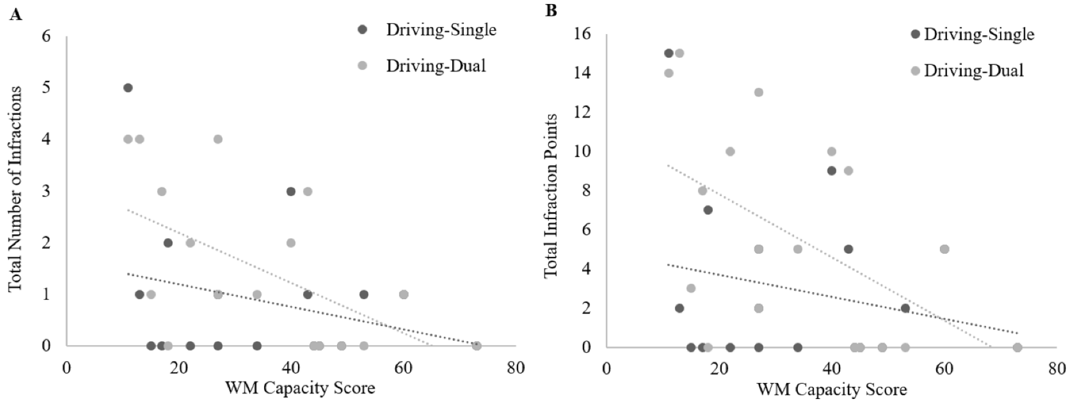

Fig. 3. Scatter plot graph and trend lines to show the relationship between working memory capacity based on the OSPAN score and (A) the total number of infraction points, and (B) total infraction points in the single-task condition and dual-task condition.

As well as increasing their efforts on the primary task under increased cognitive load, the participants also altered their gaze behaviour. Drivers' gaze became more centralised and less dispersed, which was manifested in fewer, longer duration, fixations – primarily on the road. Dwell time on the mirrors, especially the right wing mirror, decreased in the dual-task conditions. Because voluntary shifts of attention increase demands on working memory (Rosen et al., 1999), the changes in participants' gaze behaviour may reflect the freeing-up of attentional resources to maintain driving performance (Engström et al., 2005; Recarte & Nunes, 2003; Ellmers et al., 2016). While drivers tend to spend a large proportion of time fixating straight ahead, both on the road and at the car in front (Underwood et al., 2003), proactive scanning behaviour is critical for detection of hazards and appears to be a fundamental difference between experienced and novice drivers (Alberti et al., 2014; Chapman et al., 2002; Underwood et al., 2002; Konstantopoulos et al., 2010). Although the changes we observed in participants' gaze behaviour did not adversely affect their driving performance, this may be due to the simulated traffic environment: Participants were required to drive along a country highway with single and dual lane carriageways with no pedestrians or junctions. Previous research has shown that visual scanning behaviour is more prevalent in more complex scenarios such as in urban environments because there is a more pressing requirement to do so (Mackenzie & Harris, 2017; Foy & Chapman, 2018). For example, if a driver approaching a busy urban junction does not check their mirrors frequently prior to making a nearside turn, then they may fail to see an undertaking cyclist or motorcyclist. Hence, any detrimental effects of attending to secondary tasks may be somewhat contingent on environmental demands.

The current study also provided a novel exploration into the relationship between WM capacity and driving performance under single-task and dual-task conditions. Individual differences in WM capacity underpin executive function ability (Engle, 2002; Engle & Kane, 2004; McCabe et al., 2010). In the current study, the number of driving infractions and the amount of infraction points did not correlate with WM capacity under single task conditions, suggesting that participants were able to complete the driving task equally well, regardless of individual differences in WM capacity. However, under dual-task conditions there was a significant negative relationship between WM capacity and driving performance: Individuals with lower OSPAN scores tended to accrue a greater number of infractions and infraction points than those with higher scores. This is consistent with previous findings regarding the influence of individual differences in WM capacity on driving performance (Ross et al., 2014; Wood et al., 2016). Those with lower WM capacity appear to have become overloaded by the distracting secondary task, despite increased effort and gaze behaviour changes, culminating in inferior driving performance.

The current study builds on the work of Foy and Chapman (2018), by combining fNIRS and eye tracking technology to provide insight regarding changes in cognitive load and gaze behaviour when driving. Furthermore, we provide evidence that fNIRS can capture prefrontal rSO_2 changes resulting from a cognitively demanding secondary task when driving (Lohani et al., 2019; Liu et al., 2016). Moreover, we were able to provide support for the use of the RSME as a measure of mental workload: Findings from this measure aligned with those obtained via fNIRS, in contradiction to recent findings showing that retrospective reports of mental effort using the RSME did not correlate with psychophysiological measures (Gredin et al., 2020). However, this may be due to the nature of the cognitive load manipulation: We used the modified 2-back task, which is demonstrably a cognitively demanding task (Braver et al., 1997; Manoach et al., 1997; Ragland et al., 2002) whereas many real-world secondary tasks, such as listening to music or talking to a passenger, are somewhat automated and consequently may not be perceived as demanding. Further research is needed to triangulate retrospective reports of mental effort with objective psychophysiological measures, for a variety of tasks. Given the simplicity of administering retrospective self-report measures such as the RSME, it would be prudent to assess the efficacy of doing so during real-world driving, which would help to further confirm the relationship between drivers' mental workload and road incidents (da Silva, 2014).

While the present study provides novel evidence for the effects of a secondary task on cognitive demand, gaze behaviour and driving performance, as well as the potential mediating influence of WM capacity, we did not provide any comparisons between experienced and inexperienced drivers (e.g., Underwood, 2007; Konstantopoulos et al., 2010) or between different complexities of driving environments (e.g., Mackenzie & Harris, 2017). Future research should look to examine whether driving experience or environment complexity mediates the impact of individual differences in WM capacity on driving performance. It would also be interesting to examine the role of individual differences in WM capacity on driving performance when coping with distractors that have been shown to specifically impact driving, such as talking on the phone or to a passenger (Drews et al., 2008), listening to music (Brodsky & Slor, 2013), monitoring a navigation system (Jamson & Merat, 2005) or fatigue (Smith et al., 2009). This could inform driver education programs (Alvaro et al., 2018) and the development of in-vehicle systems, which add to drivers' workload and consequently affect driving performance (Lansdown et al., 2004).

Another limitation of the current study is the use of a driving simulator with relatively basic performance metrics. Future research should examine whether similar findings would occur using a real-world driving task and whether greater insight into the impact of cognitive load on driving performance can be found using more sensitive metrics (e.g., standard deviation of lateral position, steering reversal rates, lateral acceleration, brake pressure). The successful use of combined fNIRS and eye tracking technology in the current study in which the task had similar visuo-motor requirements to actual driving, suggests that this approach could be used in the real world. However, drivers are subjected to acceleration and jerk forces in the real world, as well as road vibrations, that do not exist in typical driving simulator setups (Balters et al., 2021); these can elicit substantive motion artefacts and therefore noisy data. Hence, artefact removal algorithms may be required when using eye tracking and fNIRS technologies during real-world driving tasks.

The novel finding regarding the role of individual differences in WM capacity for driving performance has potential implications. There is the possibility of enhancing individuals WM capacity through commercially available, computer-based working memory training programs that include visuospatial and verbal working memory tasks (e.g., http://www.cogmed.com; http://www.cognifit.com/). However, the evidence for these training programs is mixed and interventions often only produce short-term and specific training effects that do not generalize to real-world activities (for a *meta*-analysis, see Melby-Lervåg & Hulme, 2012). For example, Cuenen et al. (2016) showed that an adaptive WM training intervention enhanced the cognitive ability of older drivers, but there was limited evidence for the transfer of this improvement to their driving ability. Future research should investigate the benefits of WM training interventions for driving ability in more depth, perhaps with the aim of developing driving-specific interventions to enhance WM capacity, as this could be integral in enhancing driver safety and preventing road traffic incidents.

In conclusion, we used a unique combination of fNIRS, self-report and eye tracking data to demonstrate that a cognitively demanding secondary task altered drivers' gaze behaviour but that driving performance could be maintained in the dual-task condition. However, explorative analysis suggests that the maintenance of driving performance under dual-task conditions may be mediated by individual differences in WM capacity. The study adds to the growing body of research to highlight the effect of increased cognitive load on gaze behaviour and driving performance, and that individual differences in executive function may help to mitigate performance decrements under cognitively challenging driving conditions. Future research is encouraged to examine the important role of individual differences when examining and predicting driver behaviour.

CRediT authorship contribution statement

David P. Broadbent: Conceptualization, Methodology, Validation, Supervision, Writing – original draft. **Giorgia D'Innocenzo:** Methodology, Investigation, Formal analysis, Writing – review & editing. **Toby J. Ellmers:** Methodology, Validation, Writing – review & editing. **Justin Parsler:** Methodology, Software. **Andre J. Szameitat:** Writing – review & editing. **Daniel T. Bishop:** Conceptualization, Methodology, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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