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The effects of distraction on younger drivers: A neurophysiological perspective☆

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ABSTRACT

Distracted driving remains a significant cause of traffic accidents globally, including in Australia. However, many younger drivers still admit to using a phone while driving. A simulated driving study investigated the neurophysiological effects of visual, auditory, and higher-order cognitive (i.e., requiring the use of executive functions) distraction on young drivers. In total, 24 young adults aged 18–25 years completed four 8 min simulated driving sessions while concurrently engaging in various distractor tasks. Neurophysiological arousal was measured via EEG. Additionally, subjective workload and objective driving performance were assessed. Frontal beta and gamma power exhibited their highest levels during tasks involving higher-order cognitive and visual demands. The higher-order cognitive condition was rated as the most mentally demanding. In comparison, the visual condition had the most significant impact on both the standard deviation of speed and standard deviation of lateral positioning. This study has significant implications for all road users, particularly those aged 18–25 years, and it reinforces the importance of not using a phone while driving.

1. The effects of distraction on younger drivers: a neurophysiological perspective

1.1. Younger drivers

In Australia, over 26% of drivers involved in traffic crashes between 2001 and 2010 suffered life-threatening injuries; the highest rates were found among those aged 15–24 years (Australian Institute of Health and Welfare, 2015). Young drivers are particularly susceptible to road crashes, primarily due to inexperience and engagement with risky behaviours such as phone use (Arnett, 2002; Bates et al., 2014; Petroulias, 2011). Despite the fact that using a phone (excluding hands-free) while driving is prohibited in Australia (Department of Infrastructure, 2011), and indeed many other countries around the world, a 2011 Australian Government survey (n = 1387) revealed that 98% of 15-24-year-olds own a mobile phone, and 65% of these individuals admitted to using a phone (i.e., talking via a call or texting) whilst driving (Petroulias, 2011). By contrast, 24% of those over 60 years and 58% of all licence holders combined use a phone while driving (Petroulias, 2011). Thus, it is evident that phone use is of particular concern amongst younger drivers.

1.2. Effects of distraction on driving performance

Driving is a multidimensional task that involves the coordination of several perceptual, motor, and cognitive processes (e.g., visual/auditory perception, motor control, attentional control, declarative memory, and working memory; Alavi et al., 2017; Anstey et al., 2005; Moran et al., 2020; Niu et al., 2019). Whilst factors such as speed, braking reaction time, and headway are susceptible to driver distraction (Harbluk et al., 2007; Strayer and Drew, 2004; Strayer and Johnston, 2001; Victor et al., 2005), the standard deviation of speed (SDSp[1]) and standard deviation

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[1] SDSp – Standard Deviation of Speed.

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of lateral positioning (SDLP[2]), also known as lane wandering, are especially sensitive to distraction (Choudhary and Velaga, 2017; Horrey and Wickens, 2004; Niu et al., 2019; Papantoniou, 2018; Wang et al., 2019). The effects of distraction on these performance parameters are often examined in driving simulators as they have the added benefit of placing participants in a controlled environment (Papantoniou et al., 2017; Voinea et al., 2023).

Several simulator studies have sought to examine the effects of distraction on driving performance (e.g., Drews et al., 2009; Leipnitz et al., 2022; Papantoniou, 2018; Strayer and Drew, 2004; Strayer and Johnston, 2001). For example, Papantoniou (2018) found that while driving in a simulator, participants' overall driving performance was not significantly affected when talking to a passenger. However, performance was significantly impaired when conversing via a phone. Specifically, the lateral positioning of the vehicle increased substantially when a driver was conversing via a mobile phone compared to talking to a passenger (Papantoniou, 2018). Similarly, Drews et al. (2009) found that the vehicle's headway and lateral positioning significantly increased when participants used a phone while driving compared to those who did not.

Seemingly, several aspects of driver performance can be impaired via concurrent phone use (Drews et al., 2009; Louw et al., 2013; Niu et al., 2019; Nowosielski and Trick, 2017; Papantoniou, 2018), and the effects of distraction on younger drivers are particularly concerning. Strayer and Johnston (2001) found that when younger adults aged 18–30 years engaged in cell phone conversations, they missed twice as many traffic signals as those not conversing via a phone. In a subsequent study, Strayer and Drew (2004) compared younger and older adults' driving ability while engaging in a hands-free cell phone conversation. Driving performance (i.e., brake onset, following distance, and speed) was equivalent for younger and older adults. Additionally, brake onset time was significantly slower for both age groups in the dual-task condition than in the single-task condition (i.e., no distraction). Thus, considered together, the aforementioned simulator studies converge toward the idea that when individuals simultaneously engage with another task while driving, particularly a phone, it is evident that several driving performance parameters are affected (Niu et al., 2019; Strayer and Drew, 2004; Strayer and Johnston, 2001).

1.3. *Cognitive workload and multiple resource theory*

Multiple Resource Theory (MRT[3]) is a well-established model (see Wickens and Colcombe, 2007; Wickens, 1991, 2002, 2008) based on cognitive psychology principles and is helpful in understanding the resultant effects of increased cognitive load on driving performance, particularly in the context of dual-tasking (Louw et al., 2013; Niu et al., 2019; Wickens, 1991, 2002, 2008). MRT proposes a 4-dimensional model whereby several different 'cognitive resources' can be used simultaneously. For example, when two tasks being performed concurrently consist of the same input modality (e.g., visual-visual), thereby requiring the same cognitive resource (e.g., visual processing), the information from those tasks must be processed in a sequence (Wickens, 1991, 2002, 2008). By contrast, when multiple tasks consist of different input modalities (e.g., visual-auditory), thus requiring different cognitive resources (e.g., visual processing and auditory processing), the information from these tasks can be processed simultaneously (Wickens, 1991, 2002, 2008). Wickens, therefore, postulates that there will be less interference and greater efficiency of cognitive resources when using a cross-modal avenue (e.g., visual-auditory) compared to an intra-modal avenue (e.g., visual-visual) as separate resource pools are being used concurrently (see also Niu et al., 2019).

A common theme across the road safety literature is that most studies investigating driver distraction focus on visual, auditory, and cognitive distraction. However, many studies utilise distracting stimuli that typically require *lower-order* cognitive resources, with less work examining *higher-order* cognitive distraction (but see Niu et al., 2019; Strayer et al., 2016; Xue et al., 2023). As a result, the extent to which driving performance may be affected during engagement with a concurrent higher-order cognitive task when directly compared to a visual and auditory task remains relatively unexplored. In this paper, we refer to 'lower-order cognition' as a cognitive process that requires individuals to memorise information and apply basic knowledge (Cheng et al., 2021; Teimourtash and Yazdani Moghaddam, 2017). By contrast, we refer to 'higher-order cognition' as a cognitive process whereby a greater utilisation of executive functions (e.g., working memory, attentional control, task switching, and planning) is required to execute the task at hand (Burgoyne and Engle, 2020; Draheim et al., 2023; Shibata Alnajjar et al., 2013).

Many studies have explored the impact of visual and auditory distraction on driving performance (e.g., Kaber et al., 2012; Niu et al., 2019; Zhang et al., 2014). These investigations have yielded an overwhelming consensus; that is, visual distraction has a substantially more pronounced negative influence on driving performance than auditory distraction. Zhang et al. (2014) found that visual distraction impaired steering and speed variance to a greater extent than the audio-cognitive and control conditions. Interestingly, however, the audio-cognitive condition was comparable to the control condition for several performance parameters. Such a result contrasts with previous research (e.g., Strayer and Drew, 2004), which found that hands-free cell phone conversations significantly degraded driving performance compared to the no distraction condition. In a study that utilised the n-back as a higher-order cognitive distractor task, Niu et al. (2019) found that using a phone while driving significantly affected driving speed, lateral positioning, and variation of steering wheel position. Moreover, variation in lateral positioning was significantly worse for participants who engaged in a concurrent visual task than those who engaged in a cognitive task, further supporting the notion of increased interference through an intra-modal avenue (Wickens, 2008).

In relation to younger drivers, a recent study by Xue et al. (2023) found that increased cognitive load resulted in augmented lateral positioning and longitudinal speed among drivers. Additionally, the number of corrections on the steering wheel was evidence of compensatory behaviour, and this compensatory behaviour correlated with the level of cognitive distraction (Xue et al., 2023). This poorer driving performance suggests that introducing a distractor task during driving creates competition for cognitive resources, thereby diminishing the driver's responsiveness to dynamic changes in road conditions (Niu et al., 2019).

It is, however, important to note that the studies above only assessed objective driving performance. Whilst objective driving performance is a reliable indicator of distraction, the absence of neurophysiological recordings limits our understanding of how distraction impacts the driver's cognitive processes. Therefore, incorporating neurophysiological measures could offer valuable insights into the underlying mechanisms involved in driver distraction.

1.4. *Workload and EEG*

Electroencephalography (EEG) allows researchers to understand the effects of distraction as changes in electrical brain activity can be captured (Almahasneh et al., 2014). EEG is one of the most reliable and valid measures of physiological workload in simulated driving studies (McEvoy et al., 2000; Näpflin et al., 2008; Rogers et al., 2016). It has the advantage of high temporal resolution, allowing researchers to instantaneously capture brain activity (Lin et al., 2009, 2011a). Driver distraction has been associated with several neurophysiological changes. Increases in EEG theta power (4–8 Hz) are often representative of driver cognitive distraction (Almahasneh et al., 2014; Dong et al., 2011; Lin et al., 2009), with this increase commonly attributed to

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[2] SDLP – Standard Deviation of Lateral Positioning.

[3] MRT – Multiple Resource Theory.

increased mental workload and demand for cognitive resources (Savage et al., 2013). In addition to theta power, EEG beta power (13–30 Hz) has also been found to increase when individuals engage with a cognitive distractor while driving (Almahasneh et al., 2014), indicating elevated concentration and mental workload (Coelli et al., 2015; Mapelli and Özkurt, 2019). As EEG theta and beta power are good indicators of distraction, most driver distraction studies incorporating EEG have investigated these frequencies.

However, few studies (but see Lei et al., 2016; Lin et al., 2022; Sonnleitner et al., 2012) have looked at EEG gamma power (30–80 Hz), which in itself, is a shortcoming of much of the previous research, especially given that gamma is generally considered to be representative of increased concentration and the use of executive processes such as working memory and selective attention (Lei et al., 2016; McDermott et al., 2018). However, some studies suggest that gamma is representative of visual attention (e.g., Başar-Eroglu et al., 1996; Gregoriou et al., 2009), while others claim it is indicative of visual-auditory integration (e.g., Misselhorn et al., 2019; Schneider et al., 2008). Nonetheless, excluding gamma power makes obtaining a complete and comprehensive understanding of a driver's cognitive state difficult.

In a study by Lin et al. (2022), 51 young adults participated in a simulated driving task requiring them to attend to visual and auditory stimuli while driving; EEG measured participants' neural activity. Results indicated decreased gamma in the brain's frontal regions, and the authors suggest that decreased gamma could indicate auditory distraction detection (Lin et al., 2022). However, whilst the results of Lin et al. (2022) provide some insight into the possible representative nature of gamma, there is still a need for further research into the utility of gamma power in road safety research and whether it can serve as a reliable indicator of driver distraction, particularly higher-order cognitive distraction.

1.4.1. The current study

The studies discussed above offer valuable insights into how different distractions affect driving performance. Nonetheless, comparing results across these studies can be challenging due to methodological variations, highlighting the need for direct comparisons between various distractors. Furthermore, there is no consensus on the interpretation of gamma power in the context of distracted driving. Thus, further research is required to explore the underlying cognitive processes that gamma power may signify. To address these gaps, our current study will analyse the effects of visual, auditory, and higher-order cognitive distractions on objective driving performance, subjective ratings of the driving task, and neural activity via EEG. This research aims to provide a more comprehensive understanding of how distraction can impact cognitive workload while driving.

In accordance with previous research, three hypotheses were formulated. Firstly, it was expected that the higher-order cognitive and visual conditions would exhibit higher levels of beta and gamma power, respectively, compared to the auditory and control conditions (Almahasneh et al., 2014; Başar-Eroglu et al., 1996; Gregoriou et al., 2009; Lei et al., 2016; McDermott et al., 2018). Secondly, it was predicted that participants would perceive higher levels of mental workload and self-assess as less successful in driving during the higher-order cognitive and visual conditions, respectively, in comparison to the auditory and control conditions (Strayer and Drew, 2004; Strayer and Johnston, 2001; Wickens 1991, 2002, 2008). Lastly, objective driving performance, as measured by SDSp and SDLP in the simulator, was anticipated to be poorest in the higher-order cognitive and visual conditions, respectively, when compared to the auditory and control conditions (Drews et al., 2009; Niu et al., 2019; Papantoniou, 2018).

2. Method

2.1. Participants

The current study comprised 24 young adults (13 males and 11 females) aged 18–25 years ($M = 20.71$, $SD = 2.63$). Participants were recruited via the Queensland University of Technology Psychology Research Management System (SONA) for first-year psychology students, social media advertisement, and snowball sampling. Participants were required to hold a provisional 2 (P2) or open driver's licence and to have driven for at least 1 hr per week in the past 12 months. On average, participants reported driving 5.04 hr per week ($SD = 4.60$).

2.2. Design

A one-way repeated measures experimental design was used. The independent variable, distraction, comprised four conditions: no distraction, visual distraction, auditory distraction, and higher-order cognitive distraction, which were counterbalanced via a Latin square procedure. The primary dependent variable was neurophysiological arousal, quantified as EEG beta and gamma absolute power. The secondary dependent variables were subjective workload (mental demand and perceived success) and objective driving performance (SDSp and SDLP).

2.3. Materials

2.3.1. Electroencephalography

The neurophysiological arousal of participants was measured by EEG (μV), which recorded neural activity via electrodes placed on the scalp. Physiological data was recorded using the Cleveland Medical Devices BioRadio 150 device, which is a wireless physiological acquisition system. The EEG electrodes were placed at three different locations on the scalp: F5 (frontal), C3 (central), and O1 (occipital), paired with the A2 (ear) reference electrode site. All EEG data was recorded using Ag–Al electrodes. The skin beneath the electrodes was abraded with a semi-abrasive gel until an impedance of 5 kΩ was achieved, as recommended by Górecka and Makiewicz (2019) and Luan et al. (2012). EEG recordings have demonstrated a high level of reliability in several studies (e.g., McEvoy et al., 2000; Näpflin et al., 2008; Rogers et al., 2016) and have also revealed good internal and external validity (Edwards and Trujillo, 2021).

Eye-blink and movement artefacts can be problematic when analysing EEG data as non-neural artefacts can heavily contaminate the data (Maddirala and Veluvolu, 2021; Zhang et al., 2017). Therefore, instances of movement artefacts were visually confirmed and excluded from the analysis. Electrooculography (EOG) activity was recorded and used to remove eye-blink artefacts via independent component analysis. The EEG and EOG data were sampled online at 512 Hz and via an offline low-pass filter of 80 Hz. A 0.50 Hz high-pass filter was applied prior to applying the Fourier Fast transformation for the spectral analyses. The EEG data was then subject to utilising a 5 s Hanning window with a 50% overlap with the spectral analyses.

2.3.2. NASA task load index

The NASA Task Load Index (NASA-TLX[4]) is a 21-point scale self-report questionnaire that assesses workload across six independent subscales: mental demand, physical demand, temporal demand, effort, frustration, and success (Devos et al., 2020). For this study, we focused exclusively on participants' subjective ratings of mental demand and perceived success, as physical demands, time pressure, and discouragement were not of primary interest, aligning with our hypotheses. The NASA-TLX has demonstrated excellent test-retest reliability and has

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[4] NASA-TLX – NASA Task Load Index.

been extensively validated (Devos et al., 2020; Hart, 2006; Xiao et al., 2005).

2.3.3. Rosenbaum verbal cognitive battery

The Rosenbaum Verbal Cognitive Battery (RVCB[5]) is a 55-item questionnaire that assesses higher-order cognition (Rosenbaum, 1997). Example questions include: "*Which house is smaller if Jim's house is half as big as Brian's?*" and "*If three pairs of pants cost $93, what is the cost of one pair of pants?*" In the current study, the RVCB was used to simulate a complex conversation with a passenger. However, the participant's responses to the RVCB were not analysed as it was only used as a manipulation. No driving study has utilised the RVCB; therefore, its reliability and validity in the road safety literature are unknown – this will be the first driver distraction study to use the RVCB.

2.3.4. Cat task

The cat task, available in both visual and auditory versions, is a simple lower-order cognitive task that has previously served as an effective distractor in laboratory (e.g., Larue et al., 2021; Larue and Watling, 2021) and field-based studies (e.g., Larue et al., 2020). In our current study, the cat task was employed as the distractor for both the visual and auditory conditions. The cat task was presented on-screen or announced through the phone speakers. In this task, participants encountered a random sequence of five words, with '*cat*' designated as the target word and '*box, pen, desk, light,* and *switch*' as distractors. Each word was displayed for 1,000 ms, with a random inter-stimulus interval between 500 ms and 1,500 ms to eliminate anticipation effects. In the visual condition, participants were required to tap the screen upon seeing the target word, while in the auditory condition, they tapped the screen upon hearing it. Notably, the auditory condition did not display words on the screen, eliminating the need for participants to look at the phone and any associated confounding behaviours; all responses were automatically recorded by the phone. While the cat task consists of a lower-order cognitive component, its primary purpose in this experiment was to serve as a visual and auditory distractor.

2.3.5. Driving simulator

The desktop driving simulator is a low fidelity (non-moving) simulator comprising a car seat, Logitech steering wheel, and pedals to control the simulated vehicle – the forward view is a virtual driving environment with a 60-degree field of view. The driving simulator measured the standard deviation of speed (km/h) and the standard deviation of lateral positioning (meters). The driving scenario simulated a suburban setting, offering a realistic level of surrounding stimuli without introducing excessive cognitive demands (e.g., dynamic billboards, etc.) that may confound the data (Wang et al., 2021). The roadway's speed limit was 60 km/h, and oncoming traffic was present in the scenario. No cars were present in the participant's lane as headway was not being measured in the current study, nor was lateral turbulence a factor; however, simulated pedestrians were observed along the side of the road. To increase the challenge and realism of the lane-keeping task, the simulated driving route consisted of straight roads, curved roads, and intersections that contained traffic lights. Participants were instructed not to turn off at the intersections and to instead stay on the main road.

2.4. Procedure

This study obtained ethical clearance from the Queensland University of Technology Human Ethics Research Committee (clearance number 2021000263), as well as health and safety approval. Each testing session was approximately 75 min in duration. Upon arrival for the testing session, participants were taken to the driving simulator laboratory. Participants were given an information sheet containing details about the experiment and a consent form, which was required to be signed before data collection could commence. Upon signing the consent form, 30 min was allocated to preparing the participant's skin for electrode application. The physiological measures were attached to the participant following established procedures. While the physiological measures were being attached, participants were asked to complete a brief survey about demographics and driving behaviour via Qualtrics on an iPad. Once the physiological measures were attached, participants completed a 5 min familiarisation drive to become accustomed to controlling the simulated vehicle. Data collection then commenced.

The four conditions (8 min each) required participants to drive along a suburban road. Participants were instructed to drive to the speed limit of 60 km/h while staying in their lane and driving through all intersections without turning off. In the control condition, participants were asked to drive without engaging with any distractors. The auditory and visual conditions required participants to complete the cat task while driving. In the auditory condition, participants were asked to tap the phone screen once they heard the word '*cat*.' Similarly, the visual condition required participants to tap the phone screen once the word '*cat*' appeared. Participants were asked to hold the phone in their desired hand while resting it on their leg. As such, participants could only steer with one hand in these conditions. Participants completed the RVCB for the higher-order cognitive condition. The researcher sat behind the participant and read out the questions aloud, and the participant was required to state the answer verbally; participants were given 5 s to provide their answers. After completing each condition, participants were asked to complete the NASA-TLX questionnaire on an iPad. Once data collection had concluded, participants were given the option to choose an AUD$20 e-gift card or course credit to compensate them for their time.

3. Results

3.1. Descriptive statistics

The descriptive statistics in Table 1 show the mean and standard deviation. Regarding EEG, descriptive statistics show that frontal beta and gamma absolute power were highest in the higher-order cognitive and auditory conditions, respectively. Comparatively, the higher-order cognitive and visual conditions were rated as the most mentally demanding on the NASA-TLX. Participants also rated themselves as being most unsuccessful in the visual and higher-order cognitive conditions, respectively. Finally, descriptive statistics for SDSp and SDLP indicate that driving performance was at its worst in the visual and auditory conditions.

3.2. Test of hypotheses

We conducted a series of one-way repeated measures ANOVAs to test the hypotheses, with the results presented in Table 1. If the sphericity assumption was violated, we applied the Greenhouse-Geisser correction. Significant main effects of distraction were found with all dependent variables, and each main effect was large, except for EEG gamma, which was a medium to large effect (Cohen, 1977). As significant main effects were found with all dependent variables, we conducted post-hoc follow-up tests to identify significant differences between conditions. A Bonferroni correction was applied to all post-hoc comparisons to control for the type 1 error, and a summary of the pairwise comparisons can be found in the supplementary material.

4. Discussion

To date, limited research has explored the neurophysiological effects of driver distraction, specifically in relation to EEG gamma power. Therefore, the current study examined the effects of visual, auditory,

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[5] RVCB – Rosenbaum Verbal Cognitive Battery.

Table 1

Mean, standard deviation, repeated measures ANOVA, and pairwise comparisons for neurophysiological arousal, subjective workload, and objective driving performance.

Measure	Control (1)		Visual (2)		Auditory (3)		Higher-Order Cognitive (4)		ANOVA			
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*df*	*F*	η^2	Pair-wise comparisons
EEG												
Beta	18.18	12.94	19.88	13.87	22.45	14.61	24.42	12.76	2.36, 54.37	5.70*	.20	2, 1 < 3, 4
Gamma	3.78	2.46	4.15	2.99	5.13	3.96	5.47	2.96	3, 69	3.11*	.12	1, 2, 3, 4
NASA Mental	3.08	4.47	12.88	6.01	11.50	5.62	15.75	4.81	3, 69	36.02**	.61	1 < 2, 3 < 4
NASA Success	4.50	5.41	10.33	5.61	8.54	4.47	9.16	4.91	3, 69	11.03**	.32	1 < 2, 3, 4
SDSp	7.26	1.43	8.89	2.21	8.70	1.61	8.10	1.92	3, 69	4.88*	.18	1, 4 < 2, 3
SDLP	0.20	0.04	0.27	0.05	0.23	0.05	0.21	0.04	2.36, 54.19	19.97**	.47	1 < 3 < 2 < 4

Note. $N = 24$. EEG is presented as microvolts squared (μV^2); NASA Mental and NASA Success are the mental demand and success subscales on the NASA-TLX, respectively; SDSp is the standard deviation of speed (km/h); SDLP is the standard deviation of lateral positioning (meters).
$^*p < .05$. $^{**}p < .01$.

and higher-order cognitive distraction on subjective workload, objective driving performance, and neurophysiological activity among young drivers. Overall, tasks with higher cognitive demands were more likely to result in increased neural activity (i.e., EEG beta and gamma power), elevated subjective workload, and poorer driving performance. There were some minor variations between the study conditions, which are discussed below.

4.1. Distraction and EEG frontal beta and gamma power

We hypothesised that the higher-order cognitive and visual conditions would exhibit higher levels of beta and gamma power, respectively, compared to the auditory and control conditions. The results revealed that frontal beta and gamma power reached their highest levels in the higher-order cognitive condition. However, no statistically significant differences were observed among the conditions for gamma power. Conversely, frontal beta power significantly increased in the higher-order cognitive condition compared to the control condition, indicating that the former condition demanded the greatest cognitive load. Therefore, hypothesis one was partially supported.

As previously discussed, heightened beta power is typically associated with increased cognitive workload, concentration, and motor coordination (Coelli et al., 2015; Mapelli and Özkurt, 2019). The results of the present study are consistent with previous research, which has also reported elevated frontal beta power when engaged with a concurrent cognitive distractor while driving (e.g., Almahasneh et al., 2014; Lin et al., 2011a, 2011b). Driving is multidimensional in terms of the different cognitive resources required to operate a vehicle, and the demand for these resources varies depending on the driving context (Nijboer et al., 2016). Thus, introducing a secondary task while driving is likely to augment mental workload, as dual tasking is associated with increased demands on working memory (Funahashi, 2017). On the other hand, gamma power is generally considered to reflect the utilisation of executive processes such as working memory and selective attention (Lei et al., 2016; McDermott et al., 2018; Sonnleitner et al., 2012). Whilst the gamma power results in the current study seemingly support the notion above, it is important to note that the power levels were similar across the four conditions, and the differences were not statistically significant. Such a result contrasts previous research – Sonnleitner et al. (2012) attributed significant differences in gamma power to muscle movement artefacts, and the authors, therefore, take the view that it is not possible to reliably measure brain activity in the gamma band during simulated driving sessions.

However, a plausible explanation for the non-significant differences in the current study is that the four conditions were similar in their demands for cognitive resources. Although two tasks with different input modalities use separate resource pools via a cross-modal avenue, they can still compete for common perceptual resources depending on the presented stimulus (Pashler, 1998; Wickens, 2008). In the current study, the Rosenbaum Verbal Cognitive Battery (RVCB) and auditory version of the cat task were read aloud to participants, with the former prompting a verbal response and the latter requiring a touch of the phone screen. As each task involved an auditory component, thus consisting of the same input modality, they both sought access to the same perceptual resource pool (Pashler, 1998; Wickens, 2008).

Driving is primarily a visual task (Metz et al., 2011), and, therefore, when the RVCB and auditory cat task required the participant to process auditory information, the effects of these tasks on neural activity were likely similar. However, the increased gamma in the higher-order cognitive condition compared to the auditory condition, though not significantly different, can likely be explained by the fact that the RVCB also contained a higher-order cognitive component, over and above that of the cat task, which we deemed to be a lower-order cognitive task. Although such a finding contrasts with Lin et al. (2022), who suggested that decreased gamma may be an indicator of auditory distraction, our results somewhat align with other literature, which has found gamma to be representative of higher-order cognition (Lei et al., 2016; McDermott et al., 2018; Sonnleitner et al., 2012). Our findings, therefore, provide preliminary support for the idea that gamma power is representative of higher-order cognitive processes and concentration within the area of driver distraction.

When considering driving in a broader sense and acknowledging the EEG results in the current study, beta and gamma waves can offer valuable insights into a driver's cognitive state during vehicle operation. Beta waves can serve as indicators of a driver's level of arousal or preparedness to respond to stimuli (Haghani et al., 2021; Okogbaa et al., 1994; Peng et al., 2022). Similarly, gamma waves may reflect the driver's attentiveness and capacity to process multiple units of information effectively (Fries, 2009; Goddard et al., 2012; Jia and Kohn, 2011; Jokisch and Jensen, 2007; Tallon-Baudry et al., 2005). Understanding the significance of these distinct wavebands in the context of driving holds practical implications, particularly for road safety. In the field of neuroergonomics, researchers and vehicle manufacturers can use EEG data to assess the cognitive demands of various driving and non-driving tasks (Navarro et al., 2018). In turn, this knowledge can be applied to inform the design of user interfaces within vehicles to minimise unnecessary cognitive load and distractions.

4.2. Distraction and subjective workload

We hypothesised that participants would perceive themselves as experiencing the highest mental workload and rate their driving performance as least successful in the higher-order cognitive and visual conditions, respectively, compared to the auditory conditions. The results revealed that the control condition was significantly lower in terms of mental demand than the auditory, visual, and higher-order cognitive conditions. The visual and higher-order cognitive conditions were rated as the most mentally demanding among the test conditions. Interestingly, participants perceived themselves as least successful at driving in the visual condition, followed by the higher-order cognitive condition.

Moreover, participants perceived themselves as significantly more successful at driving in the control condition compared to the three test conditions. Therefore, hypothesis two was partially supported.

Previous studies on driver distraction have found higher-order cognitive and visual tasks to be the most mentally demanding while driving (e.g., Horberry et al., 2006; Kaber et al., 2012; Strayer et al., 2016), which aligns with the findings of the current study. Engaging in a secondary higher-order cognitive task alongside the visual and cognitive demands of driving increases cognitive workload (Wickens, 2008). Consequently, the driver is expected to subjectively and objectively experience heightened mental demands (Lunenfeld, 1989; Srinivasan and Jovanis, 1997); this notion is supported by the earlier discussed EEG and NASA-TLX results. However, no statistically significant difference was observed between the current study's visual and higher-order cognitive conditions – the non-significant differences could be attributed to methodological factors such as the simplicity of the driving scenario and the type of distractor tasks employed. Additionally, practice effects (discussed in the limitations) for the driving scenario may have been a contributing factor.

In contrast to the mental demand subscale findings and previous research (e.g., Strayer et al., 2016), participants perceived themselves as least successful at driving in the visual conditions, followed by the higher-order cognitive condition. The discrepancy in results is unexpected, considering that participants rated the higher-order cognitive condition as the most mentally demanding, a finding supported by the EEG results; it was anticipated that the perceived mental workload would correspond with perceived driving performance. However, a possible explanation for this inconsistency in results could be attributed to the complexity and demand of the distractor tasks employed. Strayer et al. (2016) suggest that tasks of lower complexity and shorter duration will result in lower cognitive workload than more time-consuming tasks. While the Rosenbaum Verbal Cognitive Battery (RVCB) used in the current study is a higher-order cognitive task, the questionnaire itself is not as complex or extensive as the Operation Span Task (OSPAN[6]) employed by Strayer et al. (2016). The OSPAN task requires participants to solve complex arithmetic equations while simultaneously remembering a list of unrelated words. Consequently, the added complexity of the OSPAN likely places a higher demand on working memory and higher-order cognitive resources than the RVCB (Greiff et al., 2015). Thus, both the Strayer et al. (2016) study and the current study utilised higher-order cognitive tasks that induced different levels of cognitive workload, providing a plausible explanation for the contradictory results.

It is also important to note that the RVCB was initially designed to evaluate the cognitive state of mountaineers using radio communication (Rosenbaum, 1997). However, it has not yet been employed in academic research, including studies on driver distraction. As a result, there is little evidence regarding its psychometric properties. Future studies should, therefore, focus on comparing the cognitive workload induced by the RVCB with established measures such as the OSPAN. Such research would provide valuable insights into the psychometric properties and cognitive workload implications of the RVCB in the context of higher-order cognition and driver distraction.

4.3. *Distraction and objective driving performance*

We hypothesised that objective driving performance, as measured by SDSp and SDLP in the driving simulator, would be poorest in the higher-order cognitive and visual conditions, respectively, compared to the auditory and control conditions. The results demonstrated a significant increase in SDSp and SDLP in the visual and auditory conditions compared to the control condition. Furthermore, the visual and auditory conditions had the most substantial impact on SDSp and SDLP, and a significant difference was observed between the visual and auditory conditions in terms of SDLP. Hence, the findings partially support hypothesis three, indicating that the visual and auditory conditions had a more pronounced effect on objective driving performance, while the higher-order cognitive condition did not significantly differ from the auditory condition.

The findings of the current study align with previous research, which also indicated that using a phone while driving significantly impairs one's ability to safely drive a car (e.g., Haigney et al., 2000; Niu et al., 2019; Papantoniou, 2018; Rakauskas et al., 2004; Wandtner et al., 2016). In the context of the present study, the observed outcome can be elucidated through the framework of Multiple Resource Theory. In the visual and auditory conditions, participants were asked to hold the phone in their preferred hand while resting it on their leg. Moreover, during the visual version of the cat task, participants frequently looked down to monitor the on-screen words. Hence, the implications of this are twofold: (1) it occupied their psychomotor resources, leaving only one hand on the steering wheel, potentially contributing to an increase in the standard deviation of lateral positioning (Niu et al., 2019), and (2) it consumed their visual attention, preventing consistent monitoring of speed, traffic conditions, pedestrians, other vehicles, and road directions (Niu et al., 2019; Ortiz et al., 2018). The random interstimulus interval during the cat task also disrupted the development of a routine for diverting attention to the phone. As a result, the competing demands of the cat task and the driving task led to inconsistent road monitoring, resulting in a significant increase in SDSp and SDLP (Choudhary and Velaga, 2017; Ortiz et al., 2018; Wang et al., 2019).

Another explanation for these findings is the concept of compensatory beliefs. Compensatory beliefs occur when individuals believe the risks associated with an unsafe behaviour can be counteracted by simultaneously engaging in another safe behaviour (Haigney et al., 2000; Niu et al., 2019; Zhou et al., 2016). Among drivers, the most common compensatory belief is the notion that the risk of crashing can be compensated for by reducing speed (Bastos et al., 2020; Haigney et al., 2000; Lio et al., 2021; Niu et al., 2019; Parnell et al., 2020; Strayer et al., 2003; Zhou et al., 2016).

Previous research conducted by Haigney et al. (2000) found that participants' mean speed was significantly lower when visually distracted by a phone, while SDSp was significantly higher when visually distracted. Likewise, Niu et al. (2019) observed significant impacts on steering wheel control and driving speed when drivers used a phone, with participants actively reducing their speed to enhance control of the vehicle due to the concurrent distractor consuming their psychomotor resources. Taken together, these findings suggest that individuals tend to reduce their driving speed in an effort to mitigate the potential risks of multitasking with a phone while driving, a concept supported by other literature (e.g., Alm and Nilsson, 1994; Brookhuis et al., 1991; Fairclough et al., 1993; Lio et al., 2021; Zhou et al., 2016).

4.4. *Limitations*

The current study's findings should also be considered in relation to the study's limitations. Firstly, all four conditions utilised the same driving scenario, that being a suburban neighbourhood. Consequently, participants likely developed practice effects. In the initial stages of a task, participants' performance improves quickly, but through conscious training, their performance stabilises (e.g., the negative acceleration curve; Sternberg and Sternberg, 2011). Therefore, this familiarity with the route could have led to participants becoming accustomed to what they should expect in the later conditions, potentially influencing their driving performance and subjective assessments. Moreover, only having one driving scenario restricts the ability to gather data on how different driving environments and traffic situations (e.g., rural or urban areas, heavy or light traffic, highways, neighbourhood streets, etc.) would influence neurophysiological arousal. According to Nijboer et al. (2016), cognitive resources are influenced by the specific driving context,

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[6] OSPAN – Operation Span Task.

suggesting that neural activity may vary depending on the driving environment.

The study's demographic limitations should also be acknowledged. Although the current study focused on younger drivers, a substantial portion of the participants were undergraduate university students from the psychology department. Whilst it is not expected that this factor significantly affected the results, it would have been advantageous to include individuals not currently attending university, thus enhancing the generalisability of the findings. Additionally, the study only recruited participants within the age range of 18–25 years. Consequently, it is unknown how neural activity of adults over 25 years would differ from their younger counterparts.

4.5. Future directions

In light of the limitations, it is recommended that future research examine driver distraction in various traffic environments that differ in complexity. Furthermore, incorporating several different driving scenarios and traffic situations into the same study would reduce the likelihood of practice effects confounding the data. Future research should also seek to recruit a more diverse demographic of participants to enhance the generalisability and mitigate potential biases. Although it can be challenging when targeting individuals aged 18–25 years, efforts should be made to include participants not attending university alongside those who are. Such an approach would contribute to a more representative sample and reduce potential skew in the results. Lastly, it is recommended that future studies expand their participant pool to include individuals aged over 25 years. Doing so will provide a more comprehensive understanding of how age influences cognitive processes in the context of distracted driving.

4.6. Conclusion

The current study aimed to further our understanding of the neurophysiological impacts of distraction on young drivers, alongside subjective workload and objective driving performance. The results indicated that EEG frontal beta and gamma power reached their peak levels in the higher-order cognitive condition, signifying that this condition imposed the highest cognitive demand, a conclusion supported by the NASA-TLX results. Additionally, the visual condition was linked to the poorest objective driving performance outcomes. These findings advance our understanding of the neurophysiological impacts of distraction on younger drivers and underscores the critical role of cognitive workload when driving. The findings emphasise the dangers of distracted driving, particularly visual distraction, and hold significant implications for road safety awareness, especially for those aged 18–25 years. This research is an important contribution to the literature as it has explored the intricacies of driver distraction. It has examined the domain of EEG gamma power within the area of driver distraction, which, up to this point, has received very little attention. By examining the gamma frequency, this study provides preliminary support for the idea that it is representative of higher-order cognition and concentration, adding to our understanding of the cognitive processes involved in distracted driving.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2023.104147.

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