# Working Memory Capacity, Visual Attention and Hazard Perception in Driving

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## Abstract

In two experiments we explored the influence of individual differences in working memory capacity (WMC) on hazard perception performance in a simulated driving task. In Experiment 1, we examined the relationship between WMC and hazard perception performance under control and dual task conditions, and self-reported driving behavior. Results revealed significant relationships between WMC, hazard perception performance and self-reported driving behavior. Participants lower in WMC performed poorer in dual task conditions and reported more instances of inattention when driving. In Experiment 2 we explored the gaze behavior of low and high WMC individuals whilst completing the hazard perception test under control and dual task conditions. Results revealed that low-WMC individuals had poorer hazard perception performance under dual task conditions and these performance decrements were mirrored in reductions in mean fixation durations on the hazard. Interestingly, pupillary dilation appears to discriminate between low- and high-WMC individuals and might be a useful index of attention for future research.



**Keywords:** Controlled Attention, Gaze, Eye-Movements, Driver Behavior, Pupillometry, Pupil Dilation

**Working Memory Capacity, Visual Attention and Hazard Perception in Driving**

Ninety-five percent of driving accidents have been attributed to human error (Rumar, 1985) and of these around 20-30% are thought to be a result of driver distraction (Talbot, Fagerlind, & Morris, 2013). Driver distraction has been defined as "the diversion of attention away from activities critical for safe driving toward a competing activity" (Lee, Regan & Young, 2008, p. 34), and as such reflects the importance of maintaining goal-directed attentional control to task relevant information while resisting the interference of irrelevant and distracting information. Due to the development of in-car technologies that actively increase the likelihood of distraction, it is no surprise that researchers have been quick to test the implications of such technologies on driver safety and performance. Numerous studies have shown that telephone conversations (Strayer & Johnson, 2001), conversations with passengers (Drews, Pasupathi, & Strayer, 2008), the behavior of child occupants (Koppel, Charlton, Kopinathan, & Taranto, 2011), listening to music (Brodsky & Slor, 2013), and even cell phone notifications (Stothart, Mitchum, & Yehnert, 2015) can have a significant distracting effect, and can impair driver safety. What is clear from this research is that modern day driving environments are littered with potential distractions that need to be resisted if a safe level of driving proficiency is to be maintained.

Studies on driving distraction often implicate limitations of working memory (WM) to explain these adverse driving behaviors, whereby cognitive load causes a distraction away from task-relevant information and the exhaustion of attentional capacity. Interestingly the ability to resist distraction and cognitive interference has been linked to individual differences in working memory capacity (WMC) in other applied settings like sport (Furley & Memmert, 2010; 2012) and pressurized performance contexts (Kleider, Parrott, & King, 2010; Wood, Vine & Wilson, 2015). The results of these studies add support to the contention that high-WMC individuals are generally better able to maintain cognitive control and remain task focused (Engle & Kane, 2004) whereas low-WMC individuals are likely to suffer periodic failures in goal maintenance due to their inability to inhibit distraction or interference (De Jong, Berendsen, & Cools, 1999). Surprisingly, while studies have shown that individual differences in constructs related to WMC such as cognitive failures (Allahyari et al, 2008) and mind-wandering (Galéra et al, 2012) do predict driving performance and self-reported aberrant driving behavior, there is a paucity of research that has explicitly explored the interaction between cognitive load and individual differences in WMC as a predictor of driving performance (Ross et al, 2014).

Two notable exceptions are Watson and Strayer's (2010), and Ross et al.'s (2014) exploration of braking and lane changing behavior respectively. Watson and Strayer (2010) explored the braking behavior of participants under control and dual-task (an auditory OSPAN task) conditions in a driving simulator. Their results showed that whereas the vast majority of participants showed significant performance decrements in dual-task conditions, a small percentage of participants with high-WMC (labelled as 'supertaskers' due to their exceptional multitasking abilities) suffered no decrements in braking performance. Ross et al (2014) explored the influence of WMC on the lane changing behaviors of young novice drivers under differing cognitive load conditions. Results showed that high-WMC individuals were influenced less by a cognitive load task and performed better on the lane changing driving task.

However, while lane changing and braking behavior are important skills for effective driving, the ability of drivers to anticipate potentially dangerous situations on the road ahead (i.e., hazard perception) has been identified as one of the few measures of driving-specific skill that correlates with the risk of road traffic accidents (Horswill & McKenna, 2004). Hazard perception skills involve having a continuous and dynamic composite representation of current traffic situations (Isler, Starkey & Williamson, 2009) and therefore this ability relies heavily of WM (Groeger, 2002). In fact, such is the importance of these perceptual abilities that these tests have been incorporated into licensing procedures in the UK and Australia (McKenna & Horswill, 1999). Given the importance of this task to driver proficiency and safety, and considering that modern-day driving environments are littered with the potential for distraction and interference, an explicit examination of the influence of individual differences in WMC and hazard perception performance is warranted.

## Experiment 1

The aim of this first Experiment was to investigate the relationship between individual differences in WMC, hazard perception performance and self-reported driving behavior. We hypothesized that there would be no significant relationship between WMC and hazard perception performance in the control condition with no load on WM. However, under conditions of high cognitive load we predicted a positive relationship between WMC and hazard perception performance. Specifically, we predicted that lower WMC scores would be related to poorer hazard perception performance. Due to this proposed relationship we further predicted that low-WMC scores would be related to more self-reported instances of driver error, aggressive behaviors, traffic violations and lapses in concentration in participants' driving history.

## Methods

### Participants

Forty-six drivers (mean age = 24.67, *SD* = 7.41 years) volunteered to take part in the study. All participants held a valid UK driving license and had experience of driving on UK roads (mean experience = 5.41, *SD* = 5.48 years). All participants gave written informed consent prior to commencing the testing procedures and these were approved by a local ethics committee.

## Measures

### Operation Span Task

An automated version of the operation span task (OSPAN; Unsworth, Heitz, Schrock, & Engle, 2005) was used to measure WMC. This was presented on a Dell Optiplex desktop PC connected to a 19" LED monitor running E-Prime (v.2) software. In this task participants are required to solve a series of math problems (e.g., (8 / 2) − 1 = 1? true/false?) that are each followed by an unrelated letter that needed to be remembered. The task included 15 trials (3 trials each with 3, 4, 5, 6, and 7 letters to remember) and after each trial participants had to recall as many letters as possible. The primary measure of WM capacity was the OSPAN score calculated as the total number of letters recalled across all error-free trials (Unsworth et al, 2005).

### Hazard Perception Performance

The UK Driver and Vehicle Standards Agency (DVSA) hazard perception test is a standard requirement of the UK driving license application process. The test consists of a series of 14 video clips lasting 1 minute in duration. The clips feature everyday road scenes containing at least one 'developing hazard' - but one randomized clip features two 'developing hazards'. A developing hazard is described as something that may result in the driver having to take some action, such as changing speed or direction. When the participant perceives a developing hazard they are required to press the mouse button to illustrate it has been detected. The hazard perception score is calculated by the speed at which the participant detects a developing hazard and makes a response. The faster the response the higher the score awarded. The highest score achievable for each developing hazard is 5 points descending until the failure to detect the hazard results in 0 points. The UK DVSA pass score is ≥44 out of 75.

**Secondary Task**

The secondary task consisted of an auditory tone task where participant were required to listen out for a ‘bell’ sound amongst a series of similar sounds from the Microsoft standard collection (buzz, tone, ping) during each 1-minute hazard perception clip. When the participant heard the bell sound they were required to say aloud ‘bell’ in response and this was then recorded manually by a researcher. Sounds were randomized and presented every two seconds and each participant had a practice trial at this task before doing it in conjunction with a hazard perception video. Similar tasks have been successfully used in other applied environments to increase cognitive load (i.e., surgery; Wilson et al, 2011).

**Driver Behavior Questionnaire**

The extended version of Driver Behavior Questionnaire (DBQ; Lawton, Parker, Stradling & Manstead, 1997) was used to measure aberrant driver behaviors and is one of the most widely used inventories for measuring self-reported driving behavior (de Winter & Dodou, 2010). It consists of 28 statements and participants have to indicate how often they committed each behavior in the previous year on a six-point Likert scale from 0 (never) to 5 (nearly all the time). Eight statements characterize slips or lapses in attention (e.g., realize that you have no clear recollection of the road along which you have just been travelling), eight characterize errors (e.g., fail to check your rear-view mirror before pulling out, changing lanes, etc.), eight concern ordinary violation (e.g., disregard the speed limit on a residential road) and four concern aggressive violations (e.g., sound your horn to indicate your annoyance to another road user). A meta-analysis of 174 studies revealed the DBQ to have good predictive validity of road traffic accidents (de Winter & Dodou, 2010).

## Procedures

Participants attended the lab individually and firstly completed the OSPAN task and the DBQ. The participant was then taken to a second computer that displayed the hazard perception test. Once comfortable and seated approximately 75cm away from the monitor, the participant watched a standardized instructional video explaining the test, its procedures and how it is scored. The participant was then asked to confirm that they understood the test and its procedures and was ready to continue with the experimental conditions. Participants then completed two different hazard perception tests under control and dual task conditions. Hazard perception test videos and experimental conditions were fully counterbalanced between participants. This meant that half of the participants completed the control condition with counterbalanced hazard perception videos first, while the other half of participants completed the dual task condition first with counterbalanced hazard perception videos. After completing both tests, participant were debriefed about the Experiment and thanked for their participation.

## Data Analysis

We analyzed the relationship between WMC, hazard perception performance under control and dual task conditions, and self-reported measures of driving behavior, using Pearson's correlation coefficients and corresponding 95% confidence intervals. Finally, a hierarchical multiple regression explored the influence of individual differences in WMC on dual-task hazard perception performance after first controlling for the influence of individual differences in single-task hazard perception performance.

## Results

Correlation analyses revealed that while WMC was not significantly related to hazard perception performance in the control condition, it was significantly related to performance in the dual task condition (see Figure 1). Furthermore, WMC was associated with self-reported lapses in concentration while driving. Correlation data are presented in Table 1. Hierarchical multiple regression analysis further revealed that WMC could significantly ($F(2,45) = 3.77$, $p = .031$) predict hazard perception performance in the dual-task condition ($\Delta R^2 = .11$, $p = .022$, $\beta = .43$,) even when controlling for hazard perception performance in the single-task condition ($R^2 = .04$, $p = .690$, $\beta = -.07$).

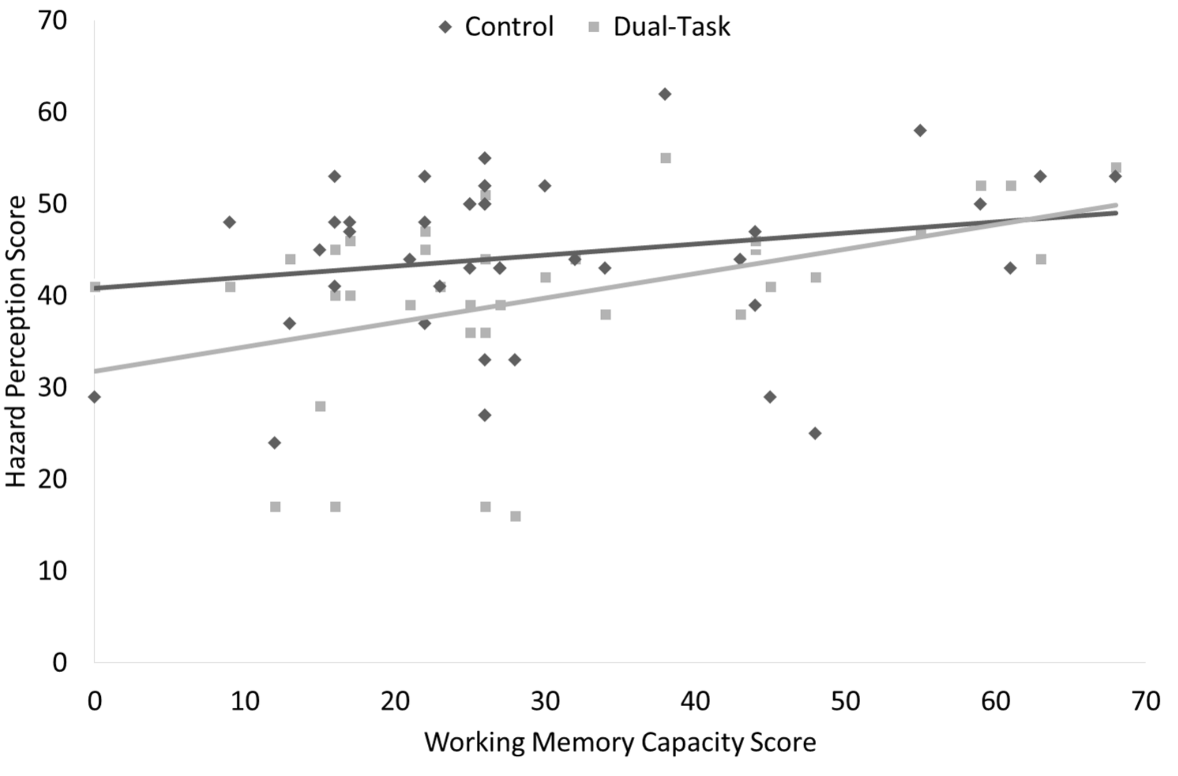


**Figure 1.** A scatterplot showing the relationship between WMC and hazard perception performance under control (black line) and dual-task (grey line) experimental conditions.

**Table 1. Correlations [95% confidence intervals] between WMC, hazard perception performance, secondary task performance and self-reported abberant driving behavior.**

| | OSPAN | Hazard Perception Control | Hazard Perception Dual Task | Secondary Task Performance | DBQ Violations | DBQ Aggression | DBQ Errors | DBQ Lapses |
|---|---|---|---|---|---|---|---|---|
| OSPAN | -- | .195 | .382* | .097 | -.138 | .035 | -.234 | -.405* |
| Hazard Perception Control | [-0.10, 0.46] | -- | .627** | -.105 | -.095 | -.131 | .036 | -.122 |
| Hazard Perception Dual Task | [0.10, 0.61] | [0.41, 0.78] | -- | -.061 | -.184 | -.092 | -.129 | -.167 |
| Secondary Task Performance | [-0.20, 0.38] | [-0.38, 0.19] | [-0.35, 0.23] | -- | -.004 | .068 | -.232 | -.267 |
| DBQ Violations | [-0.42, 0.17] | [-0.39, 0.22] | [-0.46, 0.13] | [-0.31, 0.30] | -- | .241 | .342* | .566** |
| DBQ Aggression | [-0.27, 0.34] | [-0.42, 0.18] | [-0.38, 0.22] | [-0.24, 0.36] | [-0.07, 0.51] | -- | .528** | .213 |
| DBQ Errors | [-0.50, 0.08] | [-0.27, 0.34] | [-0.42, 0.18] | [-0.50, 0.08] | [0.04, 0.59] | [0.27, 0.72] | -- | .545** |
| DBQ Lapses | [-0.63, -0.12] | [-0.41, 0.19] | [-0.45, 0.14] | [-0.53, 0.04] | [0.32, 0.74] | [-0.10, 0.49] | [0.29, 0.73] | -- |

(* $p < .05$, ** $p < .001$)

## Discussion

As predicted, WMC was not related to hazard perception performance in the control condition but was related to the ability to detect hazards in dual task conditions. In line with previous research, WMC appears to be a key discriminator in tasks where cognitive demands are high and attentional control is required. According to recent models of WM (e.g., Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000; Unsworth, Redick, Spillers, & Brewer, 2012), attentional control refers to the relative efficiency of central executive functions required to inhibit distractions, shift between relevant task stimuli, and update information in WM, in attaining a task goal. In the hazard perception task, this greater efficiency could not be determined when task demands were low (control condition), but as soon as greater demands were placed on inhibition, shifting, and updating functions of WM (dual task condition), then this increased efficiency was also related to increased task effectiveness.

Not only did WMC predict hazard detection performance under dual task conditions - even when performance in single-task conditions was controlled for - but it was also related to self-reported attention lapses while driving on the road. Specifically, those participants who were lower in WMC reported significantly more lapses in attention while driving than their high-WMC counterparts did. Moreover, instances of lapses in attention were also positively related to violations and driving errors (see Table 1). This suggests that lapses in attention have behavioral consequences that detrimentally affect driver safety. The link between WMC and lapses in attention is one that has gained recent empirical support, with low-WMC individuals suffering more instances of inattention than those with high-WMC in simple change detection tasks (Unsworth & Robison, 2015a). This study extends these findings and illustrates that WMC is related to bouts of inattention in a more complex simulated driving task.

Overall these findings indicate that WMC is related to hazard perception performance under distracting experimental conditions and also relates to driving behavior in “real-life” settings. While these findings are interesting, the mechanisms behind the relationship between WMC and hazard perception remain unclear. In the following Experiment we explore the role that visual attention plays in underpinning the relationship between WMC and hazard perception performance in driving.

## Experiment 2

Liang, Reyes and Lee (2007) have suggested that 81% of distracted drivers can be identified by disruptions in their eye-movements. Similarly, studies have shown that indices of visual attentional control are related to performance in hazard perception driving tasks. For example, the ability to fixate on the hazard as quickly as possible after its appearance has been shown to be a predictor of expertise in hazard perception performance (Crundall et al, 2012), and has been shown to become impaired with increased task demands (Mackenzie & Harris, 2015). In addition, many studies have shown that effective hazard perception performance is also underpinned by an increase in fixation duration to the detected hazard, reflecting increased attentional capture by this important information as it develops (Garrison & Williams, 2013; Underwood, Phelps, Wright, Van Loon, & Galpin, 2005; Velichkovsky, Rothert, Kopf, Dornhöfer, & Joos, 2002).

Finally, pupillary response has also been shown to underpin expertise in simulated driving performance with more proficient drivers displaying larger pupil dilations (Konstantopoulos, Chapman & Crundall, 2010). Increased pupil dilations have also been shown to be reflective of increased mental effort and cognitive load in driving studies (e.g., Recarte & Nunes, 2000; Wilson, Smith, Chattington, Ford & Marple-Horvat, 2006). Interestingly pupillary response has also been shown to be a predictor of WMC and lapses in attention, with low-WMC individuals displaying smaller pupil diameters, more lapses and poorer performance in lab-based tasks (Unsworth & Robison, 2015b).

From this evidence we derived a number of hypotheses. First, we expected no significant differences in performance or visual attention between groups under control conditions with no interference or cognitive load. However, we hypothesized that high-WMC participants would display greater hazard perception performance under dual task conditions (as Experiment 1) and that these performance differences would be reflected in fundamental differences in the time to fixate the hazards (as Crundall et al, 2012) and mean fixation durations on the hazard (as Garrison & Williams, 2013; Underwood et al, 2005; Velichkovsky et al, 2002). Specifically we predicted that low-WMC individuals would be slower to fixate the hazard and would have shorter mean fixation durations when fixating the hazard. Finally, we predicted that pupil diameter would be significantly different between groups with low-WMC groups displaying smaller pupil diameters (reflecting more bouts of inattention) compared to high-WMC individuals (as Unsworth & Robison, 2015b).

## Methods

### Participants

In an extreme group design the upper and lower quartile of participants from Experiment 1 were invited back to the lab to make up low-WMC and high-WMC groups. The high-WMC group (mean OSPAN score = 64.59, *SD* = 7.80) consisted of 12 (7 females and 5 males; mean age = 23.67, *SD* = 4.10 yrs) experienced drivers (*M* = 4.42, *SD* = 4.32 yrs). The low-WMC group (mean OSPAN score = 33.68, *SD* = 12.80) consisted of 12 (6 females and 6 males; mean age = 28.42, *SD* = 9.06 yrs) experienced drivers (M = 7.83, *SD* = 6.60 yrs). There was no significant difference between the age ($p$ = .120) or driving experience ($p$ = .159) of each group, but a significant difference was found between OSPAN score ($p$ < .001).

Participants were told that they were selected due to their prior performance on the hazard perception tests from Experiment 1. All gave written informed consent prior to commencing testing and procedures were approved by a local ethics committee.

**Measures**

**Hazard Perception Performance**

This was measured in exactly the same manner as in Experiment 1 except that the two videos used were completely different from the previous Experiment.

**Gaze Behavior**

Participants wore an Applied Science Laboratories Mobile Eye XG gaze registration system (ASL, Bedford, MA), which measures momentary point of gaze at 30 Hz. The system incorporates a pair of lightweight glasses fitted with eye and scene cameras and a portable recording device. A circular cursor, representing 1° of visual angle with a 4.5-mm lens, indicated the location of gaze in a video image of the scene (spatial accuracy of 0.5 visual angle; 0.1 precision). The recording device was connected to a laptop, located on a table behind the participant, via an Ethernet cable that allowed real-time monitoring of the data collection.

Gaze analysis was performed post-testing using GazeMap Results (ASL, Bedford, MA) software. The time of hazard onset and offset was noted from the hazard perception video for each video clip. During this time period an area of interest (AOI) was drawn around each hazard and manipulated in a frame-by-frame manner (i.e. at 30 frames per second) in order to track the hazard as it moved on the screen and to compensate for any minor head movement of the participant. The software then automatically calculated the time to first fixation on the hazard and the mean duration of fixations on the hazard during the time period it was present on the screen. Fixations were defined as a gaze that remained on a location (within 1° visual angle) for a minimum of 100ms.

**Procedure**

Participants attended individually were calibrated to the eye tracker using a 9-point grid displayed on the computer screen. Once calibrated, each participant re-watched the instructional video from the hazard perception test to remind them of its procedures and scoring system (as in Experiment 1). As in Experiment 1, hazard perception videos were fully counterbalanced between groups and across conditions. After completing both conditions, participants were thanked for their participation and debriefed regarding the aims of the Experiment.

**Data Analysis**

A series of 2 (group; Low vs. High-WMC) x 2 (condition; control vs. dual task) ANOVAs were used to analyze differences between hazard perception performance and gaze variables. An independent sample *t*-test was used to explore the difference in performance of the secondary task in the dual task experimental condition. Effect sizes were reported using partial eta squared ($\eta_p^2$) statistics.

## Results

**Performance**

*Hazard Perception*

There was no significant main effect for group $F(1,22)= 2.92$, $p = .102$, $\eta_p^2 = .12$, no significant main effect for condition, $F(1,22)= .873$, $p = .360$, $\eta_p^2 = .04$, but a significant interaction effect was found for hazard perception performance, $F(1,22)= 4.61$, $p = .043$, $\eta_p^2$

= .17. There was no significant difference between groups in the control condition, ($p$ = .871), but the high-WMC group performed considerably better than the low-WMC group in the dual task condition, ($p$ = .010; see Figure 2). While the high-WMC group maintained their performance between conditions ($p$ = .406), the low-WMC group performed worse under dual-task, compared to control conditions ($p$ = .053; see Figure 2).

*Secondary Task*

No significant difference, $F(1,23)= 0.27$, $p = .138$, $\eta_p^2 = .11$, was found in secondary task performance between low-WMC ($M$ = 95.56%, $SD$ = 5.07) and high-WMC ($M$ = 97.99%, $SD$ = 1.97) groups in the dual task condition.

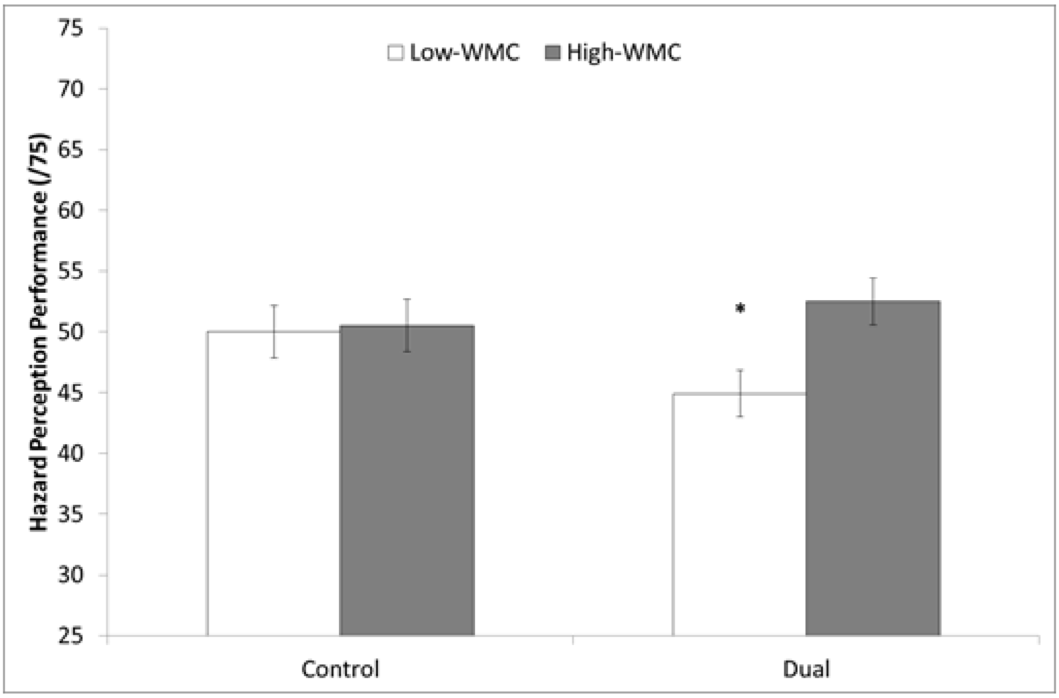


**Figure 2**. Hazard perception performance between both WMC groups and across control and dual task conditions.

## Gaze data

*Time to First Fixation on the Hazard*

A significant main effect was found for condition, $F(1,22) = 5.72$, $p = .026$, $\eta_p^2 = .21$, indicating that participants were significantly slower to fixate the hazard under dual task ($M$ = 1501ms) compared to control conditions ($M$ = 1168ms). No significant main effect was found between groups, $F(1,22) = 0.27$, $p = .610$, $\eta_p^2 = .01$, and the interaction was also non-significant, $F(1,22) = 1.96$, $p = .176$, $\eta_p^2 = .08$ (see Figure 3a).

*Mean Fixation Duration on the Hazard*

No significant main effects were found between conditions, $F(1,22) = .189$ , $p = .668$, $\eta_p^2 = .01$, or groups, $F(1,22) = .758$, $p = .393$, $\eta_p^2 = .03$, but the interaction effect was significant $F(1,22) = 6.18$, $p = .021$, $\eta_p^2 = .22$. While there was no between group differences in the control ($p = .815$) and dual task conditions ($p = .153$), the low-WMC group experienced a significant reduction ($p = .027$) in the mean fixation durations on the hazard between control and dual task conditions. The high-WMC group experienced no significant reductions ($p = .238$) between control and dual task conditions (see Figure 3b).

*Pupillary Response*

A significant main effect for group was found, $F(1,22) = 4.40$, $p = .048$, $\eta_p^2 = .17$, indicating that the low-WMC group had significantly smaller pupil dilations ($M$ = 5.34mm, $SD$ = 0.10) compared to the high-WMC group ($M$ = 6.27mm, $SD$ = 0.12). There was no significant main effect for condition, $F(1,22) = 0.37$, $p = .546$, $\eta_p^2 = .02$, and no significant interaction effect, $F(1,22) = 0.96$, $p = .338$, $\eta_p^2 = .04$ (see Figure 3c).

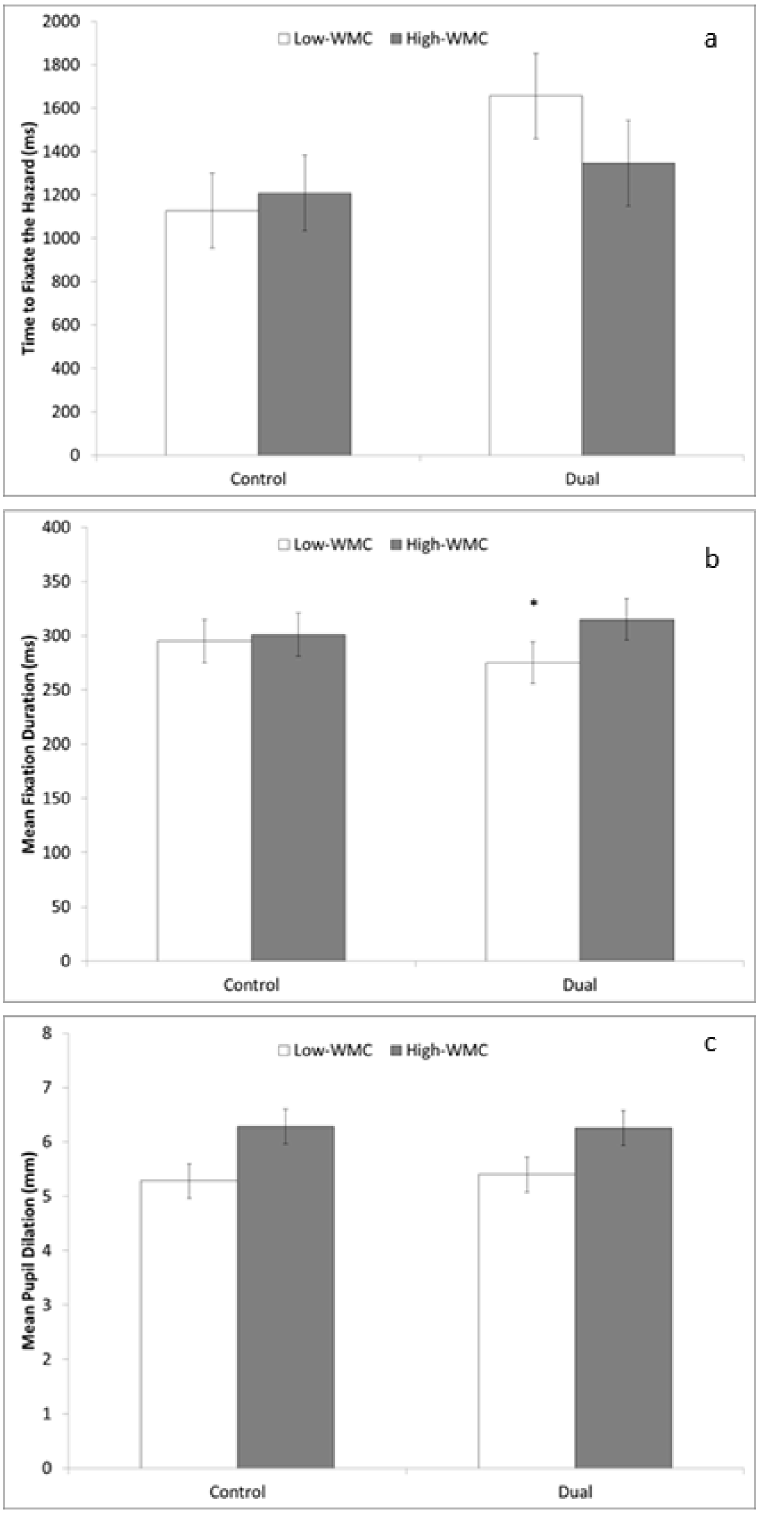


**Figure 3.** Gaze data showing (a) the time to fixate the hazard, (b) the mean fixation duration on the hazard and (c) the mean pupil dilation between both WMC groups and across control and dual task conditions.

**Discussion**

Experiment 2 sought to replicate and extend the findings from Experiment 1 by assessing objective measures of attentional control in a stratified sample of participants completing similar tasks. As predicted, there was a significant difference between groups in hazard perception performance under conditions of increased cognitive load (when dual tasking was necessary). This finding provides some test-retest reliability for Experiment 1 and further supports the contention that WMC is a good predictor of the ability to maintain attentional focus of task relevant information and resist distraction and interference (Engle & Kane, 2004).

In this Experiment we explicitly measured the control of attention via indices of gaze behavior. As previous studies have shown that the ability to quickly fixate on the hazard is a measure of effective hazard perception performance (Crundall et al, 2012), we predicted that that the interaction between WMC groups and performance would be reflected in a similar interaction in this measure. However, this hypothesis was not supported and both WMC groups increased the time taken to fixate the hazard under cognitive load conditions. While not significant, it is worth noting that the low-WMC group's time to first fixate the hazard seemed to be more affected by cognitive load (a mean increase of 529ms) compared to the high-WMC group (a mean increase of 138ms). The general finding that first fixation to a hazard is sensitive to task demands does support similar findings of the effects of cognitive load on reaction time measures in other driving studies (e.g., Mackenzie & Harris, 2015).

Our hypothesis for a significant interaction for the mean duration of fixations on the hazard was exactly in the direction that we predicted and mirrored the interaction seen in hazard perception performance. Put simply, under conditions of cognitive load, low-WMC participants fixated significantly less on the hazard and this was detrimental to their ability to interpret and react to this developing danger. The importance of this measure is well supported in the hazard perception literature (Garrison & Williams, 2013; Underwood et al, 2005; Velichkovsky et al, 2002) and our data supports the notion that the ability to maintain top-down attentional control in this manner is related to individual differences in WMC in distracting or cognitively taxing conditions (Engle & Kane, 2004).

There was a significant difference between pupil dilations between WMC groups with the low-WMC groups displaying smaller pupil dilations compared to high-WMC individuals regardless of cognitive load conditions. This interesting finding is similar to recent studies (Heitz, Schrock, Payne, & Engle, 2008, Unsworth & Robison, 2015b). In explanation of these effects, it has been suggested that smaller pupil dilations are related to inattention and lower levels of alertness or arousal (Morad, Lemberg, Yofe, & Dagan, 2000). Therefore, Unsworth and Robison (2015b) suggest that when arousal levels are low, less attention will have been allocated to the task and performance will suffer. In our hazard perception task this would suggest that the levels of arousal and attention allocation were sufficient to maintain performance in the control condition for the low-WMC group but were insufficient to maintain performance under conditions of cognitive load. However, the link between arousal, pupil size and individual differences in WMC is still poorly understood and warrants further investigation.

## Practical Applications

While this research does provide evidence for the contribution of WMC to hazard perception performance of drivers it should be noted that this obviously does not transcend to all driving environments. Rather, this may only have implications for drivers in specific situations where visual or cognitive distractions are plentiful or cognitive load is high. For example, low-WMC individuals may struggle to inhibit or disengage attention away from salient or threatening stimuli (e.g., a road accident on an adjacent carriageway) which may disrupt steering coordination and impair driver safety (Marple-Horvat et al, 2005). Also, as the novice stage of learning is typically very cognitively demanding (Fitts & Posner, 1967), having low-WMC may impede the learning process in driving. Indeed, there is some evidence that the ability to maintain attention is related to skill learning in driving contexts (Elfering, Ruppen & Grebner, 2013). These types of applied implications warrant further investigation not only in the context of driving but also in other applied environments such as aviation, surgery or sports performance.

## Limitations

While the results of both experiments provide support for the controlled attention perspective of WMC some important limitations of our study need to be addressed in future research. First, we utilized a relatively low sample size (particularly in Experiment 2). However, this sample size is comparable to similar studies looking at simulated driving behavior and visual attention (e.g., Underwood et al 2005; Velichkovsky et al, 2002) and similar studies exploring individual differences in WMC and visual attention (Wood, Vine & Wilson, 2015). Second, although the dual-task that we used was effective in increasing cognitive load, more ecologically valid distractors that require visual attention (e.g., reading text messages) or motor responses (e.g., mobile phone use) may further degrade hazard perception performance for low-WMC individuals. Therefore, future research may wish to explore the interaction of individual differences in WMC with more realistic in-car distractors. Third, as research in this area has shown that mind-wandering is an important variable for driving in performance (Galéra et al, 2012) and one that is also related to WMC (McVay & Kane, 2009), it may be the case that individual differences in WMC are more related to keeping your *mind* on the road rather than your *eyes*. We only measured overt shifts in attention via eye-movements whereas future research could examine more covert attentional shifts using thought probe techniques (as Unsworth & Robinson, 2015a). Finally, pupil size can be affected by other variables (e.g., anxiety, smoking status and caffeine intake) so we cannot rule out their influence on our results. However, in relation to this Heitz et al (2008) argued “most predictions regarding the effects of these variables would be targeted at low span [i.e. low-WMC] individuals. In other words, one might argue that low spans suffer more anxiety or that they self-medicate by ingesting caffeine or nicotine. If this were true, then one would expect larger pupil size in low spans as compared to high spans” (p.10). Our data, like theirs, does not show this.

## Conclusions

The results of both Experiments suggest that hazard perception performance in driving is related to individual differences in WMC under conditions of high cognitive load. Furthermore, we provide evidence that WMC is (a) related to actual driver behavior on the road and (b) related to the ability to control visual attention in the face of distraction or interference. These findings add further support to the controlled attention perspective of WMC (Engle & Kane, 2004) and show that the predictions of this perspective transfer to more complex, and ecologically valid environments.

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## Figure Captions

**Figure 1.** A scatterplot showing the relationship between WMC and hazard perception performance under control (black line) and dual-task (grey line) experimental conditions.

**Figure 2**. Hazard perception performance between both WMC groups and across control and dual task conditions.

**Figure 3.** Gaze data showing (a) the time to fixate the hazard, (b) the mean fixation duration on the hazard and (c) the mean pupil dilation between both WMC groups and across control and dual task conditions.