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Is improved lane keeping during cognitive load caused by increased physical arousal or gaze concentration toward the road center?

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ABSTRACT

Driver distraction is one of the main causes of motor-vehicle accidents. However, the impact on traffic safety of tasks that impose cognitive (non-visual) distraction remains debated. One particularly intriguing finding is that cognitive load seems to improve lane keeping performance, most often quantified as reduced standard deviation of lateral position (SDLP). The main competing hypotheses, supported by current empirical evidence, suggest that cognitive load improves lane keeping via either increased physical arousal, or higher gaze concentration toward the road center, but views are mixed regarding if, and how, these possible mediators influence lane keeping performance. Hence, a simulator study was conducted, with participants driving on a straight city road section whilst completing a cognitive task at different levels of difficulty. In line with previous studies, cognitive load led to increased physical arousal, higher gaze concentration toward the road center, and higher levels of micro-steering activity, accompanied by improved lane keeping performance. More importantly, during the high cognitive task, both physical arousal and gaze concentration changed earlier in time than micro-steering activity, which in turn changed earlier than lane keeping performance. In addition, our results did not show a significant correlation between gaze concentration and physical arousal on the level of individual task recordings. Based on these findings, various multilevel models for micro-steering activity and lane keeping performance were conducted and compared, and the results suggest that all of the mechanisms proposed by existing hypotheses could be simultaneously involved. In other words, it is suggested that cognitive load leads to: (i) an increase in arousal, causing increased micro-steering activity, which in turn improves lane keeping performance, and (ii) an increase in gaze concentration, causing lane keeping improvement through both (a) further increased micro-steering activity and (b) a tendency to steer toward the gaze target.

1. Introduction

Driving is a highly complex task that requires continual integration of perception, cognition, and motor response (Salvucci and Liu, 2002). However, in recent years, with the extensive application of in-vehicle intelligent systems such as navigation devices and mobile/cell phones, driving is now regularly accompanied by engagement in other competing secondary tasks. For instance, a North American survey conducted in 2013, involving 6016 interviewees, showed that 48% of drivers reported answering their cell phone when driving at least some of the time (Schroeder et al., 2013). This induced driver distraction introduces many problems for driving safety (Ranney et al., 2000). According to a report by the National Highway Traffic Safety Administration (National Center for Statistics and Analysis, 2016), in the US, distraction-affected crashes contributed to 10% of fatal crashes, 18% of injury crashes, and 16% of all police-reported motor vehicle traffic crashes in 2014. More seriously, results from the 100-Car Naturalistic Driving Study reported that 78% of crashes, and 65% of near-crashes involved driver inattention, including secondary task distraction, driving-related inattention to the forward roadway, drowsiness, and non-specific eye-glances away from the forward roadway (Klauer et al., 2006). Hence, it is of importance to investigate the impact of driver distraction on driving performance and its causation.

Driver distraction is commonly defined as *'the diversion of attention away from activities critical for safe driving toward a competing activity'* (Regan et al., 2008). Two main components are cognitive and visual distraction, described as "mind off road" and "eyes off road" respectively (Victor, 2005). The effect of these activities on driving has been widely explored in recent years (Lamble et al., 1999; Ranney et al., 2000; Engström et al., 2005; Jamson and Merat, 2005; Liang and Lee, 2010; Muhrer and Vollrath, 2011; Kountouriotis et al., 2015; Kountouriotis and Merat, 2016), where the consequences of visual

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distraction on lateral driving performance, and its causation are relatively clear. That is, compared to baseline conditions, visual distraction degrades lateral control (Angell et al., 2006; Liang and Lee, 2010; Kountouriotis and Merat, 2016), leading to a significant increase in the standard deviation of lateral position (SDLP, Liang and Lee, 2010; Kountouriotis and Merat, 2016), higher risk of lane departure (Liang and Lee, 2010), and a reduction in time-to-line crossing (Engström et al., 2005). These are considered to be due to increased eyes off-road glances during completion of visually distracting tasks (Liang and Lee, 2010; Kountouriotis and Merat, 2016).

However, the effect of cognitive distraction on driving performance is currently unclear (He et al., 2014; Kountouriotis and Merat, 2016). In the experimental/laboratory based studies, this kind of distraction is usually triggered by sound-based, cognitively loading, non-visual tasks. Although studies carried out on driving simulators generally suggest that cognitive load impairs driving performance due to the degeneration in drivers' event detection performance (Patten et al., 2006; Reyes and Lee, 2008; Haque and Washington, 2014), Naturalistic Driving Studies (NDS) show a mix of unchanged (Olson et al., 2009) and reduced (Victor et al., 2015) crash risk during (hands-free) listening or talking on a mobile phone, as reviewed by Carsten and Merat (2015).

There is relatively consistent agreement across the majority of these studies in terms of lane keeping, showing an improvement in performance during cognitively loading tasks, based on reduced SDLP (Engström et al., 2005; Jamson and Merat, 2005; Liang and Lee, 2010; Kaber et al., 2012; He et al., 2014; Kountouriotis et al., 2016). Cognitive load has also been found to lead to increased micro-steering activity (Boer et al., 2005; Markkula and Engström, 2006; Kountouriotis et al., 2016; Li et al., 2017), higher gaze concentration to the forward road center (Victor et al., 2005; Reimer, 2009; Wang et al., 2014), and higher physical arousal (Reimer and Mehler, 2011; Mehler et al., 2012).

Different hypotheses have been put forward to explain this set of observations during cognitively loading tasks (He et al., 2014). Engström et al. (2017) provide an overview in their review, and discuss which hypotheses remain compatible with the available empirical data. Here, we will only consider those hypotheses which remain unrefuted, as shown in Fig. 1.

Engström et al. (2017) suggest the *global arousal hypothesis*: that improvement in lane keeping is a byproduct of increased cortical arousal during non-automatized tasks, such as those caused by a cognitively loading task. This increased arousal then allows the driver's highly automatized lane keeping and steering behavior to be more responsive to visual stimuli which help support lane keeping in the driving environment, resulting in more frequent micro-steering corrections, in turn leading to reduced SDLP.

Alternatively, the *active gaze hypothesis* (Wilkie et al., 2008), also termed the *steer-where-you-look hypothesis* (Wilson et al., 2008; Medeiros-Ward et al., 2010; He et al., 2014), explains the lane keeping improvement as a side effect of task-induced gaze concentration, combined with drivers' tendency to steer in the direction of their gaze. A related suggestion, the *visual enhancement hypothesis* (Engström et al., 2005; He et al., 2014; Boer et al., 2016) suggests that cognitive load causes gaze concentration toward the road center, supporting a better perception of visual information in the road center, and thus resulting in a performance gain of steering which finally leads to lane keeping improvement. As discussed by Engström et al. (2017), if these gaze-mediated mechanisms are real, they are not likely to be solely responsible for SDLP reductions under cognitive load, since such reductions have been observed both without associated reductions in gaze concentration (He et al., 2014) and in conditions of experimentally controlled gaze direction (Cooper et al., 2013). However, these gaze-mediated mechanisms could still be in play, in combination with other non-gaze-mediated mechanisms, such as global arousal.

Thus, the current understanding in this area is that cognitive load affects lane keeping performance via a mediating factor of either physical arousal, gaze concentration toward the road center, or both, with different predictions made by the three competing hypotheses, as shown in Fig. 1. This study presents the first direct tests of these predictions, to investigate the causal relationship suggested by the three hypotheses.

In an initial analysis step, a time course method was used to investigate the changes in lane keeping performance, micro-steering activity, gaze concentration, and physical arousal during cognitive task performance. This analysis of change over time provided a first insight into the possible causal relationships between these measures, by means of their temporal patterns of change. Second, pairwise associations between the measures were investigated by univariate multilevel regression, on a sample by sample level, to further constrain the possible causal relationships. Third, a series of multilevel models for micro-steering activity and lane keeping performance, with explanatory variables as proposed by the three competing hypotheses, were conducted and then compared, allowing a final conclusion regarding the possible causal relationships.

2. Method

2.1. Participants

35 participants were recruited using an internet-based forum and by via poster advertisements distributed in Beijing, China. All of them held a valid driving license for a minimum of 2 years, and had normal or corrected-to-normal vision. A within-subjects design was used for the experiment. Our results are based on data from 27 participants (10 females and 17 males), since 3 participants failed to complete the

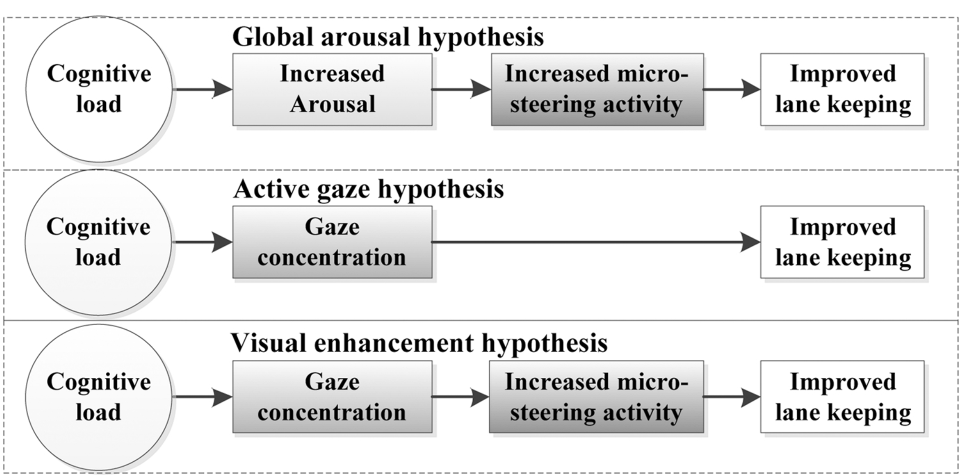

Fig. 1. The main hypotheses used to explain the improved lane keeping performance observed during cognitive load. All boxes are measurable metrics, and the arrows represent predictions. For example, the global arousal hypothesis predicts that increased physical arousal is associated with increased micro-steering activity, which in turn improves lane keeping performance.