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Effects of cognitive load on driving performance: The cognitive control hypothesis

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Abstract

Objective: The main objective of this paper was to outline an explanatory framework for understanding effects of cognitive load on driving performance and to review the existing experimental literature in the light of this framework.

Background: While there is general consensus that taking the eyes off the forward roadway significantly impairs most aspects of driving, the effects of primarily cognitively loading tasks on driving performance are not well understood.

Method: Based on existing models of driver attention, an explanatory framework was outlined. This can be summarized in terms of the cognitive control hypothesis: *Cognitive load selectively impairs driving sub-tasks that rely on cognitive control but leaves automatic performance unaffected.* An extensive literature review was conducted where existing results were re-interpreted based on the proposed framework.

Results: It was demonstrated that the general pattern of experimental results reported in the literature aligns well with the cognitive control hypothesis and that several apparent discrepancies between studies can be reconciled based on the proposed framework. More specifically, performance on non-practiced or inherently variable tasks, relying on cognitive control, is consistently impaired by cognitive load while the performance on automatized (well-practiced and consistently mapped) tasks is unaffected and sometimes even improved.

Conclusion: Effects of cognitive load on driving are strongly selective and task-dependent.

Application: The present results have important implications for the generalization of results obtained from experimental studies to real world driving. The proposed framework can also serve to guide future research on the potential causal role of cognitive load in real-world crashes.

Keywords: Cognitive load, attentional processes, automatic and controlled processing, distractions and interruptions, dual task, learning, working memory

Précis

The paper outlines an explanatory framework for understanding effects of cognitive load on driving performance and reviews existing experimental literature in the light of this framework. The general pattern of results reported in the literature aligns well with the proposed framework and several apparent discrepancies in results are reconciled.

Introduction

Driver inattention has long been recognized as one of the leading factors contributing to road crashes (Treat et al., 1977; Wang, Knipling and Goodman, 1996). Driver distraction can be viewed as a form of driver inattention, specifically referring to the engagement in activities not critical for safe driving (Binder et al., 2011; Engström, Monk et al., 2013; Lee, Young and Regan, 2009). Driver distraction thus includes engagement in activities related to objects both inside and outside the vehicle, such as looking at billboards, texting, conversing on the cell phone or with passengers, and interacting with onboard systems such as media players and navigation devices. This definition of driver distraction excludes activities critical for safe driving, such as checking the mirrors before passing a lead vehicle or visually scanning an intersection (Engström, Monk et al., 2013). Evidence, from both crash statistics and naturalistic driving studies, suggests that driver distraction is the most prevalent form of inattention in road crashes (Dingus et al., 2006; NHTSA, 2010; Wang et al., 1996).

A distinction is commonly made between (i) visual, (ii) manual and (iii) cognitive components of distraction. The two former components usually refer to modality specific interference in perceptual and motor processes (e.g., the competing needs for vision to monitor the road and read text on a display, or the concurrent need for the hands to steer the vehicle and peel a banana) while the term cognitive distraction is typically used to refer to a more general withdrawal of attention from the driving task (i.e., "mind off road", Victor, 2006). While most naturalistic tasks performed while driving involve all three (and possibly other) components (Mehler and Reimer, 2013), the present paper focuses specifically on the contribution of the cognitive component and its effect on driving performance. This relates, in particular, to the performance effects of non-visual tasks such as handsfree phone conversation. For now, we will broadly refer to the demand imposed by such tasks as *cognitive load (CL)*; a more precise technical definition of the term is outlined in the following section. It should also be noted that, while the terms cognitive distraction and cognitive load are often used synonymously, the former can be viewed as a more general concept related to the diversion of attention away from driving toward a competing activity (Lee et al., 2009). By contrast, cognitive load typically refers to the "amount" of cognitive resources demanded from the driver by a competing activity (Engström, 2013). It follows that cognitive distraction may sometimes occur in situations with high as well as low cognitive load, for example in the case of mind wandering, which has also been referred to as internal driver distraction (Martens and Brouwer, 2013). While mind wandering while driving is a very interesting topic (see He et al., 2011; Martens and Brouwer, 2013), the present paper focuses exclusively on cognitive load imposed by secondary tasks.

There is general consensus in the experimental and naturalistic driving literature that tasks taking the drivers' eyes away from driving (such as texting) impair driving performance (e.g., Angell et al., 2006; Dingus et al., 2016; Greenberg et al., 2003; Horrey, Wickens and Consalus, 2006; Lee et al., 2002) and increase crash risk (Hickman et al., 2010; Klauer et al., 2006; 2010; 2014; Olson et al., 2009; Simmons, Hicks and Caird, 2016; Victor et al., 2015). However, the situation is less clear regarding the effects of primarily cognitively loading tasks. First, the majority of the existing naturalistic driving studies have not found evidence for increased crash risk associated with primarily cognitive tasks such as talking on the phone or using the Citizen Band (CB) radio (Fitch, 2013; Hickman et al., 2010; Klauer et al., 2006; 2010; 2014; Olson et al., 2009; Victor et al., 2015; see the meta-analysis in Simmons et al., 2016). On the contrary, several of these studies have found a significant *reduction* in relative risk for such tasks (Hickman et al., 2010; Olson et al., 2009; Victor et al., 2015). This apparently protective effect of CL appears particularly pronounced for rear-end crashes and near-crashes, for which Victor et al. (2015) found phone conversation to be associated with a ten-fold reduction in risk. A particularly striking finding in the latter study was that none of the 47 rear-end crashes in this data (a subset of the SHRP2 dataset), involved driver engagement in hands-free phone conversations. Yet other studies analyzing SHRP2 crashes (including any type of crashes) have found increased crash risk associated with phone conversations (Dingus et al., 2016; Kidd and McCartt, 2015). However, these two latter analyses differ from most of those cited above in that risk was calculated against a reference (no task) condition of attentive and (in Dingus et al., 2016) non-impaired driving.

Second, a closer look at the experimental literature reveals a number of apparently inconsistent and counterintuitive findings regarding the effects of CL on driving performance (see Engström, 2011, for a review). While a large number of studies have reported various driving performance decrements due to CL, these results do not seem to generalize well across experimental conditions. Moreover, in the particular case of lane keeping there is evidence from a large number of studies (further reviewed below) that cognitive load often *improves* performance.

Thus, the relationship between cognitive load, driving performance and road safety is still an unresolved and strongly controversial issue, as shown, for example, by the recent paper by Strayer et al. (2015) and the associated peer commentaries. The present paper focuses specifically on performance effects of cognitive load reported in controlled experiments (including desktop, driving simulator, test-track or on-road studies), while the potential effect of CL on crash risk is addressed in the Discussion.

We have previously (Engström, 2008, 2010, 2011; Engström, Markkula and Victor, 2013) proposed that the apparent inconsistencies in the experimental literature on cognitive load may be reconciled based on the distinction between automatic and controlled performance (Cohen, Dunbar and McClelland, 1990; Schneider, Dumais and Schiffrin , 1984; Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). Automatic performance is effortless, generally unconscious and is established through repeated exposure to (i.e., learning of) *consistent mappings* between stimuli and responses (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). By contrast, controlled performance, relying on executive cognitive functions such as working memory, requires attentional effort and is needed to deal with novel, non-routine or inherently difficult tasks (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). Such executive cognitive functions can be generally subsumed under the concept of *cognitive control* (Miller and Cohen, 2001; see Gazzaniga, Ivry and Mangun, 2014, for a standard textbook account). The concept of cognitive control is also closely related to the Supervisory Attentional System proposed by Norman and Shallice (1986).

The general idea put forward by Engström (2011) and Engström et al. (2013) is summarized by what will henceforth be referred to as the *cognitive control hypothesis:*

Cognitive load selectively impairs driving sub-tasks that rely on cognitive control but leaves automatic performance unaffected.

Engström (2011) conducted a literature review of existing studies on CL and driving performance and found general support for this idea, across a range of driving sub-tasks, including object and event detection, lateral control and longitudinal vehicle control. We have also proposed a conceptual model of driver attention that may offer a general explanation for the effects predicted by this hypothesis (Engström, 2008, 2010, 2011; Engström, Markkula and Victor, 2013).

In the present paper, we first outline a refined formulation of our conceptual model which makes more direct contact with contemporary neuroscientific models of cognitive control, attention and automaticity, more specifically, the Guided Activation Theory developed by Cohen and colleagues (Botvinick and Cohen, 2014; Cohen et al., 1990; Feng et al., 2014; Miller and Cohen, 2000). We then provide an updated, more exhaustive, review of existing experimental evidence on effects of CL on driving performance, and how these results may be interpreted in terms of the cognitive control hypothesis. The paper concludes with a discussion of the relation between the proposed framework and existing accounts, novel specific predictions that could be tested in future experimental studies, implications for the generalizability of experimental studies to the real world and some general implications for the relation between cognitive load and road safety.

A framework for understanding effects of cognitive load on driving performance

Our previous models of attention selection in driving (in Engström 2008, 2010, 2011; Engström, Markkula and Victor, 2013) were based on the general concept of a set of perception-action mappings activated bottom-up by stimulus input and/or biased top-down by higher-level cognitive faculties (Markkula, 2015, used a similar framework as the basis for a theory of consciousness). These accounts were inspired by existing models of cognitive control developed by Norman and Shallice (1986) and Cooper and Shallice (2000) and the Guided Activation Theory (GAT) developed by Cohen and colleagues (Botvinick and Cohen 2014; Cohen et al., 1990; Feng et al., 2014; Miller and Cohen 2000).

While our previous models conceptualized these perception-action mappings in terms of *schemata*, GAT offers a more concrete neuroscientific account of automaticity and cognitive control on which the present account is based. According to GAT, perception-action mappings can be viewed in terms of neural pathways and automaticity can be understood in terms of the strength of these pathways (Cohen et al., 1990). With repeated exposure to consistent perceptual-motor contingencies that yield valuable outcomes, neural pathways gradually strengthen to the point where performance becomes automatized. Neuroscientific evidence suggest that this process can be understood based on reinforcement learning principles, where unexpectedly positive outcomes, via dopamine modulation, leads to long-term potentiation (LTP) (strengthening) of synapses in the currently active neural pathways. Conversely, unexpectedly negative outcomes are believed to result in long term depression (LTD) (see Ashby, Turner and Horvitz, 2010, for a review).

Thus, in line with the classical account of automaticity developed by Shiffrin and Schneider (Shiffrin and Schneider 1977; Schneider and Shiffrin, 1977), tasks characterized by consistent and frequent sensory-motor mappings are prone to become automatized while tasks with more variable and/or infrequent mappings have to rely on cognitive control. In other words, through sensory-motor interaction, the brain gradually adapts to behaviorally relevant statistical regularities in the world resulting in a repertoire of automatized skills. It follows that automaticity should be viewed as a graded, rather than an all-or-none phenomenon (Cohen et al., 1990).

Based on this model, limitations in multitasking may be understood as due to *cross-talk* between overlapping pathways involved in the respective tasks (Cohen et al., 1990; Feng et al., 2014). Well-practiced automatized tasks governed by stronger pathways will thus tend to override less practiced tasks governed by weaker pathways. A prototypical example of this is the Stroop task, modeled by Cohen et al. (1990), where word reading (an automatized task governed by strong pathways) interferes with color naming (a non-automatized task) when participants are asked to name the ink color of displayed words, and the words themselves are names of colors that can be incongruent with the actual ink color.

The key role of cognitive control, subsumed primarily by the frontal lobe, is then to enable flexible, non-routine behaviors by boosting weaker pathways relevant for current goals, potentially overriding stronger pathways (implementing automatized behaviors) thus resolving cross talk interference. The result is flexible behavior, typical for humans, where well-practiced, stereotyped, routine actions may be temporarily overridden in order to obtain goals relevant to the situation at hand.

Mechanistically, as demonstrated in the computational GAT implementations by Cohen et al. (1990) and Feng et al. (2014), cognitive control may be understood as a selective boost in activation of the neural pathways governing the task in question, originating in neural populations at higher levels in the neural hierarchy, in particular the pre-frontal cortex (PFC). In such a hierarchical neural architecture, the risk for cross-talk interference increases as one moves up the neural hierarchy, thus potentially limiting the number of high-level "task representations" that can be simultaneously activated (potential neural mechanisms for this are reviewed by Feng et al., 2014). Thus, cross-talk at this higher level may occur even for two (non-automatized) tasks with non-overlapping pathways at the lower, modality-specific, sensorimotor levels (e.g., hands-free phone conversation and driving through a complex intersection). Whether this implies a fundamental capacity limitation where cognitive control can only be allocated to one (non-automatized) task at a time (as proposed by central bottleneck models such as Pashler and Johnston, 1998) or whether it can, at least to some extent, be allocated concurrently to two tasks (as proposed by Meyer and Kieras, 1997) has been debated. In a study supporting the latter notion, Schumacher et al., (2011) found that with equal task priorities and a moderate amount of training, at least some subjects were able to achieve near perfect time sharing of concurrent auditory-vocal and visual-manual choice reaction tasks. Based on this, the authors suggested, with reference to the model of Meyer and Kieras (1997), that interference in multitasking may be more due to individual task scheduling *strategies* than fundamental capacity limitations in cognitive control. In a similar vein, Feng et al. (2014) propose that limitations in multitasking (of non-automatized tasks) may be due to a learned and/or evolutionarily determined optimal control policy implying that concurrent processing is generally associated with low utility or reward. Thus, "it makes 'sense' not to try to do more things than can be done since the expected returns for doing so will be low" (Feng et al., 2014, p.15). However, regardless of whether performance decrements during multitasking are due to fundamental (structural) capacity limitations in cognitive control, a functional utility optimization, or both, the key notion for present purposes is that non-automatized tasks will generally *compete* for cognitive control. Hence, when performing two (non-automatized) tasks that rely on cognitive control, performance on one or both tasks (depending on task priorities) will generally suffer, even in the absence of cross-talk interference at lower sensorimotor levels (since cognitive control is needed to boost the weak pathways for both non-automatized tasks). Thus, performing a cognitively loading (non-visual/manual) secondary task will selectively impair performance on driving sub-tasks relying on cognitive control but leave automatized driving sub-tasks unaffected (or, as we shall see below, sometimes even improve performance on certain automatized tasks). The *cognitive load* imposed by a task can then be more precisely defined as *the demand for cognitive control* (Engström et al., 2013; Engström, Monk et al., 2013; ISO, 2016), where the GAT model offers an explicit account of what types of neural mechanisms are demanded, that is, high-level task “representations” in PFC able to boost weaker pathways at lower levels when needed.

This framework thus offers a way to predict, a-priori, whether a certain driving sub-task task is likely to become automatized over time, and thus immune to cognitive load for experienced drivers. The key notion here is that the development of automaticity depends fundamentally on statistical task structure (i.e., the variability or degree of uncertainty associated with the task). Hence, automaticity (in terms of increased neural pathway strength) is expected to develop for driving sub-tasks characterized by consistently mapped stimulus-response contingencies (e.g., steering to correct for heading errors in lane keeping) but to a lesser extent for less consistent (i.e. more variably mapped, uncertain) tasks (e.g., negotiating a complex intersection with many uncertain elements). However, the development of automaticity also depends critically on task exposure or practice. Thus, even simple, consistently mapped tasks will only become automatized if they are extensively practiced. Hence, simplicity does not necessarily imply automaticity. As we will see below, examples of simple tasks typically relying on cognitive control include artificial laboratory tasks sometimes used as surrogates for driving, such as simple detection-response tasks or manual tracking.

Everyday driving involves a mix of sub-tasks characterized by more or less variable stimulus-response contingencies. Thus, for experienced drivers driving relies partly on a repertoire of automatized skills governed by strong neural pathways, while cognitive control sometimes needs to intervene in novel (not extensively practiced) or inherently uncertain situations. Viewed from this perspective, effects of cognitive load on driving performance will depend strongly on the “default” *automatized routines that the driver can fall back upon when cognitively loaded*. Thus, CL will not have a major detrimental effect on driving performance as long as the driver's repertoire of automatized routines can handle the driving situation. However, performance impairments due to CL are expected whenever these automatized routines are not able to deal with the current situation. In the following section, existing experimental results are reviewed and interpreted based on this framework.

Experimental effects of cognitive load on driving performance

A large body of experimental studies has addressed effects of cognitive load on driving performance. These studies are typically based on the *dual-task* experimental paradigm where participants are instructed to perform cognitively loading tasks while driving, and resulting effects on driving performance and/or driver state are evaluated. Cognitive tasks included in such studies range from artificial working memory or conversation tasks, natural conversation with a confederate or speech interaction with an in-vehicle device. In this section, results from existing experimental studies addressing effects of cognitive load on driving performance are reviewed.

Review methodology

The general scope of the present review is effects of cognitive load on driving performance as studied in controlled experiments (in driving simulator, on a test track or in real traffic) as opposed to naturalistic driving studies. However, in order to make the review manageable, some further inclusion criteria were adopted, as further outlined below.

The main starting point for identifying candidate articles was the existing review reported in Engström (2011), complemented with additional articles based on existing knowledge among the present authors. In addition, a new literature search was conducted using the Scopus database where the Article Title, Abstract and Keywords fields were searched using the string:

("cognitive load" OR "cognitive distraction") AND "driving performance"

which generated 176 hits.

Regardless of original source, all of the identified candidate articles were then further examined, and selected for inclusion based on the following criteria: First, articles had to describe controlled driving experiments measuring effects of purely non-visual, cognitively loading tasks on driving performance against a baseline (no task) condition. Second, only studies including active engagement in a driving- or driving-like tasks were included (thus excluding studies involving the passive viewing of static or moving images). Third, articles needed to report objective measures (thus excluding studies solely based on expert ratings) of at least one dependent variable relating to object/event detection-response, lateral control performance, longitudinal control performance or decision making. Fourth, the experimental methodology and dependent measures used needed to be defined at a detailed level. Finally, the included studies needed to include at least one group of normal, healthy, subjects in the normal age range (excluding studies that only involved very young or very old subjects; however, results for older or younger subjects are reported in the review when relevant).

This resulted in the selection of 84 articles or reports on studies investigating effects of cognitive load on driving performance and satisfying all the criteria above. The majority of these were journal and conference papers reporting a single study or a set of multiple experiments. The selected literature also involved meta-analyses and reports on a larger number of coordinated experiments. The review is organized around the four main categories of driving performance measures outlined above: object/event detection-response, lateral control performance, longitudinal control performance and decision making. Furthermore, to allow for comparison, priority was given to frequently used methods and measures (e.g., the ISO Detection Response Task, braking response to a lead vehicle, standard deviation of lane position etc.) although results obtained with other methods and measures were included when appropriate.

Object/event detection-response

Object/event detection/response performance has been measured both with artificial and more realistic stimuli (see Victor, Engström and Harbluk, 2006, for a review). Existing reviews and meta-analyses, typically focusing on mobile phone conversation (e.g., Horrey and Wickens, 2006), have suggested impaired object and event detection/response (OED) as the most reliable performance effect of

CL. However, in contrast to this mainstream view, the present framework suggests that OED performance should only be impaired for OED tasks that rely strongly on cognitive control, that is, novel, or inherently difficult detection tasks for which automaticity has not developed, or inherently uncertain (i.e., variably mapped) tasks. As we show below, a closer look at the literature seems to support this idea.

The Detection Response Task (DRT; formerly known as the Peripheral Detection Task, PDT), is an increasingly popular method specifically addressing effects of CL on OED. The method, which is defined by an international standard (ISO, 2016), involves responding to visual or tactile (and in some cases auditory; Chong et al., 2014) stimuli presented at intervals of 3-5 s. Effects of CL are measured in terms of response time or miss rate. Despite its simplicity, the DRT is typically not extensively practiced, thus not automatized, and hence relying on cognitive control. Thus, according to the cognitive control hypothesis, the DRT should be sensitive to interference from cognitively loading secondary tasks. This is confirmed by a large number of studies reporting that cognitively loading tasks increase DRT response times relative to a baseline (no-task) condition with effects typically in the range of 100-300 ms (Bruyas and Dumont, 2013; Conti et al., 2012; Chong et al., 2014; Diels, 2011; Engström et al., 2005; Engström, Larsson and Larsson, 2013; Harbluk et al., 2013; Mantzke and Keinath, 2015; Merat and Jamson, 2008; Merat et al., 2015; Ranney et al., 2011; Patten et al. 2003; Törnros and Bolling, 2005; Nilsson et al., in review; Young, 2013; see further references in ISO, 2016).

Similarly, many lead vehicle (LV) braking studies have found that CL increases the brake response time, or accelerator pedal release time, compared to a baseline (no-task) condition (e.g., Alm and Nilsson, 1995; Bergen et al., 2013; Brookhuis, de Vries and de Waard, 1991; Bergen et al. (2013); Engström et al., 2010; Lee et al., 2001; Levy, Pashler and Boer, 2006; Salvucci and Beltowska, 2008; Strayer, Drews and Johnston. 2003; Strayer and Drews, 2004; Strayer, Drews and Crouch, 2006; Sonnleitner et al., 2014).

It may seem like responding to a braking lead vehicle is a common, and ecologically valid, task that should be automatized for experienced drivers and that, hence, these results contradict the cognitive control hypothesis. However, it should first be noted that all of the studies cited above involved the onset of lead vehicle brake lights. Responding (by braking) to brake lights in real-world driving can be regarded as variably mapped since drivers normally don't have to step on the brake as soon as they detect a brake light. Hence, braking responses to brake lights *per se* are not expected to become automatized, even for experienced drivers. In existing LV braking studies, the onset of LV braking generally coincided with the onset of brake lights and, thus, the participant's task was essentially to brake as soon as they detected the brake light. In some studies, the participants were even instructed to brake as soon as the lead vehicle started braking (Alm and Nilsson, 1995), or when they detected the lead vehicle's brake light onset (Salvucci and Beltowska, 2008; Bergen et al., 2013; Sonnleitner et al., 2014; in most studies, the precise instruction given to the participants regarding the brake response task is not reported).

Moreover, each participant typically experienced several braking events, so even if not explicitly instructed to respond as fast as possible to the braking LV, the participants likely learned to look for the brake light after some repetitions of the scenario. Responding to brake light onsets under such artificial conditions could thus be regarded a strongly unnatural, non-practiced, task not usually performed in real-world driving, but rather functionally similar to the artificial Detection Response Task (DRT) described above. Thus, in terms of the cognitive control hypothesis, such a task could be regarded as relying on cognitive control and thus susceptible to interference from CL, just like the DRT.

By contrast, braking responses to strong looming (i.e., the optical expansion of the lead vehicle, which typically occurs with some time delay after the brake light onset) can be considered largely automatic, since this involves a strongly consistent stimulus-response contingency (drivers have to press the brake pedal when they experience an object looming towards them at a high rate since they will collide otherwise). This is further supported by studies showing that looming automatically captures attention in a bottom-up fashion (Franconeri and Simons, 2003) and elicits automatic avoidance responses in human and monkey infants (Náñez, 1988; Schiff, Caviness, and Gibson, 1962). Moreover, drivers' braking responses in naturalistic rear-end emergencies typically occur shortly after reaching specific looming thresholds (Markkula et al., 2016). Thus, the cognitive control hypothesis predicts that responses to looming objects should be immune to effects of CL. This critically implies that CL studies evaluating responses to looming objects not preceded by brake lights or other predictive cues should have found a null effect of CL on braking performance. This indeed seems to be the case. For example, Horrey and

Wickens (2004) investigated effects of an auditory working memory task on responses to looming objects (a pedestrian, a bicycle, or a vehicle pulling out behind an occluding object, and oncoming vehicles drifting into the driver's lane) and found no significant effect of CL. Muttart et al. (2007) conducted a lead vehicle braking simulator study with the brake lights of the braking lead vehicle turned off. As long as the braking event was not cued, no effects of CL were found on braking performance but CL did impair responses (relative to a non-task condition) in scenarios where the lead vehicle braking event was cued by downstream traffic events. Similarly, Baumann et al. (2008) conducted a driving simulator study investigating the effect of CL on the ability to use a predictive cue (a warning road sign) to guide the response to an obstacle hidden behind a curve. Similarly to Muttart et al. (2007), it was found that CL delayed response performance in the cued condition but not when the cue was absent (in which case participants had to respond solely to the looming obstacle). Mantzke and Keinath (2015) found that their cognitive task (a working memory task involving recalling a series of numbers in reverse order) increased response times for the DRT but did not affect responses to suddenly appearing pedestrians. In a similar study, Nilsson et al. (in review) evaluated effects of CL on both DRT and braking responses to a lead vehicle in a relatively urgent, unexpected, lead vehicle braking scenario, where the brake light onset almost co-occurred with the onset of looming cues. In line with the cognitive control hypothesis, they found that CL significantly delayed response time on the DRT but did not affect brake response times in the lead vehicle braking scenario. Finally, Engström et al. (2011, paper III) investigated braking and steering reactions to an oncoming vehicle which suddenly turned across the drivers' path, and found no response delays due to CL for the first, truly surprising, scenario. However, with repeated exposure to the event, the non-loaded drivers began to respond earlier in an anticipatory fashion (e.g., sometimes before the vehicles started turning), while this was generally not the case for cognitively loaded drivers. To the knowledge of the present authors, no existing study (using ecologically realistic looming stimuli) has demonstrated a negative effect of CL on braking responses to unexpected looming.

If cognitively loaded participants in LV braking studies are impaired in their responses to brake lights but not to looming, a further, more subtle, implication is that the response delay attributed to CL in lead vehicle braking studies should depend strongly on the urgency of the scenario, or, more specifically, the time from the brake light onset until the appearance of looming cues. This is because non-loaded participants will be able to respond relatively quickly to the brake light onset, while cognitively loaded drivers will not be able to respond until looming become present, which depends on the scenario kinematics (in particular the initial time headway, i.e., the time gap between the vehicles when the lead vehicle started braking). Indeed, by contrast to the DRT results, the magnitude of the response delay attributed to CL in existing LV braking studies are strongly variable, from 50 ms in the study by Salvucci and Beltowska (2008) to about 1500 ms for older drivers in the study by Alm and Nilsson (1995). Engström (2010) conducted a simple meta-analysis on a set of existing LV braking studies which indicated that the observed effect of CL on response time in the included studies depended strongly on the initial time headway implemented in the LV braking scenario. Studies reporting large effects of CL (e.g., Alm and Nilsson, 1995) had LV braking scenarios with long initial time headways while studies reporting small effects (e.g., Salvucci and Beltowska, 2008) had scenarios with short initial time headways. A regression analysis on the response delays reported in these studies against the respective initial time headways indicated an R^2 value of 0.79, indicating that 79% of the variance in the response time difference between cognitively loaded and non-loaded drivers could in fact be attributed to the initial time headway. A computational model of this phenomenon, based on the GAT framework outlined above, is presented in Engström, Markkula and Merat, forthcoming).

The results from OED studies on CL reviewed above are summarized in Table 1. Taken together, the results strongly support the notion, implied by the cognitive control hypothesis, that CL selectively impairs performance on non-practiced OED tasks relying on controlled performance, while leaving automatic responses to looming stimuli unaffected.

Table 1 Summary of effects of CL on object and event detection performance and interpretation in terms of the cognitive control hypothesis. Studies that found different effects on CL in different experimental conditions are marked with*

Aspect of driving performance/ specific measure	***Effect of cognitive load (relative to no-task baseline condition)***	***References***	***Interpretation in terms of the cognitive control (CC) hypothesis***
Response time for the Detection Response Task (DRT)	Increased RT (~100-300 ms delay) independent of stimulus modality	Bruyas and Dumont (2013), Conti et al. (2012), Chong et al.(2014), Diels (2011), Engström et al. (2005), Engström et al. (2013), Harbluk et al. (2013), Mantzke and Keinath (2015), Merat and Jamson (2008), Merat et al. (2015), Ranney et al. (2011), Patten et al. (2003), Törnros and Bolling (2005), Nilsson et al. (in review), Young (2013); see further references in ISO (2016)	The DRT is a non-practiced task, thus relying on cognitive control and subject to interference from CL.
Time to respond to brake light onsets in a lead vehicle braking scenario	Delayed responses (highly variable, depending on the criticality of the LV braking scenario, in particular the initial time headway) * No brake lights, braking event cued	Alm and Nilsson (1995), Bergen et al. (2013), Brookhuis et al. (1991), Engström et al., (2010), Lee et al. (2001), Levy et al. (2006), Muttart et al. (2007)*, Salvucci and Beltowska (2008), Strayer, Drews and Johnston (2003), Strayer and Drews (2004), Strayer et al. (2006), Sonnleitner et al. (2014)	Speeded (often instructed) responses to anticipated brake light onsets is a non-practiced task (similar to the DRT), thus relying on cognitive control and subject to interference from CL. The effect depends on the initial time headway since cognitively loaded drivers respond based on kinematic-dependent looming cues.
	No effect * No brake lights, braking event not cued	Muttart et al. (2007)*, Nilsson et al. (in review)	Braking to looming is automatized and thus unaffected by CL.
Time to respond to other looming stimuli	Delayed response * Braking event cued	Baumann et al. (2008)*	The utilization of non-standard (variably mapped) cues relies on cognitive control and is thus affected by CL
	No effect * Braking event not cued	Baumann et al. (2008)*; Engström et al. (2011, paper III), Horrey and Wickens (2004), Mantzke and Keinath (2015)	Responding to looming is automatized and thus unaffected by CL.

Lateral vehicle control

A large number of studies have investigated effects of CL on lane keeping performance, typically in terms of the standard deviation of lane position (SDLP). Lane keeping in normal (benign) conditions could be regarded as both highly practiced (for experienced drivers) and consistently mapped, and hence largely automatized. Thus, the cognitive control hypothesis suggests that CL should not impair lane keeping in normal conditions ("normal" and "benign" conditions here means cruising on a typical rural road or motorway at the posted speed limit, with no adverse visibility or road surface conditions, no heavy wind gusts etc.).

This prediction is confirmed by the great majority of existing studies on CL and lane keeping. In fact, perhaps somewhat counter to intuition, most studies have found that CL *reduces* lane keeping variation (i.e., improves lane keeping) compared to a baseline condition with no cognitive task. This effect was first reported in a field study by Brookhuis, de Vries and de Waard (1991) but has since then been replicated in a large number of studies (Atchley and Chan, 2011; Beede and Kass, 2006; Becic et al., 2010; Cooper et al., 2013; Engström, Johansson and Östlund, 2005; He, 2012; He and McCarley, 2011; He, McCarley and Kramer, 2014; Horrey and Simons, 2007; Jamson and Merat, 2005; Knappe et al., 2007; Kubose et al., 2006; Liang and Lee, 2010; Mattes, Föhl and Schindhelm, 2007; Mazzae et al., 2005; Mehler et al., 2009; Medeiros-Ward, Cooper and Strayer, 2014; Merat and Jamson, 2008; Törnros and Bolling, 2005; Reimer, 2009; see He, 2012, for a review).

While the cognitive control hypothesis, as formulated in the previous section, is not contradicted by this lane keeping improvement effect (since the hypothesis only entails that lane keeping should not be negatively affected by CL), it does not offer any explanation for the phenomenon. Some other commonly reported performance effects that often co-occur with the lane keeping improvement may provide some hints towards such an explanation. First, CL has been consistently demonstrated to induce increased steering activity (Boer, 2000; Engström et al., 2011, paper III; He, 2012; Kountouriotis et al., 2016; Markkula and Engström; 2006; Rakauskas, Gugerty and Ward, 2004; Reimer et al., 2012). A detailed analysis by Markkula and Engström (2006), replicated in Engström (2011, paper III) and Kountouriotis et al. (2016), further indicates that this effects amounts to an increase in small steering reversals on the order of 1 degree or smaller. As reviewed by He et al. (2014), it has been debated whether this effect on steering should be interpreted as a performance impairment or improvement. In support of the latter interpretation, He et al. (2014) found that CL increased the *coherence* between lateral wind perturbations and steering inputs (coherence measures the strength of co-variation between two signals, with higher values indicating a tighter coupling). This result thus indicates that the more frequent small steering wheel reversals observed during CL were performed to counter lane keeping errors induced by the wind gusts, rather than representing more noisy or erratic steering. This further suggests that the lane keeping improvement occurs as a direct result of more focused steering.

Second, many studies have found that during periods of increased CL, the driver's visual scanning behavior narrows towards the center of the road. This *gaze concentration* towards the road center (Cooper et al. 2013, Hammel, Fisher and Pradhan, 2002; Harbluk et al., 2002, 2007; Liang and Lee, 2010; Nuñes and Recarte, 2002; Recarte and Nuñes, 2000, 2003; Reimer, 2009; Reimer et al., 2012; Niezgoda et al., 2013; Victor, Harbluk and Engström, 2005; Wang et al., 2014) has sometimes been found to co-occur with the increased steering activity and improved lane keeping performance effects (e.g. Engström et al, 2005; Reimer et al., 2012) which has led to the suggestion that the improved lane keeping is at least partly caused by the gaze concentration (e.g. Engström et al, 2005). However, a number of recent studies speak against this idea. He et al., (2014) observed lane keeping improvement and increased steering wheel reversal rate without a gaze concentration effect. In line with this, Cooper et al. (2013) controlled gaze direction and still observed the lane keeping improvement effect, at least in some conditions. Moreover, a regression analysis conducted by Liang and Lee (2010) indicated that gaze concentration only explained 5 percent variance of the lane position variation. Taken together, these results indicate that the lane keeping improvement is not necessarily mediated by gaze concentration. In other words, while the gaze concentration sometimes co-occurs with the lane keeping improvement under cognitive load, the effects may not be causally related. This topic is returned to below where we discuss different possible explanations for these effects.

In contrast to the great majority of studies reviewed above demonstrating the lane keeping improvement effect, some studies have reported the opposite result, that is, CL was found to impair lateral control performance (Chan and Singhal, 2015; Drews, Pasupathi and Strayer 2008; Horrey, Lesch and Garabet, 2009; Just, Keller and Cynkar, 2008, Salvucci and Beltowska, 2008). There are several possible reasons for these deviating results. First, three of these studies (Chan and Singhal, 2015; Drews, et al., 2008; Salvucci and Beltowska, 2008) used RSME (the root mean squared error relative to the lane center), rather than SDLP, as the dependent measure. The key difference between RSME and SDLP is that SDLP is only sensitive to increased swerving while RSME is sensitive to any stationary shift in lane position (and thus cannot distinguish increased swerving from, e.g., strategic shift in lane position away from the road center).

Second, Just et al. (2008) had subjects steering a simulated vehicle with a trackball while lying in a brain scanner. Based on the cognitive control hypothesis, such artificial, non-practiced tasks would clearly be expected to suffer under CL.

Third, in three of the studies (Chan and Singhal, 2015; Horrey et al., 2009; Salvucci and Beltowska, 2008), subjects were explicitly instructed to maintain a central lane position (in Drews et al, 2008, the instruction is not reported). In terms of the present framework, the task of keeping the vehicle in the center of the lane may be considered a rather unnatural, non-practiced, task, and thus potentially vulnerable to cognitive load. Engström (2011, Paper III) aimed to test this idea by comparing effects of CL on lane keeping in conditions with and without instructions to maintain a central lane position. As expected, lane keeping improved for non-loaded participants instructed to maintain a central lane position, as compared to non-loaded participants that did not receive the instruction, thus demonstrating that lane keeping is usually performed in a non-optimal (satisficing) fashion. Also in line with expectations, the lane keeping improvement effect was only found for the non-instructed drivers. However, the predicted *impairment effect* of CL for instructed drivers (based on the assumption that optimizing lane keeping would rely on cognitive control, and thus suffer during cognitive load) was not found. It should also be noted that He et al. (2014) and Medeiros-Ward et al. (2014) both instructed their drivers to keep a central lane position and still observed the lane keeping improvement effect. Moreover, He et al. (2014) state that similar results were obtained for RSME and SDLP (although only the latter was reported). Thus, it is unclear to what extent the lane keeping instruction or the use of RSME rather than SDLP were the key factor behind these deviating results.

In general, the cognitive control hypothesis predicts that CL should impair lane keeping if the lane keeping task is made sufficiently difficult (and thus reliant on cognitive control). Medeiros-Ward et al. (2014) tested a specific version of this prediction where lane keeping difficulty was manipulated in terms of the absence or presence of cross winds. The simulated cross winds included a constant lateral wind and added wind gusts. The windy condition was further split into two levels, differing in terms of the entropy (or predictability) of the wind gusts. In line with the main body of results reviewed above, cognitive load improved lane keeping (reduced SDLP) in the absence of wind. However, lane keeping performance deteriorated significantly under CL in the most difficult condition (with a constant cross wind plus high-entropy wind gusts). This interaction effect offers strong support for the cognitive control hypothesis: Lane keeping in benign conditions is consistently mapped, thus largely automatized for experienced drivers and hence not negatively affected by CL. However, as the same task becomes more difficult (when wind is added) it relies on cognitive control and is thus negatively affected by CL.

This result may seem to be at odds with the results reported by He et al. (2014), reviewed above, who also used simulated wind gusts but still found a lane keeping improvement effect of CL, and, further, that CL led to increased coherence between the wind gusts and steering corrections. The methodology for generating wind gusts was similar in the two studies (based on Andersen and Ni, 2005). While the exact amplitude and frequency of the wind gusts differed somewhat, they were on the same order of magnitude. However, what seems to be the most likely cause of the discrepancy is the relatively strong constant crosswind (40 mph=17.9 m/s) which was present in the windy conditions in Medeiros-Ward et al., (2014) but not in He et al., (2014). Such a cross wind implies a constant lateral force which continuously needs to be countered by steering corrections, thus leading to a rather unusual lane keeping task, which is made even more difficult when adding the wind gusts. Thus, it may primarily have been the constant cross wind, rather than the entropy of the wind gusts *per se* (as suggested by the authors) that made the lane keeping task in Medeiros-Ward et al. (2014) substantially more difficult than normal lane keeping (without wind), thus causing a degradation in lane keeping performance under CL rather than the usual lane keeping improvement.

Other studies have investigated the effect of CL on artificial tracking tasks. Just like the Detection Response Task (DRT) discussed above, such tasks may be simple and consistently mapped but at the same time not extensively practiced, thus relying on cognitive control and, according to the present hypothesis, vulnerable to CL. In line with this, studies investigating the effect of CL on artificial tracking have typically found performance to be strongly sensitive to CL in terms of increased tracking variability or error (Briem and Hedman, 1995; Creem and Profitt, 2001; Demberg et al., 2013; Strayer and Johnston, 2001). In particular, the ConTRe (Continuous Tracking and Reaction) task (Mahr et al., 2012) , a driving-like yet artificial tracking task, has been demonstrated to be strongly sensitive to fine-grained manipulations of cognitive load (Demberg et al., 2013).

The results from the reviewed studies investigating effects of CL on lateral vehicle control are summarized in Table 2. Taken together, the reported performance effects of CL on lateral control follow the same general pattern as OED tasks: CL selectively affects those tasks that are not extensively practiced or variably mapped (thus relying on cognitive control) but leaves performance on well-practiced, consistently mapped, tasks unaffected. In the case of lane keeping, CL has even been reliably found to improve performance, an effect often accompanied by increased steering activity and a concentration of glances to the road ahead. Potential explanations for this effect are further discussed below.

Table 2 Summary of effects of CL on lateral vehicle control and visual behavior, and interpretation in terms of the cognitive control hypothesis. Studies that found different effects on CL in different experimental conditions are marked with*.

Aspect of driving performance/ specific measure	***Effect of cognitive load (relative to no-task baseline condition)***	***References***	***Interpretation in terms of the cognitive control (CC) hypothesis***
Lane keeping	Reduced lane keeping variability in routine (normal) lane keeping conditions. * Normal lane keeping (no wind)	Atchley and Chan (2011), Beede and Kass (2006), Becic et al., (2010), Brookhuis et al. (1991), Cooper et al., (2013), Engström et al. (2005), He (2012), He and McCarley, (2011), He et al. (2014), Horrey and Simons (2007), Jamson and Merat (2005), Knappe (2007), Kubose (2006), Liang and Lee (2010), Mattes et al. (2007), Mazzae et al., (2005), Mehler et al., (2009), Medeiros-Ward et al., 2014)*; Merat and Jamson (2008), Törnros and Bolling (2005), Reimer (2009)	Lane keeping in benign conditions is automatized and thus not negatively affected by CL. The CC hypothesis does not explain the lane keeping improvement effect but an extension of the present model accounting for this phenomenon is proposed below.
	Increased lane keeping variability * Difficult lane keeping (added constant wind plus wind gusts)	Chan and Singhal (2015), Drews et al. (2008), Just et al. (2008), Medeiros-Ward et al. (2014)*, Horrey et al. (2009), Salvucci and Beltowska (2008)	Lane keeping in difficult (Medeiros-Ward et al. (2014) or non-practiced (Just et al., 2008) conditions relies on cognitive control and is thus impaired by CL. See the text for possible explanations for the other deviating results.
Artificial tracking	Impaired tracking performance (increased tracking error)	Briem and Hedman (1995), Creem and Profitt (2001), Demberg et al., (2013), Mahr et al., (2012), Strayer and Johnston (2001)	Artificial tracking is a non-practiced artificial task, thus relying on cognitive control and subject to interference from CL.
Steering activity	Increased steering activity, in particular small steering corrections	Boer (2000), Engström et al. (2011, paper III), He (2012, 2014), Kountouriotis et al., (2016),h Markkula and Engström (2006), Rakauskas et al. (2004), Reimer et al., (2012)	Not explained by the CC hypothesis, but addressed by the extended model later in the paper.
Gaze distribution	Increased concentration of gaze towards the forward roadway.	Hammel, Fisher and Pradhan (2002), Harbluk et al., (2002, 2007), Liang and Lee (2010), Nuñes and Recarte (2002), Recarte and Nuñes (2000, 2003), Reimer (2009), Reimer et al. (2012), Niezgoda et al. (2013), Victor, Harbluk and Engström (2005), Wang et al. (2014)	Not explained by the CC hypothesis, but addressed by the extended model developed later in the paper.

Longitudinal vehicle control

Longitudinal vehicle control refers to speed selection and the control of headway in the presence of a lead vehicle. Like we just saw for object and event detection and lateral control, experimental results reported in the literature on the effect of CL on longitudinal control appear inconsistent. We will here focus on two performance measures, mean speed and mean headway.

It is well-documented that drivers engaged in *visually* demanding secondary tasks reliably reduce their speed (e.g., Antin, Dingus, Hulse, and Wierwille, 1990; Curry, Hieatt, and Wilde, 1975; Östlund et al., 2004), which can be interpreted as a compensation for the increased visual demand imposed by the dual task situation (see Kujala et al., 2016, for a more detailed model of visual demand that could explain such speed reductions as one way to control the uncertainty of visual information that builds up during glances away from the road).

However, the corresponding results for cognitively loading (but non-visual) tasks are far more heterogeneous. For mean speed, the majority of existing studies report a null effect of CL (e.g., Alonso et al., 2012; Beede and Kass, 2006; Drews, Pasupathi and Strayer, 2008; Engström et al., 2005; He et al., 2014; Strayer and Drews, 2004; Recarte and Nuñes, 2002; Reimer et al., 2011; Törnros and Bolling, 2005). In a set of thirteen parallel coordinated studies (including different experimental scenarios) conducted in the HASTE EU-funded project (Östlund et al., 2004), seven reported a null effect of CL on mean speed.

Other studies have reported that CL leads to a speed reduction (Patten et al. 2004; Reimer et al., 2012, 2013; five of the studies in Östlund et al., 2004). However, these effects are typically very small (a reduction of a few km/h) and not reliably found across experimental conditions. For example, Patten et al. (2004) found reduced speed during hand-held phone conversation but no speed effect of hand-held phone conversation.

Yet other studies report a speed increase due to CL (Recarte and Nuñes, 2002; Qu et al., 2013; one study in Östlund et al., 2004). In Qu et al. (2013), participants were instructed to maintain a rather unnatural low speed of 50 km/h on a three-lane motorway. This suggests that the observed speed increase in the CL condition occurred because cognitively loaded drivers had difficulties in following the instruction to maintain the unusually low speed. This interpretation is supported by Recarte and Nuñes (2002), who, in a field study, manipulated both speed instruction and CL. In the instruction condition, drivers were told to maintain a speed (100 km/h) that was significantly lower than the typical speed (110-120 km/h) for that road (a motorway with a posted speed limit of 120 km/h). When instructed to maintain the lower speed, speed was higher in the CL condition compared to baseline (no CL). However, in the condition without any speed instruction, CL had no effect on speed.

Similar results were obtained by Lewis-Evans, de Waard and Brookhuis (2011). In this simulator study, participants were asked to drive at their preferred speed for 1 min in a driving simulator. The vehicle speed was then automatically increased or decreased by 10, 20 30 km/h or left unchanged, and the participants were instructed to maintain the new speed for 1 min. The speed was then changed again and had to be maintained for another minute while the participant was engaged in a cognitively loading task (mental arithmetic). Finally, participants were again asked to resort to their preferred speed for another minute. This procedure was repeated for each speed manipulation (−30, −20, −10, +0, +10, +20 and +30 km/h). The results showed that cognitively loaded drivers tended to revert towards their preferred speed, thus leading to a speed increase (compared to baseline) when instructed to maintain a speed lower than the preferred speed, a speed reduction when instructed to maintain a higher speed than the preferred speed and no effect when the instructed speed was about the same as the preferred speed.

As suggested by Recarte and Nuñes (2002), these results may be explained by the notion of an optimal speed specific for each driver and traffic condition (corresponding to the preferred speed in Lewis-Evans et al., 2011). This resonates with existing driver behavior theories such as that developed by Fuller (2005), who proposed that drivers seek to maintain a constant level of task difficulty by controlling the current driving task demand (e.g., in terms of speed) based on their individual capability. Since individual capability varies, so will the individual preferred speed in a given scenario. Recarte and Nuñes (2002) further suggest that the control of this optimal speed is largely automatized and thus not affected by CL. However, intentionally deviating from this optimal speed, for example due to experimental instructions or speed restrictions in real traffic, relies on cognitive control (i.e., is cognitively loading) and is thus subject to interference from a cognitively loading secondary task. Hence, if the intended (e.g., instructed) speed is higher than the optimal speed, the theory predicts that CL would lead to a speed reduction. Conversely, if the intended speed is lower than the optimal speed (e.g., due to instruction or posted speed limits), CL would be expected to result in a speed increase. Both predictions are supported by the results of Lewis-Evans et al. (2011) while the latter is supported by Recarte and Nuñes (2002).

The speed selection theory proposed by Recarte and Nuñes (2002) can be regarded as a specific instance of the cognitive control hypothesis. The latter suggests more generally that cognitively loaded drivers resort to their individual repertoire of automatized behaviors, which in this case is represented by an optimal speed that is automatically adapted to the current task demand. This seems to reconcile the apparently contradictory results reviewed above regarding the effect of CL on speed. For example, a possible explanation for Patten et al.'s (2004) finding that CL led to a speed reduction during hand-held, but not hands-free, phone conversation is that participants' average optimal speed in the hand-held condition (when having only one hand available for steering) was somewhat lower than the posted speed limit (110 km/h). Thus, drivers loaded by hand-held phone conversation might have resorted to this lower speed, while participants with both hands on the wheel had an optimal speed closer to the speed limit (or even slightly above the speed limit, as the results showed a slight, but non-significant, speed increase in the hands-free condition). This suggests that speed reductions due to CL should mainly be found in more demanding driving scenarios where the automatized optimal speed is lower than the speed that the driver intends to maintain (e.g., due to experimental instructions to keep to the speed limit). This generally appears to be the case in studies reviewed above reporting speed reductions due to CL (e.g., three of the five HASTE studies in Östlund et al., 2004, reporting speed reductions involved urban driving), although no safe conclusions can be drawn based on this limited sample of studies. As pointed out by both Recarte and Nuñes (2002) and Lewis-Evans et al. (2011), an interesting implication of this theory is that CL may be an important factor behind unintentional speeding. This may at least partly explain the results from a recent Swedish study finding that about 60% of all drivers violated the speed limit outside schools (30 km/h) while, at the same time this speed limit is widely accepted by the society (Motormännen, 2016).

With respect to headway, several studies have found that drivers tend to increase their headway when cognitively loaded (Bergen et al. 2013; Strayer et al., 2003; Strayer and Drews, 2004; Watson et al., 2013). However, also this effect appears rather unreliable. For example, Bergen et al. (2013) found increased following distance for a cognitive language tasks with visual or motor content but not for tasks with abstract content and Sonnleitner et al. (2014) found no effect at all of CL on headway. Furthermore, in the HASTE studies (Östlund et al., 2004), where the effect of CL on headway was evaluated in nine of the thirteen experiments, four found no effect of CL, four observed significantly increased headway and one experiment found a significant reduction in headway during CL.

When increased headway is observed during CL, it is often interpreted as a compensatory effect (e.g., Young, 2014). While this explanation cannot be refuted based on the available data, an alternative (but not mutually exclusive) explanation is that the headway reduction, like the speed effects just discussed, represents a resort back to an optimal, automatized, headway. It may be suggested that this would be particularly expected if participants were instructed, or otherwise “forced”, to maintain a headway that was shorter than their preferred headway. While this hypothesis is difficult to evaluate based on the existing literature (e.g., due to the different ways to program the behavior of the simulated lead vehicle), the results of Watson et al. (2013) at least offer some support for this idea. In this study, it was found that participants’ working memory (WM) capacity was negatively correlated with following distance (after subjects were initially trained on maintaining a 2s headway). This means that drivers with high WM capacity tended to maintain the instructed headway while subjects with lower WM capacity had a stronger tendency to increase headway. As suggested by Watson et al. (2013), this seems to indicate that the increased headway was more due to failure in goal maintenance (among low WM capacity participants) than risk compensation. It would thus be very interesting to conduct a study similar to that by Lewis-Evans et al. (2011), reviewed above, but for headway instead of speed. The cognitive control hypothesis predicts that the effect of CL will depend critically on the relation between the experimentally controlled headway and the participants’ individually preferred (optimal) headway.

The reviewed results on the effects of CL on speed and headway are summarized in Table 3. A key implication of the cognitive control hypothesis is that visual-manual and primarily cognitive tasks affect longitudinal vehicle control in fundamentally different ways. While speed reductions (or headway increases) observed during visual time sharing may be explained in terms of a need to compensate for increased visual demand and associated uncertainty of visual information (Kujala et al., 2016), CL rather makes drivers resort to their optimal (automatized) speed or headway, which may be higher or lower than the current speed/headway, thus leading to apparently inconsistent effects in existing studies. This idea is clearly supported in the case of speed (Recarte and Nuñes, 2002; Lewis-Evans et al., 2011), and there are at least some indications in the headway data that also support this notion, although further studies are clearly needed.

Table 3 Summary of effects of CL on longitudinal vehicle control and interpretation in terms of the cognitive control hypothesis. Studies that found different effects on CL in different experimental conditions are marked with*

Aspect of driving performance/specific measure	***Effect of cognitive load (relative to no-task baseline condition)***	***References***	***Interpretation in terms of the cognitive control (CC) hypothesis***
Mean speed	No effect * Preferred speed similar as instructed speed ** No speed instruction ** *Hands-free phone conversation	Alonso et al., (2012), Beede and Kass (2006), Drews, Pasupathi and Strayer (2008), Engström et al. (2005), He et al. (2014), Lewis-Evans et al. (2011)*, Patten et al. (2004)**; Recarte and Nuñes (2002)***, Strayer and Drews (2004), Törnros and Bolling (2005), seven studies in Östlund et al. (2004)	When cognitively loaded, the driver falls back upon the preferred, automatized, speed. In this case, the average preferred speed similar to the instructed speed.
	Reduction * Preferred speed lower than instructed speed ** Hand held phone conversation	Lewis-Evans et al. (2011)*, Patten et al. (2004)**; Reimer et al. (2012, 2013), five studies in Östlund et al. (2004)	CL drivers resort to their preferred speed which is here *lower* than the instructed speed.
	Increase * Preferred speed higher than instructed speed ** Instructed to drive slower than typical speed for the road	Lewis-Evans et al. (2011)*, Recarte and Nuñes (2002)**, Qu et al. (2013), one study in Östlund et al. (2004)	CL drivers resort to their preferred speed which is here *higher* than the instructed speed (The average preferred speed is *higher* than the instructed speed.
Mean headway (time or distance)	No effect * CL task with abstract content ** Subjects with high WM capacity	Bergen et al. (2013)*, Sonnleitner et al. (2014), Watson et al. (2013)**, four studies in Östlund et al. (2004)	The average preferred headway is similar to the instructed headway. Subjects with high WM capacity can still utilize cognitive control under CL to maintain the instructed headway (Watson et al., 2013)
	Reduction	One study in Östlund et al. (2004)	CL drivers resort their preferred headway which was here *lower* than the instructed headway.
	Increase * CL task with visual-motor content ** Subjects with low WM capacity	Bergen et al. (2013)*; Strayer et al. (2003), Strayer and Drews (2004), Watson et al. (2013)**, four studies in Östlund et al. (2004)	CL drivers resort their preferred headway which was here *higher* than the instructed headway. Subjects with low WM capacity cannot utilize cognitive control under CL to maintain the instructed headway (Watson et al., 2013)

Decision making

There are relatively few studies that have addressed the effects of CL on decision-making aspects of driving, probably due to the difficulties associated with eliciting natural decision making behavior in controlled experimental conditions. Engström and Markkula (2007) investigated effects of CL on decision making elements in commanded lane changes, using the Lane Change Test (LCT) paradigm (Mattes, 2003; ISO, 2010). The LCT evaluates the effects of distraction in terms of the performance of lane changes commanded by road signs in simulated driving. In the standard version of the test, distraction effects on the LCT are evaluated in terms of the mean deviation from a normative lane change path. However, this composite performance metric involves aspects related to both decision making (deciding to initiate the change to a commanded lane) and lateral control (executing the lane change in a stable manner). In order to disentangle these effects, Engström and Markkula (2007) invented the *Percent Correct Lane* (PCL) metric representing the ability to shift to the lane commanded by the road sign, thus isolating the decision making element from the lateral control element. It was found that a cognitive (non-visual) task only negatively affected the decision making element (but not lateral control, in line with the results reviewed above). A more detailed analysis revealed that this effect was both due to a lack of response (i.e., staying in the same lane) and erroneous responses (i.e., shifting to the wrong lane). While the lateral control element (which in this study was strongly impaired by a visual task) could be regarded as largely automatized, deciding to change to a specified lane based on roadside commands is a strongly non-practiced task expected to rely on cognitive control. Thus, according to the cognitive control hypothesis such a non-practiced decision task would be expected to be negatively affected by CL, as confirmed by Engstrom and Markkula (2007). In line with this, Ross et al. (2014) demonstrated that the effect of a verbal cognitive task on the LCT PCL metric interacted with verbal working memory capacity (as measured by a letter span task) such that participants with low working memory capacity were more negatively affected (i.e. made more erroneous lane change decisions) by the cognitive task than participants with high working memory capacity.

Another study on the effect of CL on decision making was conducted by Cooper et al. (2003) on a test track. The study included several different scenarios, where the most clear cut effect of CL was obtained for gap acceptance decisions in a left-turn-across-path scenario, conducted on dry or wet road surface. The key performance variable was the average time gap accepted by drivers when initiating the turn. When the road was dry, the average accepted gap did not differ between cognitively loaded and non-loaded drivers. However, when the road was wet, the non-loaded drivers adapted by increasing their average accepted gap while the cognitively loaded drivers adopted the same accepted gaps as for the dry road. This result also dovetails nicely with the cognitive control hypothesis: Non-loaded drivers recruit cognitive control to flexibly adapt their behavior on the wet road to compensate for the assumed longer stopping distance of the oncoming vehicle, thus overriding the “default” automatized gap acceptance behavior applied on the dry road. By contrast, cognitively loaded drivers resort to their automatized routines also on the wet road. The results from the reviewed studies investigating effects of CL on lateral vehicle control are summarized in Table 4.

Table 4 Summary of effects of CL on decision making and interpretation in terms of the cognitive control hypothesis. Studies that found different effects on CL in different experimental conditions are marked with*

Aspect of driving performance/specific measure	***Effect of cognitive load (relative to no-task baseline condition)***	***References***	***Interpretation in terms of the cognitive control (CC) hypothesis***
Lane selection in the Lane Change Test (LCT)	Reduced Percent Correct Lane (PCL)	Engström and Markkula (2007), Ross et al. (2014)	Performing commanded lane changes in LCT relies on cognitive control and thus impaired by CL.
Accepted gap when turning at intersection	No difference *Dry road	Cooper et al. (2003)*	Gap acceptance behavior on dry roads is automatized and thus not affected by CL.
	Smaller accepted gap than for non-loaded subjects (same as for dry road) *Wet road	Cooper et al. (2003)*	Non-loaded subjects can utilize cognitive control to adapt to unusual conditions (increasing the gap on wet pavament) while cognitively loaded subjects fall back on their automatized routines.

Summary

Existing experimental results were reviewed and re-interpreted in terms of the cognitive control hypothesis. It was shown that several apparent discrepancies in the experimental literature may be resolved when the results are interpreted in terms of the control hypothesis and the underlying GAT model. Tasks that may appear functionally similar (such as lane keeping and artificial tracking, or responding to unexpected looming objects and responding to artificial light pulses), may differ critically in the degree by which they rely on cognitive control. Thus, the effect of CL on these tasks will also differ, sometimes even leading to opposite effects (such as improving lane keeping and impairing tracking, or reduced or increased speed depending on the experimental instruction given). This implies an interaction between the effects of cognitive load and degree of automaticity, which has been experimentally demonstrated for all the main aspects of driving performance: object and event detection (e.g., Muttart et al., 2007; Baumann et al., 2008; Engström, 2011, paper III); lateral control (Medeiros-Ward et al., 2014); longitudinal control (Recarte and Nuñes, 2002; Lewis-Evans et al., 2011) and decision making (Cooper et al., 2003). Moreover, the bulk of studies reviewed above offer partial support for the cognitive control hypothesis by consistently reporting performance decrements during CL for artificial, non-practiced or variably mapped (and thus non-automatized) tasks but null effects or even improved performance for well-practiced and consistently mapped (hence automatized) tasks such as lane keeping and braking responses to looming. Hence, it seems useful to think about effects of CL on driving in terms of a *resort to automatized routines* rather than a general performance impairment.

In the remainder of this paper, we first address the relation between our model and other models that have been proposed to account for effects of cognitive load on driving. We then outline some further specific predictions that can be tested in future experiments and discuss the implications of the cognitive control hypothesis in terms of the generalizability of experimental results to real-world driving. We also outline a proposal for how the present account may be extended to account for the pervasive lane keeping improvement effect, and the associated effects on steering and gaze reviewed above. Finally, we address potential implications of our model for the relation between cognitive load and road safety.

Relation to existing models

The most common approach taken to explain and model effects of CL on driving performance is in terms of limited capacity information processing (IP) models. Such models come in different varieties, such as single (Moray, 1969) and multiple resource models (Wickens, 2002) or central bottleneck models (Welford, 1952; Pashler and Johnston, 1998). More recently, detailed, IP-based, computational models of multitasking have been developed (e.g., Meyer and Kieras, 1997; Salvucci and Taatgen, 2011). Such models have also been applied to modeling the effect of CL on driving, in particular in the work of Salvucci and colleagues (Salvucci and Taatgen, 2008, 2011, Chapter 3; Salvucci and Beltowska, 2008) based on the ACT-R architecture (e.g., Andersson, 2007). The common underlying assumption behind these models in explaining effects of CL on driving is that the processing demands imposed by a cognitive task overlap with the processing demands of driving and, since processing capacity is limited, driving performance will be impaired during performance of a concurrent cognitively loading task.

IP models thus seem to be generally in line with the present account when only considering effects of CL on *non-automatized* aspects of driving relying on cognitive control. Non-automatized tasks will compete for cognitive resources (cognitive control in our terms) which leads to performance decrements on one or both tasks. However, when these models have been applied to the modeling of effects of CL on driving, they have generally failed to account for the lack of effect of CL (or performance improvement, as in the case of lane keeping) for strongly automatized tasks. This is, for example, clearly evident from the debate between single- and multiple resource theorists (Moray, 1999 and Wickens 1999), where the two authors appear to agree that phone conversation should induce a general impairment on driving but differ on what type of resource model (single vs. multiple resources) best accounts for this effect (an effect which, however, based on the present review, is misconceived). Another example concerns the effect of CL on lane keeping as modeled by Salvucci and Beltowska (2008). This ACT-R model is based on the notion of a procedural resource demanded by both the cognitive task and steering. Thus, when performing the two tasks concurrently, they need to be interleaved in a serial fashion. The model thus predicts that CL would temporarily disrupt steering, leading to impaired lane keeping performance. However, as reviewed above (and also pointed out by

Medeiros-Ward et al., 2013), these predictions contradict the large body of accumulated evidence suggesting that CL rather increases steering activity (more specifically, small steering reversals) and improves lane keeping.

This failure to account for empirical findings should not be seen as an inherent limitation of IP models, however. For example, it may be suggested that multiple resource models (Wickens, 2002) actually do predict a lack of effect of CL on automatized tasks, given that such tasks do not demand cognitive resources (although this is not the interpretation offered in Wickens, 1999). Moreover, the ACT-R modeling framework includes a mechanism for how tasks become increasingly automatized through reinforcement learning, which generally appears similar to the present account (Salvucci and Taatgen, 2011, Ch. 6). However, these mechanisms are not included in the specific ACT-R models addressing effects of CL on driving (Salvucci and Taatgen, 2011, Chapter 3; Salvucci and Beltowska, 2008).

Thus, there is nothing in principle that prevents IP models to postulate some parallel processing channel that bypass the assumed cognitive control bottleneck (thus accounting for automatic performance). One example of this approach is Hierarchical Control Theory (HCT), originally developed by Logan and Crump (2009) to explain skilled typewriting, adopted by Medeiros-Ward et al. (2014) to explain their observed interaction between cognitive load and lane keeping difficulty (reviewed above). This model postulates an outer, resource-demanding and effortful control loop needed to deal with novel and difficult tasks. With practice, some of this work can be offloaded to an inner loop, which is more automatic and requires little effort for efficient performance. With extensive practice, performance gets encapsulated by the inner loop and almost completely automatized. On the assumption that normal lane keeping is automatized and thus mainly governed by the inner loop, and lane keeping in difficult conditions requires the capacity-limited outer loop, HCT accounts for the interaction effect observed by Medeiros-Ward et al. (2014), as well as the general pattern of results reviewed above. As described above, the idea that CL selectively affects non-automatized driving tasks has also been independently proposed by Cooper et al. (2003), Lewis-Evans et al. (2013) and Recarte and Nuñes (2002).

While the theories and models proposed by Medeiros-Ward et al. (2014), Cooper et al. (2003), Lewis-Evans et al. (2013) and Recarte and Nuñes (2002) are generally compatible with the cognitive control hypothesis, the present GAT-based model goes one step further in outlining an explicit, neuroscientifically grounded explanation for the development of automaticity and cognitive control, based on the gradual strengthening of neural pathways with frequent and consistent exposure. As outlined above, this enables clear-cut a-priori predictions of which tasks that are expected to be impaired by cognitive load based on the amount of exposure (degree of practice) and inherent task structure (consistent vs. variable mapping). Furthermore, while the previous accounts were developed to explain the results of specific studies, the present framework represents a more generalized account that applies across a variety of driving sub-tasks (including, but not limited to, object/event detection-response, lateral control, longitudinal control and decision making).

Finally, the idea that the development of automaticity depends on inherent statistical uncertainty in task structure makes contact with contemporary *predictive processing* accounts in cognitive science and computational neuroscience (e.g., Clark, 2016). Such models suggest that a key role of attention (or precision-weighting) is to regulate the balance between top-down expectations and bottom-up sensory evidence by means of modulating the gain of prediction errors based on the estimated uncertainty of the top-down prediction. While, the present account (based on the GAT model) seems amenable to a predictive processing interpretation, this is not further pursued here. However, the predictive processing framework represents an interesting direction for future development of the present model. A general predictive processing account of driving is outlined in Engström et al. (in review).

Novel predictions

The cognitive control hypothesis, and the underlying GAT-model, leads to a variety of novel predictions, all based on the key notions that (1) CL selectively impairs performance on tasks relying on cognitive control and (2) whether a task relies on cognitive control depends on individual exposure (degree of practice) and task structure (i.e., the consistent versus variable mapping of sensorimotor contingencies).

One general implication of the cognitive control hypothesis is that the effect of CL is expected to be strongly idiosyncratic, depending on the driver's individual history and the resulting repertoire of automatized behaviors developed through exposure to the traffic environment. In particular, all other things being equal, it can be predicted that novice drivers should be more susceptible to task interference from CL than experienced drivers. However, the individual driver's history will also depend on the type of traffic environment and traffic culture that the driver has been exposed to. Thus, the effects of cognitive load will not only depend on the amount of driving experience, but also on the *type* of experience (as determined, for example, by the local traffic culture), since this would be expected to critically shape the repertoire of automatic behaviors that a driver falls back upon when cognitively loaded. In addition, it may be speculated that not only driving experience, but the more general sensorimotor experience matters. For example, basic aspects of steering (such as optical flow changes in response to steering input) learned early in life from other forms of locomotion such as walking, driving toy cars and cycling, may influence the later acquisition of automatized driving skills (we thank an anonymous reviewer for this suggestion).

Regarding task structure, a general implication of the present account is that the development of automaticity will depend on the inherent (statistical) variability (or uncertainty) of the task as well as the frequency at which a task is encountered in the real world. Thus, frequent and consistently mapped tasks such as lane keeping are expected to become automatized relatively quickly, while the development of automaticity of more complex, and/or less frequent, tasks such as visual scanning at an intersection may take substantially longer (it should be kept in mind that, according to the present account, automaticity is viewed as a gradual process where completely controlled and automatic tasks are just endpoints on a scale). This further implies that the predicted interaction between driving experience and CL will be strongly task-dependent. For example, lane keeping may be relatively automatized even for novice drivers while visual scanning may not. The precise relations between CL, driving experience and task variability (uncertainty) have not been systematically investigated to date and thus constitute an important avenue for further research.

When driving experience is controlled for, the present account yields a number of more specific predictions. Several of these have been partly confirmed by existing results reviewed above, but have not yet been tested in a single experiment. For example, in a lead-vehicle braking study, CL should mainly impair braking in response to expected brake lights (e.g., Alm and Nilsson, 1995) but should only have a minor effect (or no effect at all) on braking reactions to looming when brake lights are turned off (e.g., Muttart et al., 2007). Furthermore, CL should impair lane keeping if the steering wheel is replaced by a non-standard steering device (e.g., a joystick or trackball, as in Just et al,. 2008) but not when a standard steering wheel is used and the lane keeping task is otherwise benign (rather, in the latter case, the lane keeping improvement effect is expected, for which possible explanations are discussed below).

With respect to longitudinal control, cognitively loaded drivers are predicted to revert to their "default" safety margins, in terms of speed and headway. As reviewed above, this prediction has been confirmed for speed (Lewis-Evans et al., 2011; Recarte and Nuñes, 2002) but similar predictions apply to headway control. Thus, as outlined above, if participants in an experiment are instructed to maintain a specified headway, the magnitude as well as the direction of the effect of CL should depend on the difference between the instructed headway and the driver's "default" (automatized) headway in the given scenario.

Another prediction is that extensive practice on simple, consistently mapped, artificial tasks commonly used for CL evaluation (such as the DRT or ConTRe, reviewed above), would reduce, and finally eliminate, sensitivity of such tasks to cognitive load. However, the amount of practice needed for this to happen would likely by far exceed the amount of practice given in typical DRT or ConTRe experiments (and, hence, this may not threaten the sensitivity of these CL evaluation methods in practice).

Finally, the cognitive control hypothesis suggests that the ability to adopt flexible scanning strategies to deal with novel, uncertain situations (e.g., when entering into a complex non-signalized intersection), should be impaired under CL. By contrast, routine scanning in situations with low uncertainty, for example, when driving through a familiar signalized intersection with a green light, should be relatively unaffected by CL.

Explaining the lane keeping improvement effect

As reviewed above, one of the most reliable effects of cognitive load on driving performance is the lane keeping improvement effect, typically accompanied by increased steering activity and sometimes by a gaze concentration towards the road center. While this does not speak against the cognitive control hypothesis, the present account, as outlined so far, does not offer any clear explanation for these effects. In this section we discuss different explanations proposed in the literature and offer a suggestion for how the GAT model outlined above may be extended to account for the lane keeping improvement, steering and gaze concentration effects.

He (2012) and He et al. (2014) review a number of proposed explanations for the lane keeping improvement effect. The *rigidified steering hypothesis* (e.g., Reimer, 2009) suggests that shifting attention away from driving to the cognitive task results in more intermittent and unresponsive steering, implying that observed reduced lane keeping variability actually represents an impairment rather than performance improvement. A similar interpretation is suggested by Salvucci and Beltowska (2008), as discussed above. However, the common finding that steering activity increases (rather than reduces) during cognitive load (e.g., Markkula and Engstrom, 2006) speaks strongly against this idea. Other authors who observed increased steering activity under CL have suggested that it represents more “noisy” or more abrupt steering (Boer, 2000; Liang and Lee, 2011). However, the common result that lane keeping variability is reliably reduced during CL and the further finding by He et al. (2014) that CL increases the coherence between steering corrections and lateral perturbations offer strong evidence for the idea that the observed effect actually represents more precise, or focused, steering resulting in improved lane keeping.

Several other hypotheses start from this assumption. *The automatic steering hypothesis* (Kubose et al., 2006; Medeiros-Ward et al., 2014) is based on the common observation that skilled performance, such as a golf swing, becomes impaired when explicitly attended to (Beilock et al., 2002). Thus, during normal (baseline) driving, the driver may consciously focus on the lane keeping task, leading to disruption of (the more precise) automatic lane keeping performance. However, this explanation faces several challenges. First, on the assumption that lane keeping (as opposed to golf!) is normally performed in satisficing mode (Engström, 2011, Paper III), it seems unclear why drivers would attend consciously to lane keeping if not explicitly instructed to. Second, the automatic steering hypothesis implies that instructing drivers to maintain a central lane position would impair performance. However, as reviewed above, this prediction is contradicted by Engström (2011, Paper III) who found that explicit instructions to focus on lane keeping significantly *improved* lane keeping performance. Finally, it is not clear how this explanation would account for the observed increased frequency of steering corrections or the gaze concentration effect.

The visual enhancement hypothesis, originally put forward by the present authors (see e.g., Engström, 2011; Engström et al., 2005; Victor, 2006) suggests that CL causes gaze to “lock” to the road ahead, thus leading to the gaze concentration effect. According to this account, this happens because active visual exploration relies on cognitive control resources which are occupied by the cognitive task. The resulting increased visual input from the road ahead enhances the already strongly automatized lane keeping task, thus leading to more frequent steering corrections and, as a consequence, improved lane keeping. Hence, according to this explanation, the lane keeping improvement effect is *mediated* by gaze concentration. This mechanism is further illustrated by a quantitative driver model presented in Boer et al. (2016).

However, the visual enhancement hypothesis is challenged by the results from Cooper et al. (2013), reviewed above, who reported a lane keeping improvement effect even when gaze was fixed to a specified point on the forward roadway. In line with this, as also reviewed above, He et al. (2014) observed lane keeping improvement under CL without any gaze concentration and Liang and Lee (2010) found that gaze concentration explained only 5 percent of the lane position variation. This clearly speaks against the idea that the lane keeping improvement effect of CL is mediated by gaze concentration, as suggested by the visual enhancement hypothesis. Rather, these results suggest that the gaze concentration and the improved lane keeping are independently caused by some other factor.

What could this factor be? One possibility is *the lateral prioritization hypothesis*, advocated by He et al. (2014) and previously proposed by Engström et al. (2005). This hypothesis suggests that the lane keeping improvement occurs due to a strategic prioritization of the lateral control task, in order to compensate for the increased perceived risk associated with the dual task situation. However, this leaves it open why drivers chose to protect lane keeping in response to CL, rather than reducing speed (see the review of CL effects on longitudinal control above), as this would seem a less energetically costly way to increase safety margins. Such speed reductions are reliably observed during performance of visual-manual tasks (Antin, Dingus, Hulse, and Wierwille, 1990; Curry, Hieatt, and Wilde, 1975; Engström et al., 2005; Östlund et al., 2004) but not under CL. Hence, if drivers do self-regulate also in response to cognitive load to increase safety margins, it is unclear why they would not prefer the same strategy as for visual tasks (i.e., reduce speed).

Here we briefly outline a novel explanation which can be viewed as an extension of the GAT model outlined above. A computational implementation of this model is presented in Markkula and Engström (forthcoming), including a demonstration of how the increased steering and lane keeping improvement effects can be reproduced in simulation. The general idea is that the lane keeping improvement under CL occurs due to a global enhancement in neural responsiveness (i.e., targeted neurons become more easily activated) associated with the deployment of cognitive control. There is substantial neuroscientific evidence for such global enhancement effects during the deployment of cognitive control, and that such effects are related to neuromodulatory processes originating in the reticular activation system in the brainstem, in particular noradrenergic modulation from the nucleus locus coeruleus (Aston-Jones and Cohen, 2005; Gilzenrat, Nieuwenhuis and Jepma, 2010; Posner and Fan, 2008). More specifically, it has been proposed that the key effect of noradrenergic modulation is to increase the *gain* in cortical neurons, thus making them more responsive to stimulus input (Shea-Brown, Gilzenrat and Cohen, 2008; Servan-Schreiber, Prinz and Cohen, 1990). These effects, which have been referred to as *cortical arousal* (Kent, 2007), also seem to correlate with physiological arousal, as indicated, for example, by the finding that neural activity in locus coeruleus is closely tracked by pupil dilation (Gilzenrat, Nieuwenhuis and Jepma, 2010). Moreover, based on laboratory studies it has been proposed that neural sensitivity (conceived in terms of the rate of neural evidence accumulation) scales up and down with increases (Jepma et al., 2009) and decreases (Ratcliff and van Dongen, 2011) in arousal.

Thus, when cognitive control is allocated to support a non-automatized task, governed by weak neural pathways, this is associated with a global enhancement of neural responsiveness with the primary purpose to protect the non-automatized task from interference. The key proposal here is that this global neural enhancement will also enhance other ongoing, non-interfering, automatized tasks governed by strong pathways. In other words, ongoing automatized tasks may be enhanced as a side-product of the enhancement of the weak pathways governing the (non-automatized) cognitive task.

In the case of lane keeping, the key proposal is thus that the enhanced responsiveness of neurons in the strong lane keeping pathway leads to an increased sensitivity to visual stimuli representing lane keeping error. This results in more frequent steering corrections which, in turn, lead to reduced variability in lane position. Such an explanation would thus accommodate the results of Cooper et al. (2013), allowing for the observed steering and lane keeping effects also when gaze is already fixed by instruction. The gaze concentration effect can then be understood as an independent effect of CL (though often correlating with the steering and lane keeping enhancement), resulting mainly from the blocking of other visual activities relying on cognitive control (this part of the theory is thus in line with the visual enhancement hypothesis mentioned above).

One way to test this model would be to induce arousal experimentally, for example by exposing participants to loud noise (Hockey, 1970), in which case the model predicts similar effects on driving as observed for cognitive load (i.e., an increase in small steering reversals and improved lane keeping). These predictions do not seem to be implicated by any of the other accounts proposed to explain the lane keeping improvement phenomenon reviewed above.

A further implication of this model is that the task improvement effect of CL should only occur for tasks *that are normally performed in a non-optimal fashion*, meaning that there is room for improvement. As reviewed above, evidence suggests that lane keeping is indeed normally performed non-optimally, that is, in satisficing mode (Engström, 2011, Paper III)). This may explain why the improvement effect has not been found for automatized emergency responses such as braking to looming (since such behaviors would be expected to be performed in a more optimized fashion). It may well be the case that lane keeping in driving is a rare example of a driving sub-task that satisfies both the requirement of being strongly automatized and normally being performed in satisficing mode. Interestingly, effects of CL similar to the lane keeping improvement effect have been found in the field of human posture control (Andersson et al., 2002; Fraizer and Mitra, 2008), a naturalistic task which seems to share both the automaticity and satisficing criteria with lane keeping.

Implications for generalization from experimental studies

The cognitive control hypothesis implies that detrimental effects of cognitive load will only be expected when participants are asked to do something that is not part of their repertoire of automatized skills. While most laboratory tasks used in psychological experiments are of this sort, driving is a prime example of a natural task where participants typically bring a repertoire of existing automatized skills into the laboratory. As reviewed above, the most clear-cut examples of this are lane keeping and avoidance responses to looming objects. It follows that great caution is needed when generalizing from experimental CL studies to real-world, naturalistic, driving. Thus, while artificial tasks, such as the DRT and ConTRe, may be very useful as tools for measuring the cognitive demands of secondary tasks with high sensitivity and specificity (Young, 2013), they cannot be regarded as valid surrogates for aspects of real-world driving that are automatized for experienced drivers. The same argument holds for more realistic driving studies involving artificial experimental tasks not usually performed in naturalistic driving, such as responding as fast as possible to expected brake light onsets or steering with a trackball.

Relation between cognitive load and road safety

What can the cognitive control hypothesis tell us about the relation between cognitive load and crash risk? A general implication of the cognitive control hypothesis is that it is difficult to address this question solely based on the results of experimental dual task experiments. First, as discussed in the previous section, the measured performance on artificial, non-automatized tasks such as the DRT or responses to expected brake light onsets cannot be validly used as surrogates for emergency avoidance reactions in the real-world. Second, the performance decrements typically found in existing studies are relatively small (e.g., response delays up to 300 ms in DRT studies or lead vehicle braking studies with more urgent scenarios) and thus seem unlikely to represent a critical mechanism behind crashes. By contrast, response delays due to glances off the forward roadway are often on the order of seconds, indicating a much more direct relation to crash causation (see Victor et al., 2015, for a detailed analysis of naturalistic data, showing how looking away from the road causes rear-end crashes in the real world).

Moreover, relating the present account to the findings from naturalistic driving (ND) studies investigating the relation between engaging in cognitively loading tasks (in particular phone conversation) and crash risk is not straightforward, partly since the reported estimated risk associated with CL differs between existing ND studies (as reviewed in the Introduction). Moreover, these risk estimates cannot be used to infer underlying causal mechanisms. Thus, it seems critical to conduct more detailed, in-depth analyses of naturalistic crashes involving phone conversation (or other cognitively loading tasks) in order to understand if and, if so, how these crashes were actually caused by cognitive load (in a similar vein as the analysis carried out in Victor et al., 2015, on the causal relation between crashes and eyes taken off the forward roadway). The present account offers some theoretical guidance for such an analysis. First, crash-causation mechanisms associated with CL would not be expected to involve decrements in basic operational control such as delayed emergency reactions or impaired lateral control. Rather, CL would be expected to contribute to crashes in situations where the automatized routines that the cognitively loaded driver relies on fail to match the actual driving situation. For example, a cognitively loaded driver may be particularly prone to what Norman (1981) refers to as *capture errors*, where a partial match to a familiar situation triggers an inappropriate behavior (in this case, a behavior that induces a crash). This may, for example, be the case when approaching a signalized intersection with a red light, but other salient cues (for example a green light for vehicles in the adjacent lane and the fact that these vehicles are moving forward) suggest to the driver that she has the right of way. If these cues capture the habit of moving forward into the intersection, the outcome may be very serious if vehicles with the right of way are approaching fast from the intersecting road.

Another subtle type of error potentially induced by cognitive load relates to the inability of cognitively loaded drivers to flexibly adapt to novel or unusual driving situations. This includes the proper use of predictive cues (Baumann et al, 2008; Muttart et al., 2007), in which case the cognitive control hypothesis suggests that CL will prevent the flexible use of novel cues that are not part of the driver's repertoire of automatized behaviors (i.e., cues that are infrequent or variably mapped to the intended response, thus requiring cognitive control to be utilized). Such cues may include road signs (Baumann et al., 2008) or some unusual activity on the road further ahead that a non-loaded driver can use to infer a need to take action (e.g., a vehicle backing up onto the road further ahead causing a lead vehicle in front of the driver to brake). This also relates to the significant impairments of cognitively loaded drivers in following explicit roadside instructions, as reported by Engström and Markkula (2007). Similarly, as indicated by the results by Cooper et al. (2003), CL may impair drivers' ability to properly adapt to unusual road conditions, in this case adjusting gap acceptance in intersections to compensate for a wet (and potentially slippery) road. A similar, but potentially even more serious, case would be a cognitively loaded driver failing to adapt speed under conditions of black ice. This may lead to a loss of traction potentially resulting in a road departure or a high-speed crash with oncoming traffic.

While such potential CL-induced errors may be very infrequent (and difficult to recreate in controlled experiments), they may still be a key component cause in the rare circumstances that lead to severe crashes such as entering a main road with high-speed traffic, hitting a vulnerable road user, running off the road or crashing with an oncoming vehicle. Thus, the performance effects of cognitive load relevant for crash causation may be subtle, and not primarily related to the performance measures traditionally used in dual task studies, but it is still possible that these effects play a key role in the rare sets of circumstances that lead to severe crashes. However, in the absence of a detailed analysis of the causal mechanisms of crashes involving cognitive tasks, these suggestions remain speculative.

Conclusions

The present paper outlined a novel framework for understanding effects of cognitive load on driving performance, formulated in terms of the cognitive control hypothesis suggesting that cognitive load selectively impairs (non-automatized) aspects of driving relying on cognitive control, but leaves automatized tasks unaffected, and sometimes even improves performance. From this perspective, it is useful to think about performance effects of cognitive load in terms of a resort to a repertoire of automatized routines (specific for the individual driver) rather than as a general decrement in dual task performance.

An extensive literature review suggested that existing experimental results generally align with the cognitive control hypothesis. This hypothesis, and the underlying GAT model, also leads to several novel predictions that could be tested in future studies. A key implication of the present account is that performance effects of cognitive load obtained in experimental dual task studies using artificial surrogate tasks or unnatural (non-practiced) driving tasks cannot be validly generalized to real-world driving. Thus, the safety implications of such findings are unclear. However, it is possible that cognitive load has other, more subtle, effects that play a key role in the genesis of severe crashes but further research, combining experimental studies and naturalistic crash data, is needed to establish this.

Finally, implementing the key mechanisms underlying the cognitive control hypothesis in computational simulation models yields more specific quantitative predictions which can be tested against human data. As mentioned above, we have initiated the development of such models and initial results are presented in Engström et al. (forthcoming) and Markkula and Engström (forthcoming).

Key points

- The proposed *cognitive control hypothesis* suggests that cognitive load selectively impairs driving sub-tasks that rely on cognitive control but leaves automatic performance unaffected.
- Automaticity can be understood in terms of the strength of neuronal pathways which develops gradually through exposure to driving situations/tasks.
- The development of automaticity depends on exposure and statistical task structure, where automaticity develops for frequent tasks that are consistently as opposed to variably mapped.
- The reviewed literature aligns well with the cognitive control hypothesis and resolves several apparent discrepancies between results reported in the literature.
- Effects of cognitive load can be viewed as a resort to a repertoire of automatized routines (specific for the individual driver) rather than as a decrement in dual task performance. This has strong implications for the use of surrogate driving tasks in the context of cognitive load evaluation.

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