Tenth International Conference on Managing Fatigue: Abstract for Review

Simulating effects of arousal on lane keeping: Are drowsiness and cognitive load opposite ends of a single spectrum?

Gustav Markkula, Institute for Transport Studies, University of Leeds, g.markkula@leeds.ac.uk

Johan Engström, Virginia Tech Transportation Institute (corresponding author), jengstrom@vtti.vt.edu

Problem

Both drowsiness and cognitive load have been demonstrated to significantly affect driving performance. By drowsiness, we here refer to a reduced level of *alertness*, where alertness is assumed to be governed by circadian cycle sleep homeostasis processes (Borbely and Achermann, 1999). By cognitive load, we refer to the need for cognitive, or executive, control to perform driving and/or non-driving related tasks such as cell phone conversation (Engström et al., in press). One important negative effect of drowsiness on driving can be broadly construed as a less responsive brain reacting more slowly to hazardous stimuli (Lin et al., 2010). This is manifested, for example, as increased lane keeping variability and an increased frequency of relatively large steering corrections (Liu et al., 2009). By contrast, a large number of studies (see reviews in He et al., 2014, and Engström et al., in press) have found that cognitive load, somewhat counterintuitively, *reduces* lane-keeping variability which is typically accompanied by an increase in *small* steering corrections (Markkula and Engström, 2006). Several explanations for this improvement effect of cognitive load on lane keeping have been offered in the literature, but none appears to be fully in line with the available evidence (Engström et al., in press). Here we suggest, based on a conceptual model outlined by Engström et al. (in press), that the observed performance effects of drowsiness and cognitive load on lane keeping and steering may be due to a single shared mechanism, that is, neural responsiveness, modulated by cortical arousal, determining the drivers' sensitivity to lane keeping error. This mechanism is implemented in a computational model and it is investigated, by means of simulation, whether the model can reproduce the empirically observed effects.

Method

The present computational model builds on a recent theoretical account (Engström et al., in press) suggesting that the improved lane-keeping observed under cognitive load is a by-product of increases in cortical arousal induced by the cognitively loading task. Transient arousal acts to allow and protect performance of non-routine tasks (requiring cognitive control), and may, it is suggested, collaterally enhance the responsiveness of a strong, highly automatized, neural pathway for lane-keeping that runs in parallel; see Figure 1.

It is here further suggested that drowsiness (i.e., reduced alertness) is associated with a reduced level of cortical arousal and, hence, decreased neural responsiveness in the lane keeping pathway. This would offer a parsimonious explanation why cognitive load typically induces an increase in small steering corrections and enhanced lane keeping while drowsiness has essentially the opposite effect.

In the present paper, this hypothesis is operationalized in more detail, using a recent framework for quantitative modelling of driving control (Markkula, 2014; Markkula et al., submitted). Quantitative models of driving performance make the underlying cognitive mechanisms explicit and generate detailed performance predictions that can be tested in simulation.

Based on contemporary neuroscientific models of perceptual decision-making (e.g., Gold and Shadlen, 2001), the proposed modelling framework suggests that intermittent control adjustments occur after integration to threshold of perceptual evidence for the need of control (in this case the perceived lane keeping error). This evidence accumulation process is here represented in terms of the expression $dA/dt=kp(t)$ where A represents the accumulated level of perceptual evidence, $p(t)$ is the perceived lane keeping error and k is a scaling constant representing the gain determining the rate of accumulation. When A reaches a threshold, a steering correction is triggered and executed by a steering control model based on the principles described in Markkula et al. (submitted). Crucially, based on laboratory studies, it has been proposed that 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. These findings are leveraged here by varying the gain parameter k in the evidence accumulation part of the model, thus affecting responsiveness. Low gain (emulating drowsiness) makes the model less sensitive to lane keeping errors while high gain (emulating cognitive load) enhances the sensitivity.

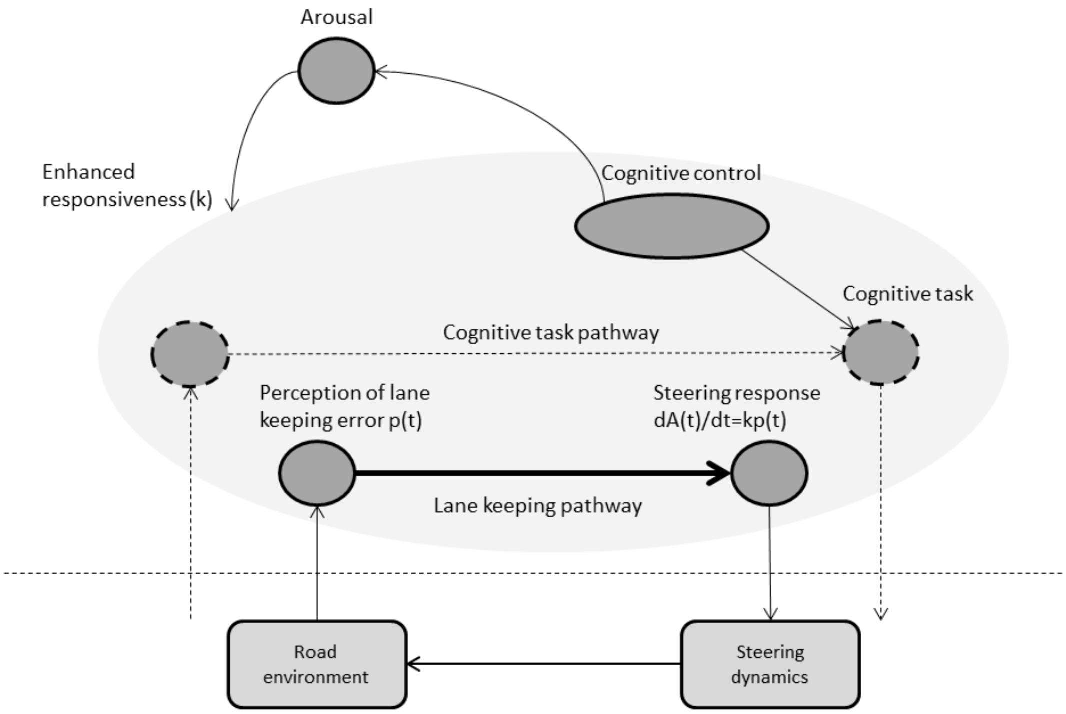

Figure 1. Conceptual overview of the computational model.

Results

Simulations with the proposed computational model show that varying the single accumulation gain parameter *k* is sufficient to reproduce the general pattern of empirical results reported in the literature. Lower gain values, representing drowsy driving, lead to increased variability in lane position (in terms of increased standard deviation of lane position, SDLP), an overall reduction in steering wheel reversals, but an increased frequency of larger steering reversals (>4 degrees). Conversely, higher gain values, emulating higher levels of cortical arousal induced by cognitive load, lead to reduced SDLP and an increased frequency of smaller steering adjustments (in particular adjustments smaller than 1 degree). See Figure 2 for example simulations, and Figure 3 for aggregated simulation results.

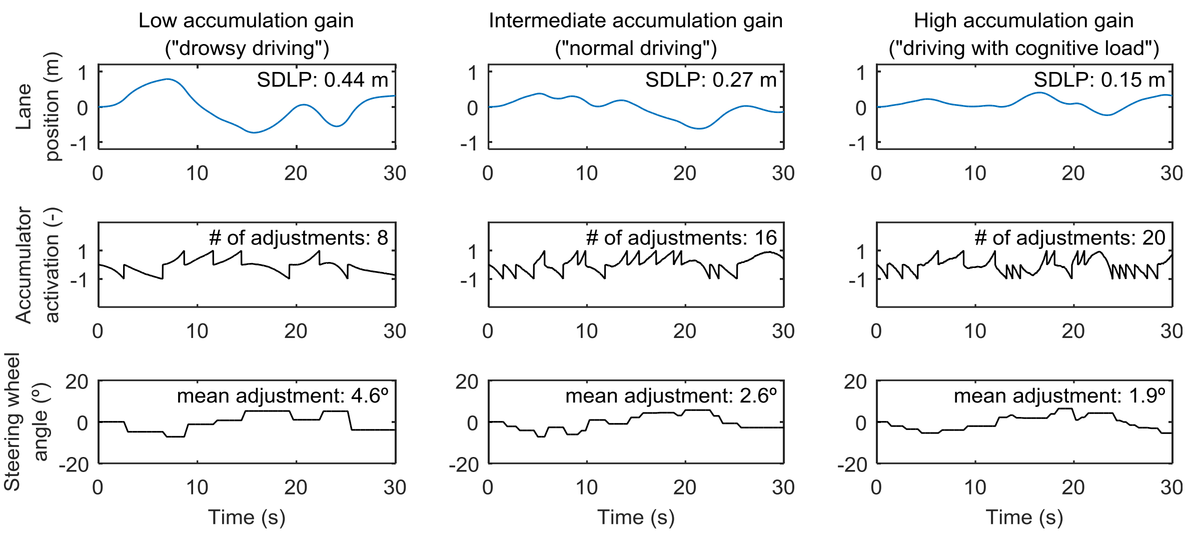

Figure 2. Three example simulations of lane-keeping on a moderately winding road. These simulations are identical in terms of road geometry, initial conditions, noise, and model parameters; the only exception is the accumulation gain parameter (set to 10, 30, and 50, in the same arbitrary unit as in Figure 3).

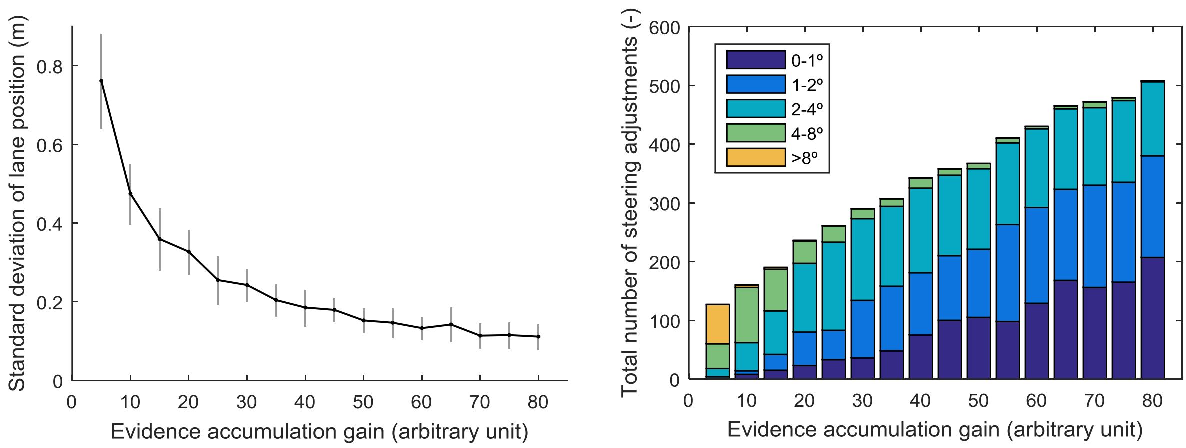

Figure 3. Overall effect of evidence accumulation gain on standard deviation of lane position (left) and total number of steering adjustments of various amplitudes (right). Twenty 30-second simulations were performed per accumulation gain setting.

Discussion

The computational model presented here lends further support to the idea outlined in Engström et al. (in press) that performance effects on lane keeping can be explained in terms of cortical arousal, suggesting that drowsiness and cognitive load can be viewed as opposite ends on a single spectrum (with respect to their effects on lane keeping). As can be seen in Figure 2 and Figure 3, reducing the evidence accumulation gain (here assumed to be associated with low cortical arousal and drowsiness) means that it takes longer for a given perceived lane keeping error to generate a steering correction. Hence, a steering action is not triggered until the lane deviation has grown relatively large, thus requiring a large steering correction to bring the vehicle back to the desired heading. This leads to less frequent but larger steering corrections and increased variability in lane position (i.e., increased SDLP). By contrast, when the evidence accumulation gain is increased (due to cognitive load and associated arousal), steering corrections are triggered earlier, leading to an increased frequency of smaller corrections and improved lane keeping.

Thus, representing this spectrum by a single accumulation gain parameter quantitatively reproduces the lane keeping performance and steering effects reported in the literature for both drowsiness and cognitive load. The model is also consistent with empirical findings that cognitive tasks have been shown to counteract effects of drowsiness (Oron-Gilad, Ronen and Shinar, 2008; Gershon et al., 2009), and the conceptual account underlying the present model (Engström et al., in press) could help to explain these observations.

The model is comparable to an existing ACT-R model of lane keeping and drowsiness proposed by Gunzelmann et al. (2011). In that model, arousal modulates the expected utility of actions, such as steering adjustments, and thereby how frequently these actions occur. This leads to similar behavioural predictions for effects of drowsiness, but based on a somewhat different underlying mechanism. Furthermore, existing ACT-R models of the effects of cognitive load on driving have assumed a single central processing bottleneck for both cognitive tasks and lane keeping (e.g., Salvucci and Beltowska, 2008).Thus, in contrast to the present model and the bulk of empirical evidence (see Engström et al., in press), these models predict that cognitive load should increase SDLP and reduce steering reversal rate.

It should be emphasized that drowsiness is a complex phenomenon that cannot simply be reduced to decreased cortical arousal. Thus, the present suggestion that drowsiness and cognitive load may be viewed as opposite ends on a single spectrum should be viewed as specifically concerning effects on lane keeping performance. Moreover, lane keeping may clearly be affected by other mechanisms not accounted for by the present model such as the basic interruption of visual information intake due to glances off the forward roadway or during periods of (drowsiness-induced) long eye closures. Furthermore, the present model does not account for more long-term effects related to time on task (what is often discussed in terms of *fatigue*, e.g. Williamson et al., 2009).

In future work, the present model could be evaluated at a more detailed level against empirical data from drowsy and cognitively loaded drivers, preferably collected in a single experiment.

Summary

A computational model of the effects of driver drowsiness and cognitive load on lane keeping and steering performance was presented, suggesting that empirically observed effects may be explained by a single mechanism, where neural responsiveness (here modelled in terms of accumulation gain) is modulated by cortical arousal. Low global neural responsiveness (due to drowsiness) makes the driver less sensitive to lane keeping errors, leading to fewer and larger steering corrections and increased lane keeping variability. Conversely, high global responsiveness (needed to protect performance of a non-routine cognitive task) increases the sensitivity, inducing more frequent and smaller steering corrections. The proposed model thus offers a novel, mechanistic, and neurobiologically plausible explanation for the effects on lane keeping of both drowsiness and cognitive load.

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