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

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The opposite effects of drowsiness and cognitive load on lane keeping performance

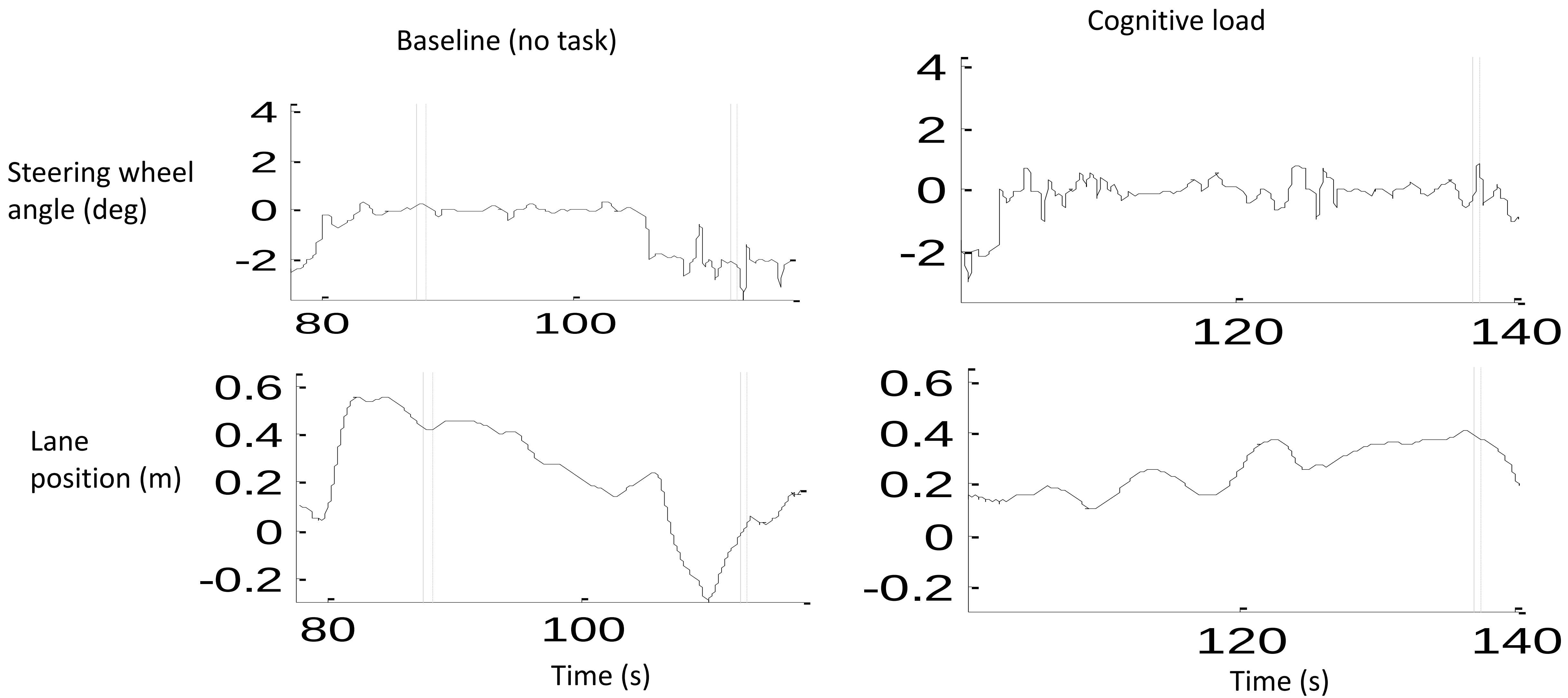
- Definitions
  - *Drowsiness:* Reduced level of *alertness*, where alertness is assumed to be governed by circadian cycle sleep homeostasis processes (Borbely and Achermann, 1999)
  - *Cognitive load:* The demand for cognitive, or executive, control (imposed by non-visual, working-memory loading, secondary tasks such as phone conversation)
- Effects of drowsiness on lane keeping
  - Increased lane keeping variability (Liu et al., 2009)
  - Fewer small steering corrections but more large corrections (Thiffault and Bergeron, 2003)
- Effects of cognitive load on lane keeping
  - *Reduced* lane-keeping variability (Atchley and Chan, 2011; Brookhuis et al. (1991), 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 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; see He, 2012, and Engstrom et al., 2017, for a reviews).
  - Increase in *small* steering corrections (Markkula and Engström, 2006; Engström (2011, paper III), Kountouriotis et al. (2016)

Explanation for the effects of drowsiness on lane keeping (Liu et al., 2009)

- The drowsy driver cannot detect small lane deviations (which can be corrected by small steering wheel movements (SWMs)
- Large SWMs needed to correct for large lane deviations
- This leads to increased lane keeping variability, fewer small steering corrections but an increased frequency of large corrections

Effects of cognitive load on lane keeping

Example data (Östlund et al., (2005)



Proposed explanations for the lane keeping improvement effect of cognitive load

- The rigidified steering hypothesis (e.g., Reimer, 2009)
- The automatic steering hypothesis (Kubose et al., 2006; Medeiros-Ward et al., 2014)
- The visual enhancement hypothesis (Engström, 2011; Engström et al., 2005; Victor, 2006)
- The lateral prioritization hypothesis (Engström et al., 2005; He et al. (2014)

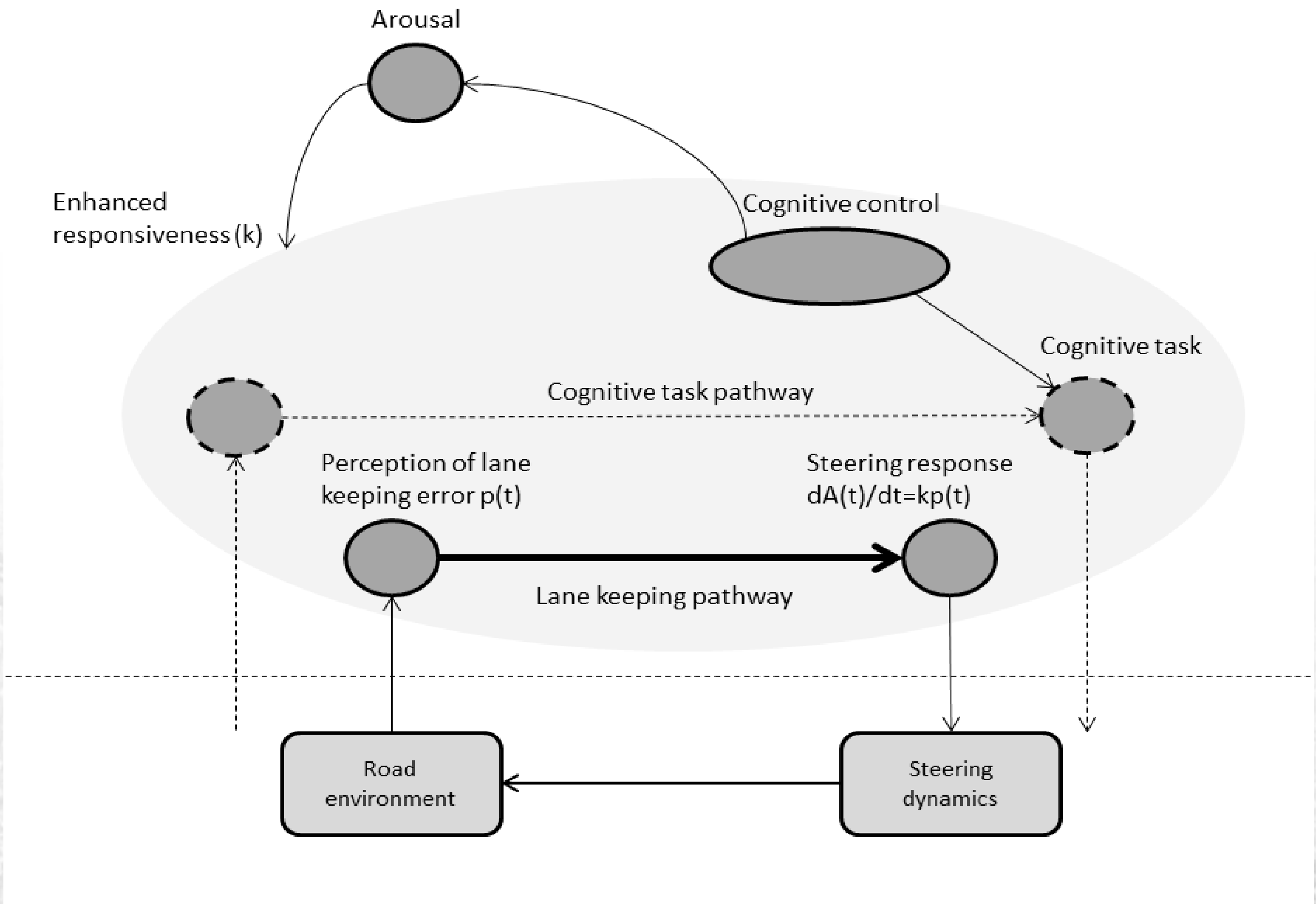
- However, all these hypotheses face challenges (see reviews in He et al., 2012, and Engstrom et al., 2017)

Novel hypothesis: “The cortical arousal enhancement hypothesis” (Engstrom et al., 2017)

- Neural responsiveness, modulated by cortical arousal, determines the driver’s sensitivity to lane keeping error
- Neuroscientific support
  - Global neural enhancement during the deployment of cognitive control related to neuromodulatory processes originating in the reticular activation system in the brainstem (Aston-Jones and Cohen, 2005; Gilzenrat, Nieuwenhuis and Jepma, 2010; Posner and Fan, 2008)
  - Key effect 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)
- Higher arousal induced by cognitive load -> increases sensitivity
- Lower arousal induced by drowsiness -> reduces sensitivity
- Single mechanism may account for both effects

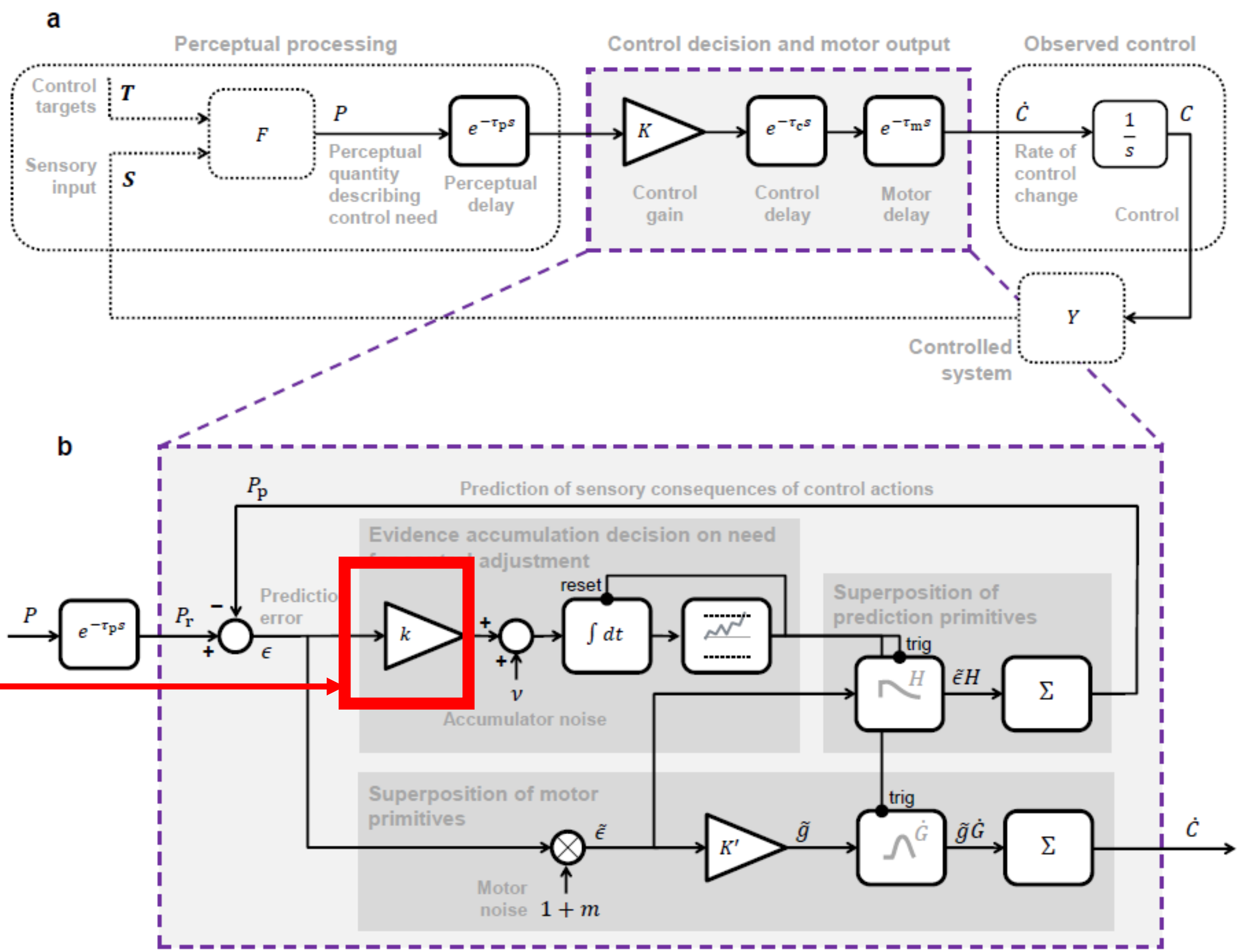
Conceptual model (based on Engström et al., 2017)

- Lane keeping is a strongly automatized task, governed by a strong neural pathway
- Performing cognitively loading secondary task (e.g., phone conversation) increases global cortical arousal
- Increased arousal enhances the responsiveness of both the cognitive task pathway and the lane keeping pathway
- Neural responsiveness can be modelled in terms of the rate of neural evidence accumulation (Jepma et al., 2009; Ratcliff and van Dongen, 2011)



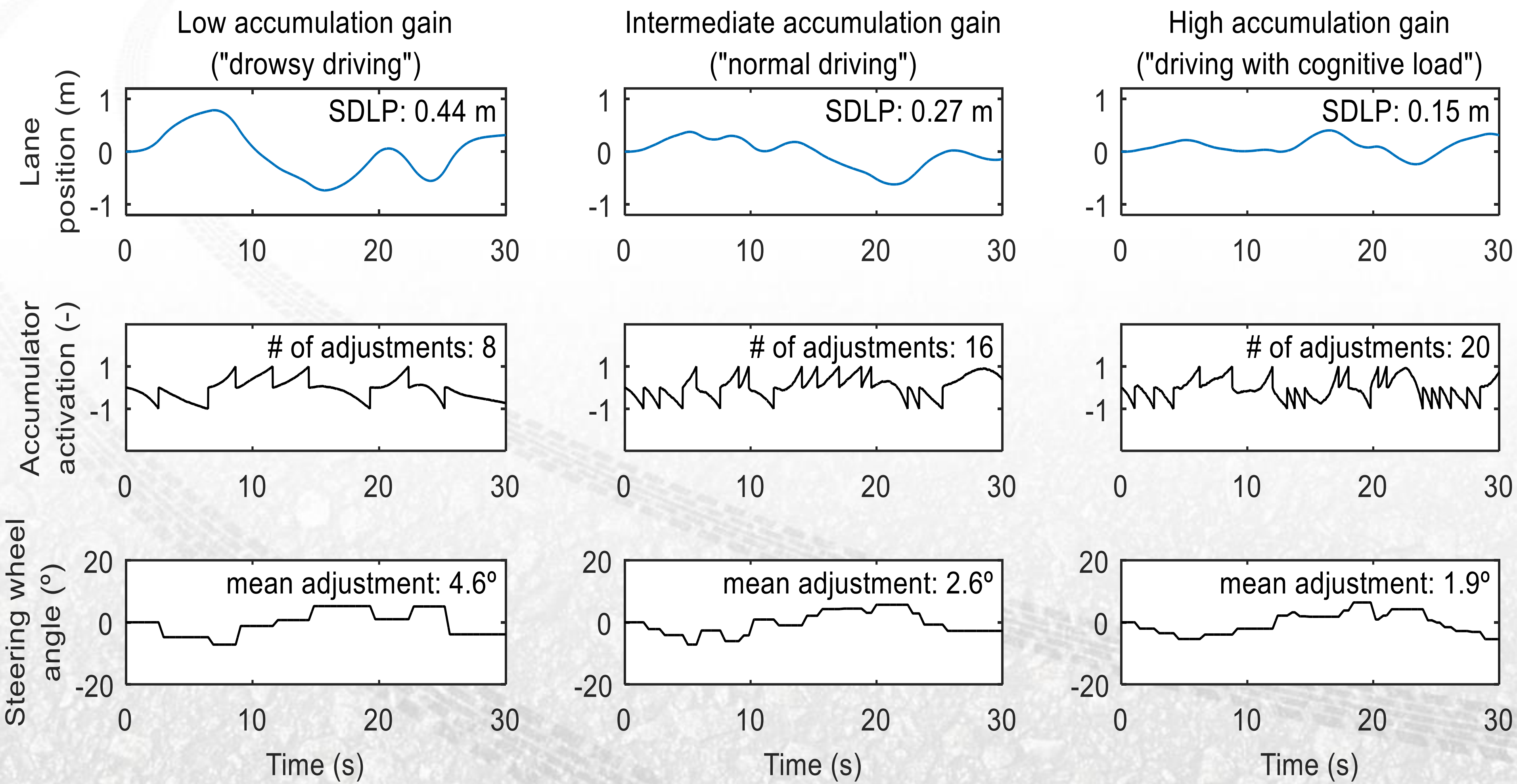
Computational steering model (Markkula, 2014; Markkula et al., submitted)

- General framework for sensorimotor control
- Based on contemporary neuroscientific models of perceptual decision-making (e.g., Gold and Shadlen, 2001)
- Intermittent control adjustments occur after integration to threshold of perceptual evidence for the need of control (in this case the perceived lane keeping error)
- Neural responsiveness represented by the accumulation gain *k*
- *k* scales up with increases in arousal (due to cognitive load) and down with reduced arousal (due to drowsiness)



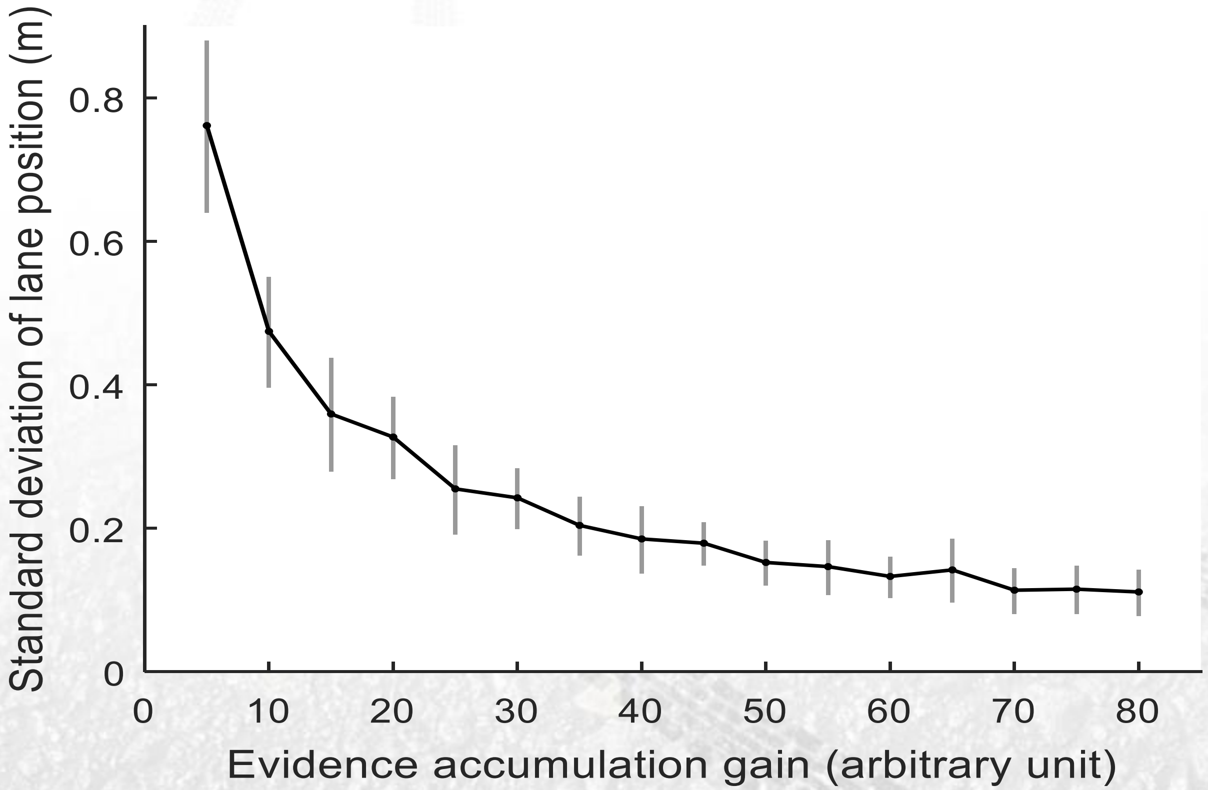
See https://arxiv.org/abs/1703.03030 for a pre-published version of Markkula et al., (submitted)

Simulation results (1)



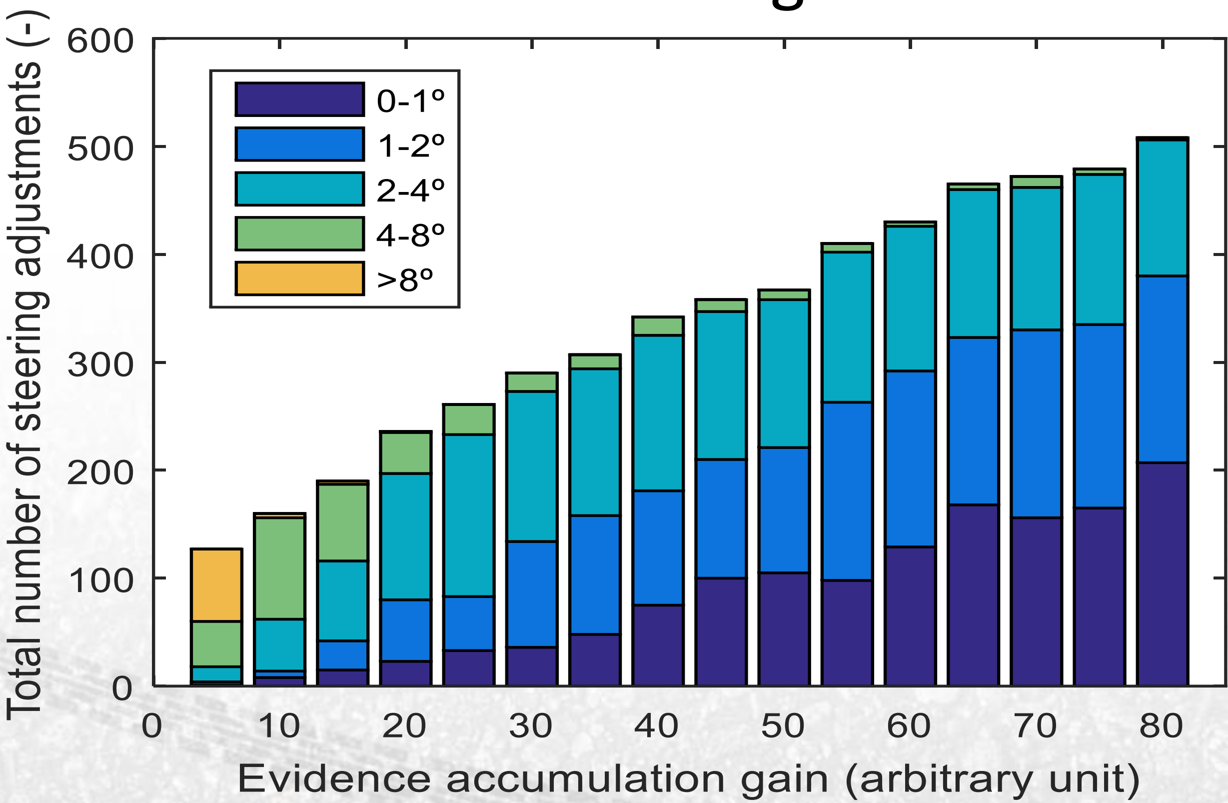
Simulation results (2)

Lane keeping



“drowsy driving” “normal driving” “cognitive load”

Steering



“drowsy driving” “normal driving” “cognitive load”

Increasing “arousal”

Interpretation

- Replicates effects in literature
  - Drowsiness: Increased lane keeping variability, fewer small steering corrections but more large corrections
  - Cognitive load: Reduced lane-keeping variability, increase in *small* steering corrections
- Mechanism, drowsiness
  - Reduces the evidence accumulation gain (drowsiness reducing "arousal")
  - Takes longer for a given perceived lane keeping error to generate a steering correction
  - Steering action is not triggered until the lane deviation has grown relatively large
  - Large steering correction required to bring the vehicle back to the desired heading
- Mechanism, cognitive load
  - Increasing the evidence accumulation gain (cognitive load increasing "arousal")
  - Steering corrections triggered earlier
  - Increased frequency of smaller steering corrections
  - Improved lane keeping

Conclusions

- The simulation results support to the idea outlined in Engström et al. (2017) that performance effects on lane keeping can be explained in terms of cortical arousal
- This suggests that drowsiness and cognitive load can be viewed as opposite ends on a single spectrum (with respect to their effects on lane keeping).
- 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.