Utilizing ACT-R to investigate interactions between working memory and visuospatial attention while driving

Moritz Held[1,2] (Moritz.held@uol.de), Jelmer Borst[2] (j.p.borst@rug.nl), Anirudh Unni[1] (Anirudh.unni@uol.de), Jochem W. Rieger[1] (Jochem.rieger@uol.de)
[1]Dept. of Psychology, University of Oldenburg, Germany
[2]Bernoulli Institute, University of Groningen, the Netherlands

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Introduction

Autonomous driving is an area which has seen rapid growth in recent years A long-held belief in this field is that more automation will equate more safety. However, some researchers continue to challenge this conviction in an argument for adaptive automation (Hancock et al., 2013).

In the context of driving, man-machine systems implementing adaptive automation are envisioned to continuously engage the driver in the driving task and at the same time, dynamically adapt the task-load depending on the driver's momentary cognitive ability. A key step towards this approach is to continuously monitor the driver's mental state and predict when the automation system should take more responsibilities and when to give them back to prevent drivers from mentally disengaging in the driving task.

Predicting mental workload has been done in recent studies using neuroimaging data (e.g., fNIRS; Unni et al., 2017; Scheunemann et al., 2019) but has come with limitations as different types of cognitive workload were interacting instead of adding at the brain level, which led to a decrease in prediction accuracy for two cognitive concepts relevant to driving: working memory load and visuospatial attention. In this study, we developed a cognitive model in the cognitive architecture ACT-R that integrates these two cognitive concepts to provide insights into how, when and where these concepts interact.

Methods

The model used in this study was a modification of the Java ACT-R driving model[1], which itself was a re-implementation of the Lisp ACT-R model (Salvucci, 2006). The model performed two tasks simultaneously using threaded cognition (Salvucci & Taatgen, 2011): a driving task and an n-back task, based on Unni et al. (2017).

In the driving task, the model must maintain a safe position on the road while driving along a three-lane highway with some concurring traffic.

To manipulate visuospatial demands, the road alternates between a regular highway with standard lane width (3.5m) and a construction site with narrower lanes (2.5m) where the left-most lane is blocked by red-white pylons.

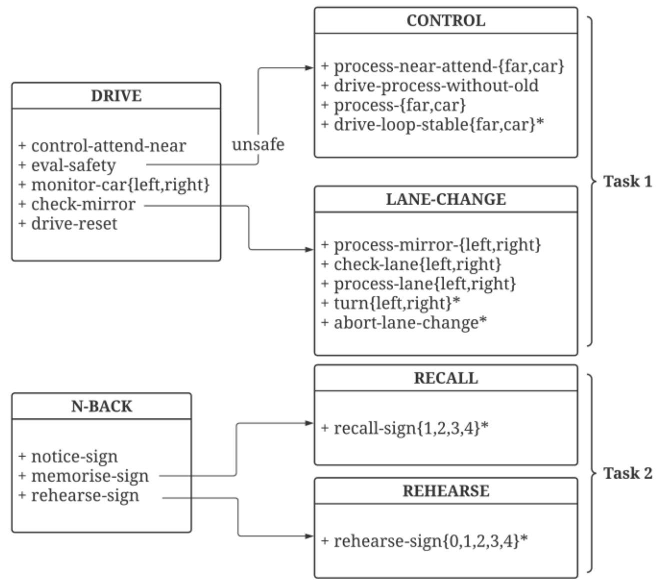

Figure 1: Model production system. Box titles indicate goal types and names below indicate production rules. Asterisks indicate production rules that allow the model to return to parent goal.

The second task consists of a modified n-back task. As the model is driving along the highway, speed signs appear on the right side of the road every 20s indicating a speed. Upon encounter, the model must memorize the speed sign, update a mental list of task-relevant speed signs, recall the appropriate sign depending on the n-back level and drive according to its speed. The difficulty in the n-back task ranges from 0-back to 4-back.

Driving model

The driving model is an adaptation of the model presented by Salvucci (2006). As the control loop of this driving model is independent of lane-width and it can thus not account for the effect of narrower lanes, we added a 'low-control loop' to the model. When the car is at least 0.7m away from either lane edge, the model enters this low-control loop. During this loop, the model can only fire productions with the high-level Drive goal as can be observed in Figure 1. This loop does not involve steering-control. When the position of the car

[1] https://www.cs.drexel.edu/~salvucci/cog/act-r/

becomes too close to the lane-edges, the model re-enters the high-control loop to steer back to the center. After re-entering the high-control loop, the model cannot switch back to the low-control loop for a period of 3s to ensure smooth steering to a safe position.

As the construction site has a narrower lane-width, the car does not enter the low-control loop in the construction site as it will never be sufficiently far away from the lane edge.

If other cars need to be overtaken, lane-changes are initiated after the model checks the appropriate mirror and lane. If the model is not in the right-most lane, it attempts to change lanes after making checks in a similar manner.

N-back model

The n-back model works by a sequential memorizing mechanism. Each sign is stored in declarative memory with a unique ID when encountered. To successfully recall a sign, the model sequentially goes through the speed signs back in time to remember the desired speed. Importantly, the number of backward steps is dependent on the n-back level, e.g., in a 3-back, the model goes back three times. Errors are modelled by partial matching.

The model rehearses the task-relevant sequence of signs up to three times or until the rehearsal process is interrupted by the encounter of the next sign (cf. Salvucci & Taatgen, 2011).

Results

As can be seen in Figure 2, n-back performance decreased with increasing n-back level showing a similar effect as human participants (Scheunemann et al., 2019). There was no difference in n-back performance between lane-widths. This effect can be explained by the fact that the model must perform a higher number of retrievals in higher n-back levels. This leads to a higher chance of a mismatch when compared to lower n-back levels.

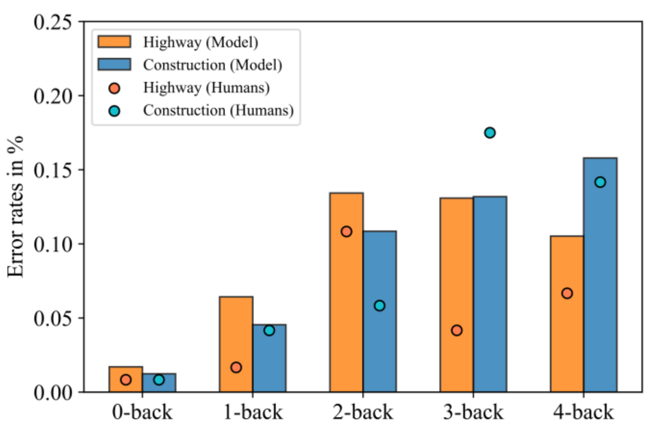

Figure 2: Average error rates in the n-back task

Analysis of steering reversal rates revealed increased steering reversals in the construction condition across all n-back levels, indicating an increase in driving difficulty (Fig. 3). Additionally, steering reversal rates decrease with increased n-back difficulty.

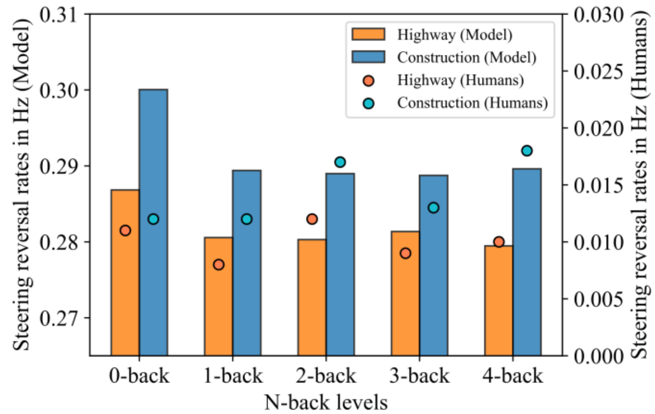

Figure 3: Average steering reversal rates.

As the difficulty in the driving task increases, the model spends more time in the high-control loop which leads to increased steering movements and thus reversals. Moreover, the increase in n-back difficulty requires a higher number of productions to successfully accomplish this task, which has the opposite effect on steering reversals. As more time is spent on the n-back task, less time is available for driving.

Discussion

The ACT-R model is able to show how both tasks compete for available resources: driving behavior is influenced by n-back level because of a competition for access to procedural and declarative memory. These results indicate an interaction at common task-unspecific level.

Because there is limited behavioral data available regarding driving behavior with varying lane-widths, some model parameters had to be estimated when developing the model (e.g., overtaking distance). We are currently conducting a behavioral study with human participants to remedy these factors and further validate the model.

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