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An on-the-road study

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Towards a Real-Time Driver Workload Estimator: An On-the-Road Study

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Abstract Driver distraction is a leading cause of crashes. The introduction of in-vehicle technology in the last decades has added support to the driving task. However, in-vehicle technologies and handheld electronic devices may also be a threat to driver safety due to information overload and distraction. Adaptive in-vehicle information systems may be a solution to this problem. Adaptive systems

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could aid the driver in obtaining information from the device (by reducing information density) or prevent distraction by not presenting or delaying information when the driver's workload is high. In this paper, we describe an on-the-road evaluation of a real-time driver workload estimator that makes use of geo-specific information. The results demonstrate the relative validity of our experimental methods and show the potential for using location-based adaptive in-vehicle systems.

Keywords Driver distraction · Adaptive in-vehicle information (systems) · Driver workload estimation

1 Introduction

Driver distraction is a leading contributor to road traffic crashes [1]. A recent naturalistic driving study showed that as much as 78 % of crashes were related to distraction [2]. Because of the increasing prevalence of technological aids, road safety has improved considerably in the last decades. However, certain in-vehicle technologies such as infotainment systems and handheld electronic devices are themselves a source of distraction and crash risk [1, 3–6]. Distracted driving not only reduces lane-keeping accuracy [7, 8] but also increases the brake reaction time to critical environmental events [9]. Furthermore, a complex in-vehicle display may result in an 'information overload' [10].

A potential remedy to these problems may be the use of adaptive information systems [11]. Adaptive information systems aid the driver by warning for upcoming high-workload situations or by adapting the information presentation. For example, when driver workload is high, an adaptive system may (1) switch to auditory presentation instead of visual presentation, (2) reduce the amount of information, or (3) present no information.

An workload-adaptive in-vehicle information system not only requires knowledge of the current driver workload. An estimate of the *future* workload is required as well. The use of the momentary workload only as input to the adaptive in-vehicle system would result in the adaptation being too late for the driver, and therefore drivers would not benefit from such a system [12]. Prediction of driver workload may seem a difficult task [13] due to the dynamics of traffic, interactions between road users, and moment-to-moment driver variability. Verwey [4, 14] found that the traffic situation is a vital determinant of workload that could be used for real-time workload estimation.

Similar to the approach by Verwey [4], we propose to estimate driver workload based on the location of the vehicle in the world. Specifically, using GPS coordinates and an online route map database, the driver's workload was estimated in real time based on road type, distance to junctions, and vehicle speed and acceleration. In our project, we explored the feasibility of using the workload estimate for real-time adaptation of visual information presentation on a navigation device (see also [15]).

Previous research has demonstrated the measurement of driver workload using physiological measures [16–18], measures of driver performance [19], and self-report evaluations [20]. In the present paper, we evaluated our experimental vehicle and our driver workload estimator in an urban, rural, and highway environment. Specifically, we evaluated vehicle speed, driver inputs, heart rate, respiratory rate, eye gaze, pupil diameter, and self-reported effort as a function of travelled distance along the route, a secondary mental arithmetic task, and the estimated workload level.

2 Methods

2.1 Participants

Six participants from the HAN employee community volunteered to participate in this research. Participants filled out an intake questionnaire with general items (age, gender, wearing glasses, driving history, use of navigation systems).

The participants were four males (mean age: 28.5, *SD* = 7.8) and two females (mean age: 29.0, *SD* = 1.4). Participants were in possession of a driver's license for an average of 8.7 years (*SD* = 5.1) with a minimum of 3 years and reported a mean annual mileage of 12,217 km (*SD* = 11,398). Four participants mentioned the use of glasses, one participant wore glasses during the experiment, and one participant reported the use of contacts. All participants indicated the use of navigation devices in their normal driving.

2.2 Apparatus

The experiment was conducted using a manual drive E91 320d BMW test vehicle. The vehicle was equipped with data acquisition connected to the CAN bus, allowing the collection of vehicle state variables (e.g., speed) and driver input variables (e.g., steering angle). Participants' physiological responses were measured using ECG electrodes and a respiration belt from TMSi (PolyBench, software version 1.30.0.3521) placed around the chest. Eye and head movements were recorded using a remote-mounted eye tracker from SmartEye (SmartEye Pro, software version 6.1.4). All data were synchronized and stored using The Observer XT (Noldus, software version 12.0.825 NBD) at sampling rates varying from 5 to 60 Hz. The navigation device was an Android tablet with prototype TomTom navigation software (Samsung Galaxy Tab 2, P3110 with Android 4.0).

2.3 Driver Workload Estimator

TNO, in collaboration with TomTom, developed the real-time workload estimator prototype. The estimator made use of vehicle and driver input data as well as road type estimated from the geographical location, based on GPS coordinates and a route map database.

On a high level, the estimation process had several components: road type, time/distance to junctions ahead, acceleration of the car, driving speed (with respect to the speed limit), and time-on-task (how long the driver has been driving without a break). For each component, decision rules were specified that indicated the relationship between the component and workload. The components were merged into a final output of the driver workload estimator, representing a 6-point workload estimate ranging from *very low* to *very high*.

2.4 Procedures

Before the start of the experimental sessions, participants received oral instructions explaining the experiment and procedures. Furthermore, participants filled out the intake questionnaire, a consent form, and a traveling cost form. Next, participants performed a Landolt C test [21] to determine their visual acuity. If the visual acuity was at least corrected-to-normal, the participants were allowed to participate.

After the visual acuity test, participants received oral instructions about the driving task. Furthermore, the self-report procedures and the secondary task were explained and practiced by the participants. After taking place in the vehicle, participants adjusted their seat to their own preference. The ECG and respiration hardware was connected to the participants, and the eye tracker was calibrated by means of a series of eye and head movements.

Participants drove three sessions: a baseline session and two times the same route of approximately 40 min. Participants drove the baseline session starting from the university campus to the starting point of the first session, a drive that took approximately 5 min. After the first 40 min session, participants had a 10 min break after which they drove back to the starting point. After completing the second 40 min session, participants drove back to the campus. When arrived at the campus, participants filled out a questionnaire regarding their driving behavior and received a gift card.

While driving, participants performed a secondary arithmetic task and rated their effort using the Rating Scale Mental Effort (RSME) [22]. An experimenter sat on the passenger seat, and initiated the secondary task and marked the RSME scores. Furthermore, the experimenter marked sudden events (e.g., pedestrians crossing, unpredictable behavior of other road users).

2.5 Driving Task and Environment

Prior to the baseline session, participants received oral instructions to drive as they would drive their own car, to adhere to Dutch traffic rules including speed limits, and to be aware of other road users. In addition, drivers were asked to perform a secondary task to temporarily add workload to the driving task. Specifically, at several moments during the drive, the experimenter instructed the participants to countback in steps of three from a random number between 60 and 100.

The route was identical for all participants and both sessions, and started and ended at the same locations. Each participant drove the same route twice. A tablet with TomTom navigation concept software provided the participants with driving directions by means of a Dutch voice. After completing the first session, participants drove from the endpoint of Session 1 to the starting point of Session 2.

The route was chosen so that different traffic situations were likely to occur. The route was near the city of Arnhem (NL) and had a length of 21.5 km. The route consisted of intersections (with and without traffic lights), roundabouts, urban areas with a 30 kph speed limit, a small segment of rural area, and a highway.

The countback task and RSME rating were performed at several locations along the route. On average, participants were requested to score their RSME 6 times per session and perform the countback task 5 times per session.

2.6 Dependent Measures

The following dependent measures were computed per session. The measures can be categorized as (1) vehicle performance, (2) driver input, (3) driver physiology, (4) subjective reports, and (5) the driver workload estimate.

1. Mean speed (kph) and absolute vehicle acceleration (m/s^2) were calculated as a measure of task efficiency, driving style, and driving safety.
2. The mean absolute steering speed (°/s) and steer steadiness (%, defined as the percentage of time the absolute steering speed was lower than 1 °/s) were used to represent steering activity [23, 24]. The mean absolute throttle speed (%/s) was used to indicate throttle activity.
3. The mean heart rate (1/min) and the mean respiration rate (1/min) were recorded from the ECG and the respiration belt hardware, respectively. The mean pupil diameter (mm) measured by the eye tracker data was used as a measure of workload [25]. Eye gaze data were classified into four regions of interest: (1) the road center (defined as a cone with 8° radius around the road center), (2) the peripheral area (defined as the region outside the road center, but within the windscreen perimeter), (3) the dials and navigation, (4) and other. For a definition of the dials and navigation, see Fig. 2. The mean percentage gaze at

the road center (GRC, %) represents the amount of attention directed to the road ahead [26]. Eye movement data were low-pass filtered at 5 Hz because the eye tracker data were sensitive to external noise, such as vibrations. Missing data (e.g., eye blinks and camera obstructions) were automatically removed.

4. The mean RSME (0–15) was determined from the rating scale [22] that was administered during driving. To keep interference with the driving task to a minimum, the participants indicated their effort orally on a scale from 0 to 15 (equivalent to the RSME vertical line of 15 cm) where 3 is 'normal driving' or 'a comfortable task load' and 12 is more than 'extreme effort'.
5. The driver workload estimate (1–6) was obtained from the online estimator. As mentioned above, workload was estimated based on vehicle location and vehicle state.

3 Results

Due to low quality eye tracker data (defined as less than 20 % reliable data), the gaze data of two participants were removed. Of the remaining four participants, on average 30 % (*SD* = 14 %) of eye tracker data were removed, due to the tracker's inability to record eye movements. One participant made a navigation mistake and drove an additional segment (approximately 1.06 km) during the first session. The data of this additional segment were removed.

3.1 Descriptive Results

Figure 1 provides an overview of several of the variables during the experimental route. The figure illustrates the diversity in road types (e.g., the first 4.5 km of the route consisted of a highway) and the differences in driving speed and steering activity along the route. The figure also shows the percentage of gaze at the road center, illustrating the gaze activity near corners and intersections. The RSME values seem to reveal an elevated self-reported workload at travelled distances of 5 and 19 km. Furthermore, the driver workload estimator shows that levels 3 and 4 occurred most frequently, whereas level 5 occurred intermittently.

Figure 2 shows the gaze distribution of one selected participant, illustrating the regions of interest and the main areas of visual attention. The gaze samples are centered on the 8° circle that represents the road center (averaged across the two sessions, participants directed their gaze 60 % of the time at the road center). The dials and the navigation device were glanced at for 5 % of the time (for all participants during both sessions). The gaze swirls to the left and right of the road center indicate lateral eye movements, for example while driving in a curve.

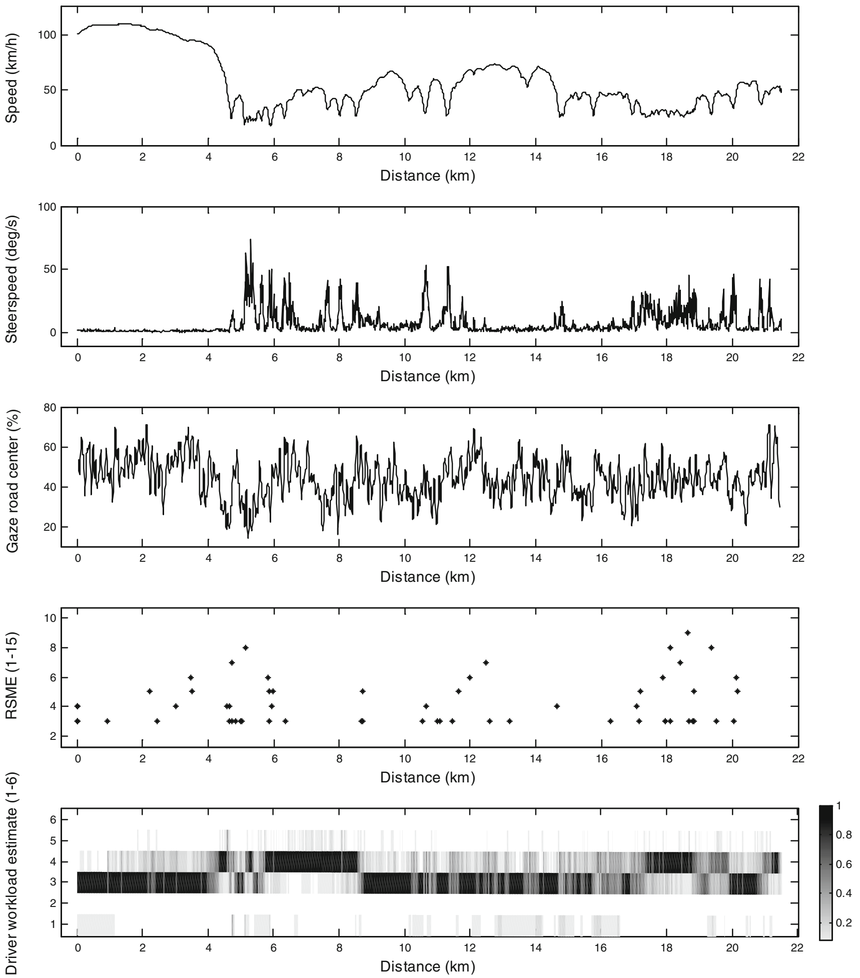

Fig. 1 Driving speed, absolute steering speed, gaze road center, Rating Scale Mental Effort (*RSME*), and workload estimate distribution as a function of travelled distance along the experimental route. The speed, absolute steering speed, and gaze road center were averaged across participants and sessions. All RSME reports for all participants and both sessions are shown. The workload estimate distribution was determined by averaging across the six participants and two sessions, and ranges from 0 out of 12 (*white*) to 12 out of 12 (*black*)

Figure 3 illustrates the association between driving speed and gaze distribution (left) and between driving speed and steer steadiness (right). It suggests that participants were more likely to allocate attention to the road center with increasing driving speed (left). Moreover, steering steadiness increases with increased driving speed (right).

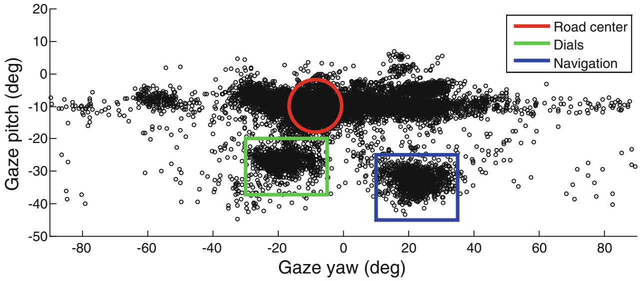

Fig. 2 Raw gaze data of one selected participant, together with regions of interest

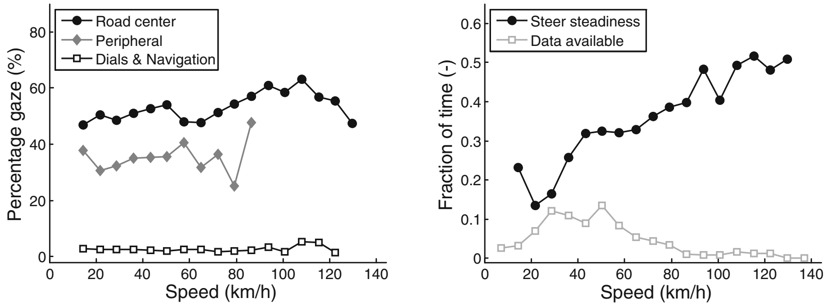

Fig. 3 Gaze distribution (*left*) and steering activity (*right*) as a function of driving speed. Data were extracted per 7.2 kph wide bin, and averaged across participants and both driving sessions. The data from 0 to 10.4 kph were removed from the figure. Note that participants drove faster than 90 kph for less than 5 % of the time, which explains the oscillatory behavior of the distributions for speeds greater than 90 kph. The *gray line with square markers* in the right figure indicates how much data were available at a given driving speed

3.2 Countback Task

Table 1 shows the results of selected measures averaged across the 10 s period before and the 10 s after the start of the countback task. Figure 4 illustrates the effect of the countback task on participants' heart rate and respiration rate. No statistically significant differences and small effect sizes between the two periods were observed for the driving performance measures (mean speed, steer speed, and throttle speed). The heart rate increased slowly from the start of the countback task and peaked at about 10 s after the start of the countback task. Furthermore, the respiration rate decreased after the start of the countback task. No clear differences were observed for the pupil diameter before versus after the start of the countback task.

A scatter plot of the 45 trials (of all participants) of the countback task illustrates the small increase in heart rate (Fig. 5 left) and decrease in respiration rate (Fig. 5 right). Furthermore, large differences between participants can be seen.

Table 1 Means (standard deviations in parentheses) for the 10 s period before and the 10 s period after the start of the countback (CB) task

Dependent measure	10 s before CB	10 s after CB	*p* value ($\|d_z\|$)	Correlation (ρ)
Mean speed (kph)	10.95 (3.1)	10.54 (2.2)	0.380 (0.43)	0.943
Acceleration (m/s^2)	0.48 (0.14)	0.40 (0.15)	0.449 (0.56)	−0.543
Steer speed (°/s)	15.93 (8.7)	15.88 (6.1)	0.992 (0.01)	0.143
Throttle speed (%/s)	6.25 (1.1)	5.75 (2.5)	0.620 (0.24)	0.086
Heart rate (1/min)	77.37 (8.2)	78.22 (8.1)	0.053 (1.13)	1.000
Respiration rate (1/min)	18.20 (1.6)	15.25 (3.2)	0.076 (1.00)	0.314
Pupil diameter (mm)	1.99 (0.37)	1.99 (0.50)	0.994 (0.00)	0.900
Gaze navigation (%)	2.91 (1.16)	2.99 (1.40)	0.791 (0.17)	1.000
Gaze road center (%)	53.0 (15.5)	52.5 (17. 3)	0.920 (0.06)	0.800

p values from the dependent *t* test (effect size in parentheses) and correlations (Spearman ρ, $N = 6$, $N = 4$ for the gaze measures) between the before and after segments are shown. Effect sizes were determined as Cohen's $d_z = t/N^{0.5}$

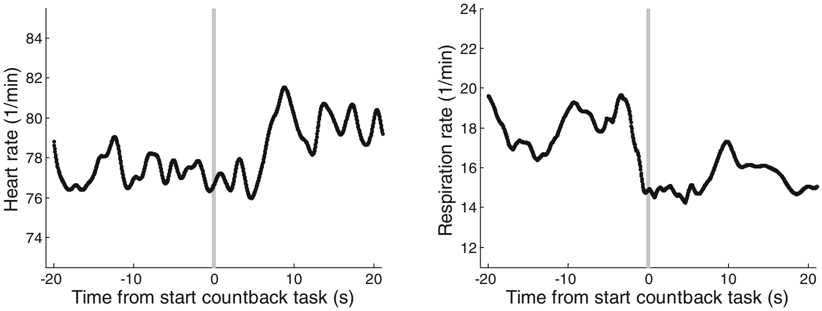

Fig. 4 Mean heart rate (*left*) and respiration rate (*right*) before and after the start of the countback task. Means were computed by averaging across all trials. The start of the countback task is indicated by the *vertical line* at 0 s. The countback task lasted approximately 10 s. Note that due to the manual annotation, the starting time slightly varied across trials

3.3 Evaluation of the Driver Workload Estimator

Table 2 shows the means and standard deviations of the dependent measures per estimated workload level. The driver workload was estimated to be either level 3 or level 4 for over 80 % of the total time. As can be seen by the low mean speed, the first level of the workload estimator was related to low speeds or the vehicle standing still. The fifth workload level occurred less than 2 % of the total time and was related to strong vehicle accelerations, indicated by the throttle speed and the acceleration. The missing values for workload levels 2 and 6 can be explained by

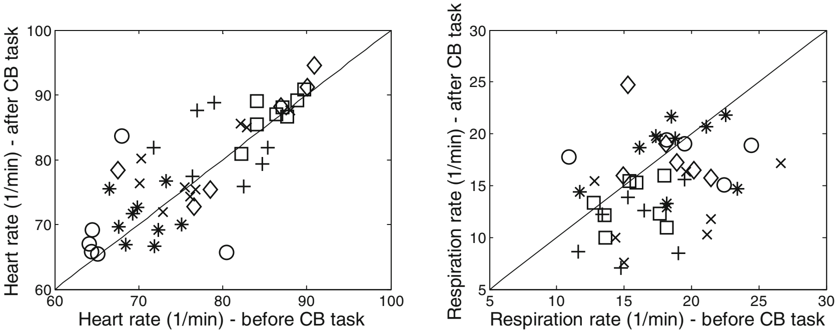

Fig. 5 Scatter plot of the mean heart rate (*left*) and the mean respiration rate (*right*) for the period 10 s before and the period 10 s after the start of the countback (*CB*) task. Each participant is indicated by a different marker

Table 2 Means (standard deviations in parentheses) of the dependent measures for the different levels of the estimated driver workload ($N = 6$, $N = 4$ for the gaze measures)

Dependent measure	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Fraction of time (%)	6.5 (3.2)	0 (0)	42.6 (11)	40.8 (9.1)	1.9 (1.5)	0 (0)
Mean speed (kph)	18.8 (23.0)	0 (0)	49.7 (3.1)	34.3 (3.5)	35.6 (7.0)	0 (0)
Acceleration (m/s^2)	0.39 (0.15)	0 (0)	0.45 (0.04)	0.49 (0.05)	0.62 (0.14)	0 (0)
Steer speed (°/s)	5.9 (2.5)	0 (0)	9.4 (1.8)	15.1 (2.4)	13.6 (5.5)	0 (0)
Throttle speed (%/s)	7.0 (3.5)	0 (0)	5.7 (0.9)	6.8 (0.5)	8.3 (4.0)	0 (0)
Heart rate (1/min)	76.8 (7.7)	0 (0)	77.0 (7.6)	77.8 (7.1)	79.3 (8.7)	0 (0)
Respiration rate (1/min)	17.9 (3.6)	0 (0)	17.5 (2.1)	18.2 (2.2)	18.5 (2.8)	0 (0)
Pupil diameter (mm)	2.22 (0.54)	0 (0)	2.22 (0.36)	2.27 (0.44)	2.34 (0.5)	0 (0)
Gaze navigation (%)	2.5 (1.5)	0 (0)	3.0 (1.3)	2.8 (1.4)	5.6 (4)	0 (0)
Gaze road center (%)	45.7 (17.9)	0 (0)	54.6 (14.5)	52.6 (11.8)	49.5 (9.4)	0 (0)
RSME (0–15)	3.8 (1.4)	0 (0)	4.3 (1.4)	4.5 (1.7)	4.4 (1.7)	0 (0)

the absence of criteria for the estimator to estimate these levels within the current experimental scenarios.

Several dependent measures showed an increase from level 3 to level 4. Figure 6 shows the effects between level 3 and level 4 for the heart rate (left), respiration rate (middle), and RSME reports (right). It can be seen that individual differences were large relative to the difference between level 3 and level 4.

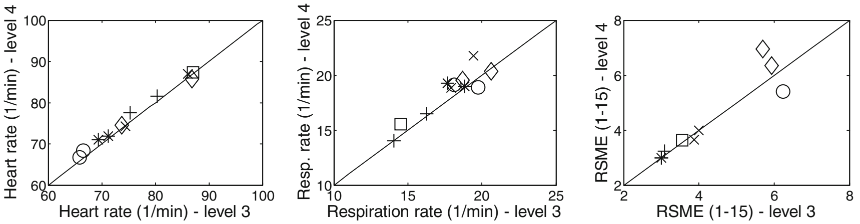

Fig. 6 Scatter plot of heart rate (*N* = 11), respiration rate (*N* = 11), and Rating Scale Mental Effort (RSME; *N* = 9) between level 3 and 4 of the driver workload estimator. Markers are session-averaged values per participant. Each participant is indicated by a different marker

4 Discussion

In this paper, we described the methods and results of an on-road experiment including an online driver workload estimator. Consistent with results from Verwey [4], the results suggest that driver workload is location-dependent. Averaged across participants, the RSME values were high at specific locations in our experimental route. This is further illustrated by the steering activity and gaze behavior along the route, ranging from low steering activity and a higher percentage of gaze directed to the road center on the highway to high steering activity and a lower percentage of gaze directed to the road center in the urban area.

The percentage of gaze directed at the road center tended to increase with increasing driving speeds, whereas the steering activity decreased (i.e., steering steadiness increased) with increasing driving speeds. These results are similar to results found in driving simulator studies [23, 24, 27], and illustrates the relative validity of the measurements obtained with our experimental setup.

Consistent with the literature, the secondary arithmetic task resulted in an elevated physiological response. Specifically, the secondary task resulted in increased heart rate, a finding consistent with Reimer [28] who found similar results when participants performed an n-back arithmetic task (see also [29]). Our results also illustrate that the heart rate response was relatively slow (Fig. 4) [24]. The respiration rate responded quickly to the elevated cognitive load as the participants initiated the countback task. However, this response may be caused by the nature of our secondary task; literature has shown a reduction of respiration rate as participants engage in speech tasks [30]. No substantial effects of the secondary task were found on the control activity of the participants. This finding may be explained by the small cognitive impact of the secondary task as compared to the complex driving task.

Our driver workload estimator estimated the workload to be at intermediate levels (levels 3 or 4 on the 6-point scale) for more than 80 % of the time. Trends were observed between the workload estimate and the RSME results, heart rate, and respiration rate. However, further research into the workload estimator is recommended. Considering the fact that individual differences are large, particular attention is needed to creating person-specific baseline values.

Conducting experiments in a complex naturalistic environment entails several limitations. Because of the exploratory nature of this research, our small sample size does not allow firm conclusions. The naturalistic environment has strong ecological validity, but also introduces side effects (e.g., weather conditions, varying traffic, and vibrations). These effects not only influence experimental control, but also influence the quality of the physiological data. For example, we found no significant effect of the arithmetic task on pupil diameter, which could be explained by the influence of variable lighting conditions [31].

With this study, a first step has been taken to explore the feasibility of estimating workload in a naturalistic driving environment. Our results correspond to previous findings in driving simulators and in the literature, and demonstrate the validity of the instrumented vehicle for assessing driver workload. The implementation of geo-specific data for driver workload estimation shows promise for application in future adaptive in-vehicle information systems.

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