

**The effects of time pressure on driver performance and physiological activity  
A driving simulator study**

Rendon Velez, Elizabeth; van Leeuwen, Peter; Happee, Riender; Horvath, I; van der Vegte, Wilfred; de Winter, Joost

**DOI**

[10.1016/j.trf.2016.06.013](https://doi.org/10.1016/j.trf.2016.06.013)

**Publication date**

2016

**Document Version**

Final published version

**Published in**

Transportation Research. Part F: Traffic Psychology and Behaviour

**Citation (APA)**

Rendon Velez, E., van Leeuwen, P., Happee, R., Horvath, I., van der Vegte, W., & de Winter, J. (2016). The effects of time pressure on driver performance and physiological activity: A driving simulator study. *Transportation Research. Part F: Traffic Psychology and Behaviour*, 41(Part A), 150-169. <https://doi.org/10.1016/j.trf.2016.06.013>

**Important note**

To cite this publication, please use the final published version (if applicable).  
Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights.  
We will remove access to the work immediately and investigate your claim.

***Green Open Access added to TU Delft Institutional Repository***

***'You share, we take care!' – Taverne project***

**<https://www.openaccess.nl/en/you-share-we-take-care>**



# The effects of time pressure on driver performance and physiological activity: A driving simulator study

E. Rendon-Velez <sup>a,1</sup>, P. M. van Leeuwen <sup>b,\*,1</sup>, R. Happee <sup>b</sup>, I. Horváth <sup>a</sup>, W.F. van der Vegte <sup>a</sup>, J.C.F. de Winter <sup>b</sup>

<sup>a</sup> Delft University of Technology, Faculty of Industrial Design Engineering, The Netherlands

<sup>b</sup> Delft University of Technology, Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, The Netherlands

## ARTICLE INFO

### Article history:

Received 21 March 2015

Received in revised form 25 February 2016

Accepted 13 June 2016

Available online 13 July 2016

### Keywords:

Simulation

Virtual reality

Workload

Psychophysiology

## ABSTRACT

Speeding because of time pressure is a leading contributor to traffic accidents. Previous research indicates that people respond to time pressure through increased physiological activity and by adapting their task strategy in order to mitigate task demands. In the present driving simulator study, we investigated effects of time pressure on measures of eye movement, pupil diameter, cardiovascular and respiratory activity, driving performance, vehicle control, limb movement, head position, and self-reported state. Based on existing theories of human behavior under time pressure, we distinguished three categories of results: (1) driving speed, (2) physiological measures, and (3) driving strategies. Fifty-four participants drove a 6.9-km urban track with overtaking, car following, and intersection scenarios, first with no time pressure (NTP) and subsequently with time pressure (TP) induced by a time constraint and a virtual passenger urging to hurry up. The results showed that under TP in comparison to NTP, participants (1) drove significantly faster, an effect that was also reflected in auxiliary measures such as maximum brake position, throttle activity, and lane keeping precision, (2) exhibited increased physiological activity, such as increased heart rate, increased respiration rate, increased pupil diameter, and reduced blink rate, and (3) adopted scenario-specific strategies for effective task completion, such as driving to the left of the lane during car following, and early visual lookout when approaching intersections. The effects of TP relative to NTP were generally large and statistically significant. However, individual differences in absolute values were large. Hence, we recommend that real-time driver feedback technologies use relative instead of absolute criteria for assessing the driver's state.

© 2016 Elsevier Ltd. All rights reserved.

## 1. Introduction

### 1.1. The dangers of 'time pressure'

A large portion of road traffic crashes occurs because drivers have been speeding or committing other types of traffic violations, such as tailgating and dangerous overtaking (Elander, West, & French, 1993; Elvik, Christensen, & Amundsen,

\* Corresponding author at: Delft University of Technology, Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Mekelweg 2, 2628 CD Delft, The Netherlands.

E-mail address: [P.M.vanLeeuwen@TUDelft.nl](mailto:P.M.vanLeeuwen@TUDelft.nl) (P. M. van Leeuwen).

<sup>1</sup> Joint first authors.

2004; Evans & Wasielewski, 1982; Organisation for Economic Co-operation & Development, 2006; Parker, Reason, Manstead, & Stradling, 1995). Speeding is a factor in between 10% and 40% of accidents on European roads (Organisation for Economic Co-operation & Development, 2006; Treat et al., 1979). McKenna (2005) reported that 33% of 9470 surveyed speeding offenders indicated that they were in a hurry at the time of their speeding offence. Another survey study by Collinson (2014) indicated that 77% of 150 people who were caught speeding did so because they lacked time to make the journey.

Several factors may explain why drivers decide to speed and violate the traffic rules. This includes personality factors, such as thrill seeking, pleasure in fast driving, and aggressiveness, as well as environmental factors, such as peer pressure, and perhaps most importantly, a shortage of available time (e.g., Beck, Daughters, & Ali, 2013; Beck, Wang, & Yan, 2012; Cœugnet, Miller, Anceaux, & Naveteur, 2013; Cœugnet, Naveteur, Antoine, & Anceaux, 2013; Matthews, 2002; Rendon-Velez, Horvath, & Van der Vegte, 2012; Rothengatter, 1988). Note, however, that a time constraint alone is not a necessary condition for speeding; the driver also has to *believe* it is important to complete the task in time (Benson & Beach, 1996; Cœugnet et al., 2013).

### 1.2. Models that describe how time pressure influences (driver) performance

A model of Wickens, Lee, Liu, and Gordon-Becker (2004) describes how (1) information input, (2) information-processing efficiency, and (3) task performance are influenced by external 'stressors' (such as pressure to complete a task in time). Specifically, Wickens et al.'s model illustrates that external stressors have *direct* influences on the quality of the information input and task performance (e.g., through increased levels of noise, lighting, or vibrations). The direct consequence of driving faster is that a higher amount of information has to be processed per unit of time. Thus, driving speed has a *direct* influence on the information input rate. Stress also has *indirect* psychological influences. For example, having to complete a task in a short amount of time could lead to high mental workload, anxiety, frustration, and anger, which in turn reduces information processing efficiency.

Maule and Hockey (1993) describe the effects of time pressure by means of a two-level control model. According to this model, the human cognitive system is self-regulatory. On the lower control level, small discrepancies between the current and target mental state are regulated by subconscious corrective actions (e.g., changes in speed, memory use, timing). When the discrepancy between the current and target state is large and subconscious control strategies are inadequate, control temporarily shifts to a higher level of cognitive (conscious) control (Maule & Hockey, 1993; see also Robert & Hockey, 1997). At this higher level, four modes are available to cope with high task demands: (1) increasing effort (trying harder) and accelerating control actions, (2) adopting a strategy that requires less effort, (3) changing the environment by removing stressors (e.g., re-negotiating the time deadline), or (4) doing nothing to reduce task demands (for further studies, see Edland & Svenson, 1993; Miller, 1960; Wright, 1974). When a driver adopts mode 1, this will be reflected in measures of speed as well as physiological measures associated with the activity of the sympathetic nervous system (Maule & Hockey, 1993). Modes 3 and 4 are usually not feasible when having to drive to a destination in a fixed amount of time, as the driver can control the state of his own vehicle in the environment but can hardly modify the environment itself. In this paper, our focus is on modes 1 and 2. That is, in the present study, we evaluated whether drivers modify their lateral/longitudinal driving behavior, posture, and gaze patterns by increasing their effort (mode 1) or by modifying their behavior in such a way that the driving task becomes easier to carry out (mode 2) while maintaining a high average driving speed in order to arrive at the destination in time.

### 1.3. Previous research that investigated the effects of time pressure on driving performance

Several previous studies have demonstrated the effects of time pressure on measures of driving performance. Van der Hulst, Rothengatter, and Meijman (1998) studied car following behavior in fog conditions using a driving simulator. Participants who were instructed to drive on a fixed time schedule showed less variability in their time headway due to decelerations of lead vehicles compared to a control group instructed to drive as they would normally do. The improved precision in the control of the vehicle suggests that the drivers adapted to the time constraint by increasing their level of alertness (Van der Hulst et al., 1998), an effect that corresponds to mode 1 (trying harder) in the model of Maule and Hockey (1993). Cnossen, Rothengatter, and Meijman (2000) instructed drivers to drive as fast as possible in a simulated environment. The results showed that participants had poorer lane keeping accuracy when they drove as fast as possible compared to when asked to adhere to the speed limits as if they were taking a driving test. In another driving simulator study, Zhai, Accot, and Woltjer (2004) found that drivers slowed down when they were required to maintain lane position accurately. Conversely, when the lane width increased, drivers were able to drive faster. These latter two studies suggest that the effects of time pressure can be described as a speed-accuracy tradeoff (see also Szalma, Hancock, & Quinn, 2008, for a meta-analysis on the effects of time pressure on measures of speed and accuracy).

Performance measures of speed and accuracy are advantageous for driver assessment applications because they represent an objective and observable state of the vehicle in its environment. Another advantage of these measures is that they are closely related to safety and accidents (Aarts & Van Schagen, 2006; Cooper, 1997; Lajunen, Karola, & Summala, 1997). A disadvantage of performance measures of speed and accuracy is that they cannot readily be used to identify whether a driver is subjected to time pressure or not, because these measures are highly situation-dependent (e.g., Cantin, Lavallière, Simoneau, & Teasdale, 2009). For example, a driver under time pressure may be stuck in a traffic jam, as a result of which

speed/accuracy measures of driving performance are not informative at all. Similarly, a measure of lane keeping accuracy will be meaningless when a time-pressurized driver is frequently overtaking other road users.

#### 1.4. *The potential of psychophysiology for studying the effects of time pressure on car driving*

When humans are subjected to stressors (such as time pressure), they tend to show a variety of physiological responses such as pupil dilation, increased heart rate, slowed digestion, and a constriction of blood vessels, mechanisms that are collectively known as the 'fight-or-flight' response (e.g., Cain, 2007; Kramer, 1991; Wickens et al., 2004). Furthermore, visual and cognitive tunneling occurs, referring to the fact that a stressed person stops carrying out secondary tasks and processes the cues that are most immediate and familiar (Hancock, 1989; Hancock & Szalma, 2008).

Various experimental studies in flight/driving simulators and real vehicles (e.g., Backs, Lenneman, Wetzel, & Green, 2003; Brookhuis & De Waard, 2010; Veltman & Gaillard, 1996) have measured physiological responses as a function of task demands. Examples include physiological measurements during the presence/absence of a secondary task (Mehler, Reimer, Coughlin, & Dusek, 2009), as a function of road infrastructure (Dijksterhuis, Brookhuis, & De Waard, 2011), or for different levels of automated driving (De Winter, Happee, Martens, & Stanton, 2014). An experiment by Clossen et al. (2000) showed increased heart rates when participants drove as fast as possible compared to driving as accurately as possible.

Car driving is predominantly a visual task (e.g., Sivak, 1996), and a large body of research has evaluated the effects of task demands on drivers' visual scanning behavior (e.g., Crundall & Underwood, 1998; Recarte & Nunes, 2000; Reimer, 2009; Wikman, Nieminen, & Summala, 1998). In a driving simulator study, Rogers, Kadar, and Costall (2005) increased the task demands by increasing the driving speed during a straight-lane driving task. Their findings showed that participants, regardless of their level of driving experience, narrowed their gaze distribution when the driving speed was increased. Recently, remote eye trackers have shown to be promising tools for measuring the pupil dilation response as a function of cognitive task demands in low-cost measurement setups (Klingner, Kumar, & Hanrahan, 2008; Marquart & De Winter, 2015) as well as in driving simulators (Palinko, Kun, Shyrovkov, & Heeman, 2010).

In addition to the human physiological response, time pressure also influences bodily posture and kinetics (Birch, Juul-Kristensen, Jensen, Finsen, & Christensen, 2000; Bongers, De Winter, Kompier, & Hildebrandt, 1993; Van Galen & Van Huygevoort, 2000). Using pressure sensors in the seat, Riener, Ferscha, and Matscheko (2008) found that drivers adjusted their posture in curves as a function of curve radius and driving speed. Tran and Trivedi (2010) showed using a vision-based motion tracking system that relaxed drivers took a more 'leaned back' posture, whereas concentrated drivers showed a more 'forward leaning' posture during a highway-driving task in a simulator.

#### 1.5. *The present study*

In a driving simulator experiment, we evaluated two levels of time pressure: a baseline condition with no time pressure (NTP) and a time pressure (TP) condition in which drivers drove with a time constraint imposed on their driving task. Participants drove along an urban road in which various scenarios occurred: car following, overtaking an obstacle, and crossing intersections. We evaluated the effects of time pressure on a large number of dependent measures (including measures of eye movement, pupil diameter, cardiovascular and respiratory activity, driving performance, vehicle control, limb movement, head position, and self-reported status) to explore which of these measures are indicative of driving under time pressure.

Based on the models of Wickens et al. (2004) and Maule and Hockey (1993), we derived three broad hypotheses. Our first hypothesis was that drivers under time pressure drive at a higher speed and execute their tasks at a higher rate. This first hypothesis provides what is essentially a manipulation check as to whether, and to what extent, the task instructions cause participants to arrive at the destination in a shorter amount of time compared to driving without time pressure. We also investigated auxiliary measures of driving speed, such as braking and throttling activity, as well as lane keeping accuracy (accuracy was expected to decrease when driving faster, as predicted by the speed-accuracy tradeoff). The second hypothesis was that drivers react physiologically to the presence of the time pressure stressor. Although it is well established that stress causes signs of sympathetic arousal, what is less well known is which of the physiological measures are most sensitive to time pressure instructions in a car driving task. Furthermore, the present study exhibits several features that allowed us to test this hypothesis with a high level of spatiotemporal detail. Specifically, we synchronized the driving performance and physiological signals, allowing us to explore which of the measures are indicative of driving under time pressure at the different scenarios along the route. The third hypothesis was that drivers adapt their behavior by means of adjusting their driving strategy. As described above, we defined a change in strategy as a change in driving or visual behavior (other than simply driving faster) that allowed the driver to achieve the goal of arriving at the destination with greater effectiveness.

In the analysis, we put special emphasis on physiological data, because physiological data can provide a real-time assessment of the driver's state without requiring an overt reaction from the driver (De Waard, 1996; Kramer, 1991). For example, it might be possible to detect an altered physiological state of a driver when the driving speed is restricted or when the driver does not physically move the wheel or pedals. Compared to vehicle-centered performance measures, measures based on

human physiology can provide person-centered indicators of time pressure that may be of value in the development of driver monitoring and feedback applications (cf. Mehler et al., 2009; Reimer, 2009).

## 2. Methods

### 2.1. Participants

Fifty-six participants (48 males and 8 females) were recruited from the Delft University of Technology student and employee community. Participants were in possession of a valid driver's license and had normal or corrected-to-normal eye sight. Prior to the experiment participants filled out a 18-item intake questionnaire consisting of general items (age, gender, wearing glasses or contact lenses, medication, educational qualification, occupation), simulation-related items (playing computer games, prior experience in driving simulation, number of participated simulator experiments in the past), and driving experience items (e.g., driving frequency and mileage in the past 12 months, and accident involvement and traffic violations in the past 36 months). Some of these items were derived from the Driving Habits Questionnaire (Owsley, Stalvey, Wells, & Sloane, 1999).

Of the 54 participants who completed the experiment, there were 46 males (mean age = 28.5,  $SD = 4.3$ ) and 8 females (mean age = 27.0,  $SD = 2.9$ ). On average participants had their driving license for 9.1 ( $SD = 4.5$ ) years, with a mean annual mileage of 6350 ( $SD = 8116$ ) km. Three participants reported the use of medication (insulin, Aeries and folate, and paracetamol, respectively) and 18 participants wore contact lenses or glasses during driving. Twenty participants reported prior experience in a driving simulator, with a mean of 0.59 ( $SD = 1.12$ ,  $N = 54$ ) experiments per participant. For an overview of the results of the intake questionnaire, see Table 1. Before commencing the experiment, all participants provided written informed consent. The research was approved by the Human Research Ethics Committee of the Delft University of Technology.

### 2.2. Apparatus

A fixed-base driving simulator (Green Dino, Wageningen, the Netherlands) was used in this experiment. The simulator cabin was equipped with the following components: steering wheel, ignition key, gear lever, single seat, and pedals. The steering wheel, pedals, gear lever, and indicators were obtained from a regular passenger car, and the dashboard, interior, and mirrors were integrated in the projected visuals, as shown in Fig. 1. Steering wheel force feedback was provided by a passive spring system. Surround sound was used to provide auditory wind, tire, and engine feedback. The simulator provided a horizontal field of view of 180 degrees by means of three projectors. The front view projection (front projector: NEC VT676) had a resolution of  $1024 \times 768$  pixels, and the side views (side projectors: NEC VT470) featured a resolution of  $800 \times 600$  pixels. The simulation ran at a frequency of 100 Hz, and the frame rate of the visual projection was estimated to be greater than 25 Hz (i.e., high enough to guarantee a smooth visual experience throughout the experiment).

Eye and head movements were recorded using a Smart Eye eye-tracking system (software version 5.9), consisting of three remote mounted cameras (Sony XC-HR50) and two infrared illuminators. The data from the simulator and eye tracker were sampled and stored synchronously at 60 Hz. The participant's electrocardiogram (ECG) was obtained using a lead II configuration with three disposable snap electrodes and was recorded on a portable Mobi8 device (Twente Medical Systems International). The expansion of the thorax during inhalation and exhalation was measured using an inductive effort belt (Sleep Sense) worn around the chest. This belt was connected to a respiration effort sensor (RespiV6) which in turn was connected to the Mobi8 device. Both ECG and respiration data were received wireless and stored at 256 Hz. Limb movements were measured using four wireless inertial 3D motion trackers (Xsens MTw) placed at the ankles and wrists. The limb movement data were received wirelessly and stored at 75 Hz.

A trigger signal was sent when the clutch was pressed as the participant started the driving session. Using this trigger signal, data from the peripheral hardware were synchronized with the driving simulator data during post-processing.

**Table 1**

Distribution of participants ( $N = 54$ ), for frequency of playing computer games, driving frequency, and educational qualification.

On average how often did you play computer or video games in the last 12 months?		On average, how often did you drive a car in the last 12 months?		What is your highest educational qualification?	
Every day	0	Every day	7	Primary/elementary school	1
4–6 days/week	3	4–6 days/week	5	Secondary/high school	0
1–3 days/week	3	1–3 days/week	14	Bachelor degree	15
About once a week	12	About once every two weeks	13	Postgraduate degree	38
Less than once a month	14	About once a month	7		
Never	22	Less than once a month	5		
		Never	3		



**Fig. 1.** One of the experimenters in the driving simulator, with inertial sensors and eye tracker.

### 2.3. Independent variable

The independent variable was the time constraint imposed on the driving task. In the no time pressure (NTP) session, the participant had sufficient time to complete the driving task. In the second session, time pressure (TP) was imposed by requesting the participants to complete the driving task within 80% of their NTP completion time, with a minimum of 7 min 20 s (defined as an absolute minimum according to pilot tests by the authors). Thus, the time constraint was different for each individual. In both sessions, the elapsed time was displayed on the virtual dashboard. Furthermore, during the NTP and TP sessions, auditory information was provided: the voice of a previously recorded fictitious ‘passenger’ was played back during both sessions. In the NTP session, the passenger was talking about casual things, while in the TP session, the passenger was complaining about being late and was motivating the participant to hurry up. In both sessions, the passenger sentences were uttered every 15 s.

### 2.4. Procedures

Prior to the simulator drives, participants received a paper handout explaining the experiment and procedures, and filled out the 18-item intake questionnaire. Additionally, participants filled out the Mini Driver Behavior Questionnaire (Mini-DBQ) to measure aberrant driving behaviors (Martinussen, Lajunen, Møller, & Özkan, 2013) and the Multidimensional Driving Style Inventory (MDSI) for assessing driving style (Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). Next, participants watched a 5-min instruction video, explaining the driving simulator operation, the sensor instrumentation procedures, and the instructions for the training and NTP sessions. The video informed the participants only about the upcoming training and the NTP sessions, in order to ensure that participants were naïve to the specific instructions of the TP session while driving the training and NTP sessions. After watching the instruction video, the inertial motion trackers were attached to the ankles and wrists of the participants, and the three ECG electrodes were placed below the left and right clavicle and below the left pectoral muscle in a lead II configuration. The respiration belt was placed at the diaphragm level of the sternum and tightened sufficiently without causing discomfort.

Participants then seated themselves inside the driving simulator. Next, participants carried out a series of head movements and eye movements to calibrate the eye tracker. Participants completed three sessions in the following order: training session (T), no time pressure session (NTP), and time pressure session (TP). Before commencing with the training session, participants were told to relax, and the instructions regarding the training and NTP sessions were repeated orally by the experimenter. After having completed the NTP session, participants received a tablet showing the video instructions for the TP session. After each session, a 5-min break took place during which participants remained seated in the driving simulator. During these breaks, participants filled out the NASA task load index (TLX) for measuring workload (Hart & Staveland, 1988). Furthermore, participants filled out a questionnaire measuring their perceived time pressure, as well as a 6-item confidence questionnaire measuring their confidence in the driving task (see Section 2.8.5). The order of the driving sessions was not counterbalanced, to facilitate the individually adapted time constraint in the TP condition.

### 2.5. Driving task

Prior to the training session, participants received video instructions to drive straight ahead, to cross the intersections, and to overtake the obstacles when required. Participants were instructed to obey traffic rules and were informed that their

lane was not a priority lane. For the NTP session, participants received instructions to drive safely and in a relaxed manner, as if they drove a fictitious friend to the airport without any time constraints. After the NTP session participants received oral and video instructions to drive to the airport with a time constraint. All sessions started with the vehicle from standstill at the center of the lane, and participants were requested to start the vehicle by pressing the clutch pedal. Participants were required to accelerate, brake, steer, and use the clutch and gear lever to operate the manual gearbox.

## 2.6. Driving environment

The driving environment consisted of an urban area with regular traffic conditions, identical in both the NTP and the TP sessions. The two-way road had a length of 6970 m and a lane width of 4 m. The road consisted of 17 segments and 16 intersections with stop signs and without traffic lights. Several traffic situations were triggered on passing specific positions in the virtual scenery. The traffic situations included: (1) free driving, (2) car following with traffic in the opposing lane, (3) obstacle overtaking with and without traffic in the opposing lane, and (4) intersections with and without approaching traffic. During the car following scenarios, traffic in the opposing lane prevented participants from overtaking the lead car. Traffic in the opposing lane during the obstacle overtaking events required participants to decelerate before the obstacle until the traffic in the opposing lane had passed the obstacle. During the intersection scenarios with traffic, participants were unable to cross the intersection until the traffic had cleared from the intersection. During the training session the environment was identical to the TP and NTP sessions, but included three additional obstacle overtaking scenarios. See Table 2 for an overview of the traffic scenarios during the three sessions and Fig. 2 for screenshots of the four scenarios.

## 2.7. Data processing

The driving simulator, eye-tracker, physiological, inertial, and force data were synchronized and re-sampled to 100 Hz prior to post-processing. Data were analyzed from the start of each session to the point where participants were 380 m past the final intersection (i.e., after having traversed 6835 m). At this location the end of the road was visible. The following post-processing was performed on the recorded signals:

### 2.7.1. Steering signal

Steering signal data were low-pass filtered with a 3 Hz cut-off frequency, to remove the high frequency noise.

### 2.7.2. Eye movements and head movements

Eye movements and head movements were low-pass filtered with cut-off frequencies of 10 Hz and 5 Hz, respectively. Data loss with remote mounted eye trackers occurs when the system is unable to detect a participant's facial features, pupil, or corneal reflections due to an obstruction of the eye-tracker cameras or due to large head movements (e.g., Prado Vega, Van Leeuwen, Véléz, Lemij, & De Winter, 2013; Van Leeuwen, Gómez i Subils, Ramon Jimenez, Happee, & De Winter, 2015; Van Leeuwen, Happee, & De Winter, 2014). Eye closures were classified as a blink when the eye opening was smaller than 50% of the participant's median eye opening. Gaze data during blinks as well as data from 0.2 s before to 0.2 s after segments of missing data were removed. When more than 60% of data had to be removed, all the eye-tracker data of the respective session were removed from the analysis.

### 2.7.3. The pupil diameter

The pupil diameter is highly sensitive to illumination (Watson & Yellott, 2012). During the simulation, the illumination intensity was a function of the virtual environment and varied with the participant's location in the virtual world. The pupil diameter measurements were corrected for illuminance intensity at each traveled distance in the virtual scenery using measured illumination intensity data (see supplementary material).

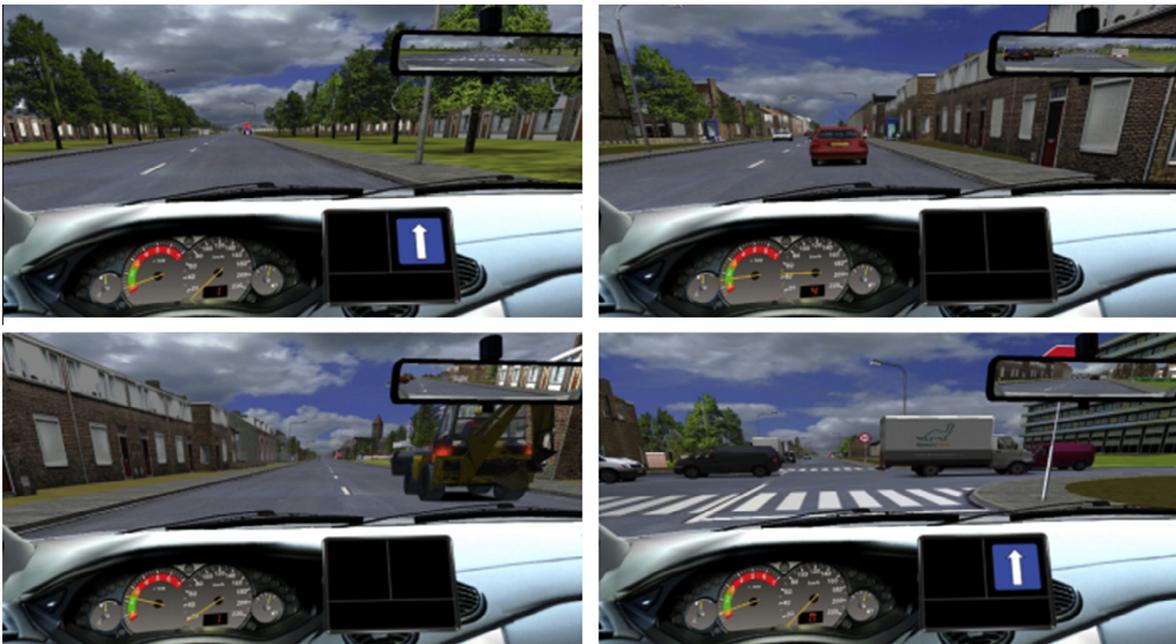
### 2.7.4. Physiological data

Physiological data were filtered before further processing. Specifically, the ECG signal was high-pass filtered at 10 Hz, to remove low frequency drift from the signal. The resulting QRS complex of the ECG signal was de-noised using wavelets

**Table 2**  
Overview of traffic scenarios.

Scenario	Traffic condition	Starting positions (m)
Free driving	Without traffic in opposing lane	1710, 2875
Intersection crossing	Without traffic in intersection lane	810, 2635, 3775, 4100, 4935, 5260, 6100
	With traffic in intersection lane	180, 1135, 1680, 2005, 2845, 3150, 4305, 5470, 6425
Car following	With traffic in opposing lane	210, 2035, 3850, 4965, 5500
Obstacle overtaking	Without traffic in opposing lane	1495, 3320 <sup>a</sup> , 3980 <sup>a</sup> , 4665, 6635
	With traffic in opposing lane	960, 2785, 3510, 4250, 4500 <sup>a</sup> , 5410, 6250

<sup>a</sup> Only during the training session.



**Fig. 2.** Screenshots of the four traffic scenarios; free driving (top left), car following with traffic in the opposing lane (top right), obstacle overtaking without traffic in the opposing lane (bottom left), and intersection crossing with traffic in the intersection lane (bottom right). *Note.* The route guidance arrow was shown at each intersection.

(Addison, 2005), and inter-beat intervals were extracted from the clean R-peak signal. The respiration rate signal was band-pass filtered (0.05–1 Hz) to remove the low frequency drift and high frequency noise from the signal. The resulting signal was used to calculate the inter-breath frequency from the time between two subsequent inhalation peaks.

### 2.7.5. Inertial sensor

Inertial sensor data were low-pass filtered with a 10 Hz cut-off frequency to remove the high frequency noise component.

## 2.8. Dependent measures

A number of dependent measures were calculated per session and per participant. The dependent measures were divided into the following categories:

### 2.8.1. Driving performance

Lane keeping accuracy and precision were defined as the mean lateral position (m) (left = positive) and the standard deviation of the lateral position (SDLP) (m), respectively (cf. Van Leeuwen et al., 2014). Obstacle overtaking maneuvers were excluded from these measures. Measures of vehicle speed (mean speed and maximum speed) (m/s) were used to capture driving style and task performance. During car following situations, the time headway (s) was determined (for headways smaller than 300 m with respect to the lead car), a measure which is indicative of tailgating behavior (Vogel, 2003).

### 2.8.2. Vehicle control

Mean absolute steering speed (deg/s) and throttle variance (minimum possible = 0, maximum possible = 0.25) were calculated as measures of steering and throttle activity. Furthermore, the mean number of gear changes and the mean number of brake applications were determined to represent the amount of control actions performed during the session. Finally, the maximum brake pedal position, on a scale of 0 (minimum) to 1 (maximum), was determined as a measure of braking performance (De Groot, De Winter, Wieringa, & Mulder, 2009). Mean limb accelerations (m/s<sup>2</sup>) were determined by taking the mean of the square root of the sum of the squared x, y, and z components of the measured wrist/ankle accelerations. The limb acceleration measure is indicative of the driver's control activity.

### 2.8.3. Eye movements and head movements

Gaze road center (GRC) (%) was calculated as the percentage of time that participants gazed within an approximately 8 deg radius from the road center. This measure is representative of the amount of gaze tunneling and has been

demonstrated to be sensitive to secondary task demands (Van Leeuwen, Happee, & De Winter, 2013; Victor, Harbluk, & Engström, 2005). Additionally, we calculated the horizontal gaze variance (HGV;  $\text{deg}^2$ ), representing the spread of visual search. The percentages of time that the participants were glancing at the dials and clock were calculated from the gaze vector with respect to predefined regions on the screen. These measures were used to verify the use of the simulated dashboard instruments and the clock showing the elapsed time in the session. The mean head position (m) was defined as the longitudinal component of the distance from the participants head to the top of the steering wheel (as determined by the eye-tracker system), and was regarded as a measure of driver posture.

#### 2.8.4. Physiological responses

The mean eye blink frequency (Hz) and the mean pupil diameter (mm) were extracted from the eye-tracker data, as these measures are known to be sensitive to task demands (Beatty, 1982; Recarte, Pérez, Conchillo, & Nunes, 2008). From the respiratory measurements, the mean respiration rate (1/min) and the respiration amplitude (mm) were calculated. These measures have also been shown to be sensitive to emotions and task demands (Boiten, Frijda, & Wientjes, 1994; Wientjes, Grossman, & Gaillard, 1998). The mean heart rate (1/min) and the mean heart rate variability (HRV) were determined from the inter-beat intervals in the ECG signal. The HRV was calculated by dividing the standard deviation of the inter-beat interval by the mean inter-beat interval (De Waard, 1996). Measures of cardiac response are indicative of task demands (Backs et al., 2003; Cain, 2007).

#### 2.8.5. Self-report measures

**2.8.5.1. NASA TLX (0–100).** The participants' self-reported workload was assessed with the NASA TLX questionnaire (Hart & Staveland, 1988) consisting of the following six items: mental demand, physical demand, temporal demand, performance, effort, and frustration. The response scale for each of the six items consisted of 21 checkboxes with anchors on the left (*low*), center (*med*), and right (*high*). For the performance item, the anchors *good*, *med*, and *poor* were used from the left to right.

**2.8.5.2. Confidence (0–100).** The participants' confidence was assessed using a confidence questionnaire consisting of the following six items: (1) "I understood how to negotiate the driving situations presented in the simulation", (2) "Driving in this environment was easy", (3) "I performed well on driving the car (I was confident about my driving skills)", (4) "I think I performed better than the average participant in driving to the airport", (5) "I had a feeling of risk during driving", and (6) "I feel confident to drive in similar conditions in the real world". These items were inspired from previous questionnaires assessing driver's confidence (De Craen, 2010; De Groot, De Winter, López-García, Mulder, & Wieringa, 2011; Ivancic & Hesketh, 2000; Wells, Tong, Genderton, Grayson, & Jones, 2008). The corresponding response scale consisted of 21 checkboxes with anchors on the left (*strongly disagree*), center (*neither agree nor disagree*), and right (*strongly agree*).

**2.8.5.3. Simulator discomfort and time pressure.** The simulator discomfort experienced by the participants was assessed by the following question: "I have experienced motion sickness in this experiment (general discomfort felt, in cars or boats, during long trips)" on a five-point scale (1 = *never*, 2 = *little*, 3 = *somewhat*, 4 = *much*, 5 = *very much*). Furthermore, the sensation of time pressure during the experiment was assessed with three questions: (1) "During driving I felt there WAS NOT enough time to drive and arrive to the airport", (2) "During driving I felt that I have to hurry up", and (3) "How much time pressure did you feel when driving?" on a five-point scale (1 = *no pressure at all*, 2 = *a little pressure*, 3 = *moderate pressure*, 4 = *high pressure*, 5 = *very high pressure*). Finally, to assess the participant's self-reported driving speed, participants were asked the following question: "How fast did you drive in order to arrive at the airport?" (1 = *not at all fast*, 2 = *a little fast*, 3 = *moderately fast*, 4 = *fast*, 5 = *very fast*).

### 2.9. Statistical analysis

Means and standard deviations were computed over the complete session, as well as for individual scenarios (e.g., car following). Differences between sessions were statistically analyzed with paired *t* tests. The questionnaire results were fractionally ranked (Conover & Iman, 1981) over all sessions and participants, because of their skewed distributions. Results were declared significant if  $p < 0.001$ . This conservative alpha value was used to reduce the probability of Type I error, in light of the large number of dependent measures. Correlations between the NTP and TP sessions were determined with the Pearson's correlation coefficient. Additionally, because data may be sensitive to outliers, Spearman's rank correlation coefficients were calculated.

## 3. Results

Two of the 56 participants aborted the experiment because of simulator discomfort; these participants were excluded from the analyses. For the remaining 54 participants (i.e., 54 NTP sessions and 54 TP sessions), 28.6% of the eye-tracking data were removed because of data loss. For 7 of these 108 sessions (3 NTP sessions and 4 TP sessions), the data loss exceeded 60%. Therefore, the eye-tracking data for these 7 sessions were removed entirely.

### 3.1. The effects of time pressure on the dependent measures

Table 3 shows the results for the training, NTP, and TP sessions for all driving performance, vehicle control, physiology, gaze, and self-report measures. Furthermore,  $p$  values and effect sizes are tabulated for comparisons between T and NTP, T and TP, and NTP and TP. Statistically significant differences between the NTP and TP sessions can be observed for all driving performance measures. That is, consistent with Hypothesis 1 (i.e., the manipulation check of the effects of time pressure), participants increased their speed during the TP session compared to the NTP session. Furthermore, drivers in the TP session drove significantly closer to the lead car during car following, had lower driving precision (i.e., a higher SDLP), and had faster control actions (i.e., an increase of steering speed, throttle variance, and number of brake operations). Specifically, in the TP

**Table 3**

Means and standard deviations of the dependent measures for the training (T), no time pressure (NTP), and time pressure (TP) sessions.  $p$  values and effect sizes (in parentheses) are shown. The Pearson ( $r$ ) and Spearman ( $\rho$ ) correlation coefficients are shown for the NTP vs TP session ( $N = 54$ , but  $N = 50$  for the gaze and pupil diameter measures). Effect sizes were determined as Cohen's  $d_z = t/N^{0.5}$ .

Dependent measures	Session mean (SD)			p value ( $d_z$ )			Correlation	
	Training (T)	NTP	TP	T – NTP	T – TP	NTP – TP	$r$	$\rho$
<i>Driving performance</i>								
Completion time (s)	551.7 (51.9)	548.1 (38.3)	462.8 (34.6)	n/a	n/a	<b>&lt;0.001</b> (2.83)	0.656	0.628
SDLP (m)	0.26 (0.09)	0.24 (0.08)	0.30 (0.14)	0.033 (0.30)	0.021 (–0.33)	<b>&lt;0.001</b> (–0.49)	0.527	0.465
Mean lateral position (m)	–0.22 (0.2)	–0.16 (0.21)	–0.05 (0.25)	<b>&lt;0.001</b> (–0.53)	<b>&lt;0.001</b> (–0.90)	<b>&lt;0.001</b> (–0.70)	0.764	0.763
Mean speed (m/s)	12.3 (1.2)	12.3 (0.9)	14.7 (1.1)	0.782 (–0.04)	<b>&lt;0.001</b> (–1.98)	<b>&lt;0.001</b> (–2.74)	0.669	0.631
Max speed (m/s)	26.6 (3.3)	24.7 (2.4)	30.5 (3.6)	<b>&lt;0.001</b> (0.65)	<b>&lt;0.001</b> (–1.07)	<b>&lt;0.001</b> (–1.83)	0.490	0.500
Minimum time headway (s)	n/a	4.1 (2.9)	1.0 (0.6)	n/a	n/a	<b>&lt;0.001</b> (–1.09)	0.215	0.293
<i>Vehicle control</i>								
Mean steering speed (deg/s)	8.02 (1.71)	7.63 (0.99)	8.36 (1.26)	0.070 (0.25)	0.116 (–0.22)	<b>&lt;0.001</b> (–0.80)	0.684	0.755
Throttle variance (0–0.25)	0.051 (0.03)	0.043 (0.03)	0.107 (0.04)	0.009 (0.37)	<b>&lt;0.001</b> (–1.91)	<b>&lt;0.001</b> (–1.97)	0.669	0.664
Mean number of gear shifts (#)	65.3 (11.9)	63.9 (11.5)	59.4 (11.5)	0.142 (0.20)	<b>&lt;0.001</b> (0.53)	0.002 (0.44)	0.602	0.617
Mean brake operations (#)	27.7 (5.2)	24.3 (5.4)	26.4 (5.2)	<b>&lt;0.001</b> (0.59)	0.153 (0.20)	<b>0.001</b> (–0.47)	0.645	0.588
Max brake (0–1)	0.90 (0.04)	0.88 (0.07)	0.91 (0.02)	0.011 (0.36)	0.024 (–0.32)	<b>&lt;0.001</b> (–0.57)	0.505	0.530
Mean acc. right hand (m/s <sup>2</sup> )	0.059 (0.07)	0.041 (0.07)	0.068 (0.08)	0.005 (0.42)	0.037 (–0.30)	<b>&lt;0.001</b> (–0.63)	0.850	0.807
Mean acc. right foot (m/s <sup>2</sup> )	0.133 (0.04)	0.130 (0.04)	0.149 (0.04)	0.215 (0.18)	<b>&lt;0.001</b> (–0.76)	<b>&lt;0.001</b> (–0.91)	0.880	0.842
Mean acc. left hand (m/s <sup>2</sup> )	0.065 (0.05)	0.061 (0.05)	0.066 (0.05)	0.374 (0.13)	0.533 (–0.09)	0.071 (–0.25)	0.947	0.919
Mean acc. left foot (m/s <sup>2</sup> )	0.154 (0.06)	0.148 (0.06)	0.163 (0.07)	0.249 (0.17)	0.004 (–0.42)	0.002 (–0.45)	0.881	0.845
<i>Gaze</i>								
Gaze road center (%)	55.4 (12.5)	52.5 (12.5)	55.8 (11.2)	<b>&lt;0.001</b> (0.52)	0.738 (–0.05)	0.056 (–0.28)	0.696	0.777
Horizontal gaze variance (deg <sup>2</sup> )	60.8 (16.7)	68.8 (23.6)	76.9 (23.6)	<b>&lt;0.001</b> (–0.67)	<b>&lt;0.001</b> (–0.85)	0.003 (–0.44)	0.723	0.778
Percentage dials (%)	11.0 (11.2)	11.5 (10.9)	10.1 (11.5)	0.428 (–0.11)	0.143 (0.20)	0.035 (0.30)	0.906	0.742
Percentage clock (%)	1.48 (1.01)	1.31 (1.00)	2.25 (1.06)	0.120 (0.22)	<b>&lt;0.001</b> (–0.67)	<b>&lt;0.001</b> (–0.86)	0.423	0.346
Missing eye-tracker data (%)	26.7 (16.4)	29.1 (15.3)	28.4 (16.7)	0.039 (–0.29)	0.152 (–0.20)	0.674 (0.06)	0.849	0.787
<i>Physiology</i>								
Mean blink rate (Hz)	0.24 (0.15)	0.29 (0.15)	0.24 (0.11)	<b>&lt;0.001</b> (–1.09)	0.077 (–0.26)	<b>0.001</b> (0.50)	0.852	0.833
Mean pupil diameter (mm)	5.38 (0.69)	5.19 (0.68)	5.37 (0.66)	<b>&lt;0.001</b> (1.47)	0.565 (0.08)	<b>&lt;0.001</b> (–0.94)	0.956	0.951
Mean respiration rate (1/min)	20.6 (2.07)	19.0 (2.65)	20.3 (2.70)	<b>&lt;0.001</b> (1.08)	0.097 (0.23)	<b>&lt;0.001</b> (–0.81)	0.840	0.847
Mean respiration amplitude (mV)	12.7 (3.18)	12.0 (2.73)	12.2 (2.71)	0.014 (0.35)	0.243 (0.16)	0.292 (–0.15)	0.876	0.856
Mean heart rate (1/min)	82.1 (12.8)	79.2 (12.3)	82.1 (12.9)	<b>&lt;0.001</b> (1.01)	0.924 (–0.01)	<b>&lt;0.001</b> (–0.78)	0.956	0.954
Mean HRV (–)	0.069 (0.02)	0.068 (0.02)	0.071 (0.02)	0.391 (0.12)	0.249 (–0.16)	0.021 (–0.33)	0.844	0.803
Mean head position (m)	0.764 (0.05)	0.767 (0.05)	0.764 (0.05)	0.023 (–0.33)	0.918 (0.01)	<b>&lt;0.001</b> (0.50)	0.993	0.987
<i>Subjective measures</i>								
Motion sickness (1–5)	1.89 (0.98)	1.70 (0.96)	1.70 (0.98)	0.032 (0.30)	0.077 (0.25)	1.000 (0.00)	0.921	0.894
Not enough time (1–5)	1.76 (0.87)	1.37 (0.56)	3.98 (0.79)	<b>&lt;0.001</b> (0.50)	<b>&lt;0.001</b> (–1.88)	<b>&lt;0.001</b> (–2.42)	–0.283	–0.245
Feeling of hurry (1–5)	2.09 (0.92)	1.61 (0.74)	4.28 (0.76)	<b>&lt;0.001</b> (0.56)	<b>&lt;0.001</b> (–1.84)	<b>&lt;0.001</b> (–2.41)	–0.106	–0.019
Fast arrival (1–5)	1.67 (0.87)	1.70 (0.74)	3.74 (0.85)	0.766 (–0.04)	<b>&lt;0.001</b> (–1.69)	<b>&lt;0.001</b> (–1.93)	0.115	0.159
Time pressure (1–5)	1.50 (0.64)	1.35 (0.55)	3.69 (0.91)	0.146 (0.20)	<b>&lt;0.001</b> (–2.36)	<b>&lt;0.001</b> (–2.53)	0.262	0.234
Understanding (0–100)	84 (15)	87 (12)	78 (20)	0.115 (–0.22)	0.054 (0.27)	<b>&lt;0.001</b> (0.49)	0.466	0.604
Was easy (0–100)	66 (26)	78 (19)	63 (23)	<b>&lt;0.001</b> (–0.60)	0.320 (0.14)	<b>&lt;0.001</b> (0.70)	0.417	0.477
Performed well (0–100)	61 (25)	72 (20)	61 (26)	<b>&lt;0.001</b> (–0.57)	0.936 (0.01)	<b>0.001</b> (0.47)	0.478	0.441
Performed above average (0–100)	46 (17)	53 (18)	46 (23)	<b>&lt;0.001</b> (–0.53)	0.943 (–0.01)	0.005 (0.41)	0.656	0.603
Feeling of risk (0–100)	36 (27)	23 (21)	53 (28)	<b>&lt;0.001</b> (0.67)	<b>&lt;0.001</b> (–0.64)	<b>&lt;0.001</b> (–1.08)	0.370	0.366
Confident (0–100)	84 (21)	85 (18)	65 (26)	0.817 (–0.03)	<b>&lt;0.001</b> (0.80)	<b>&lt;0.001</b> (0.94)	0.580	0.626
Mental demand (0–100)	52 (21)	39 (23)	59 (20)	<b>&lt;0.001</b> (0.71)	0.008 (–0.38)	<b>&lt;0.001</b> (–1.22)	0.690	0.650
Physical demand (0–100)	27 (18)	23 (16)	38 (22)	0.033 (0.30)	<b>&lt;0.001</b> (–0.76)	<b>&lt;0.001</b> (–0.89)	0.613	0.672
Temporal demand (0–100)	28 (22)	20 (16)	71 (16)	0.012 (0.36)	<b>&lt;0.001</b> (–2.17)	<b>&lt;0.001</b> (–2.68)	0.290	0.220
Performance (0–100)	62 (26)	68 (25)	47 (25)	0.036 (0.30)	0.002 (–0.45)	<b>&lt;0.001</b> (–0.62)	0.154	0.183
Effort (0–100)	44 (25)	33 (19)	64 (16)	<b>&lt;0.001</b> (0.64)	<b>&lt;0.001</b> (–0.87)	<b>&lt;0.001</b> (–1.54)	0.341	0.304
Frustration (0–100)	30 (23)	21 (20)	49 (27)	<b>&lt;0.001</b> (0.59)	<b>&lt;0.001</b> (–0.75)	<b>&lt;0.001</b> (–1.16)	0.503	0.474

Statistically significant effects ( $p < .001$ ) are denoted in boldface.

session, drivers moved their limbs more rapidly, especially their right foot (which is used for operating the throttle) and their right hand (which is used for changing gears). No statistically significant differences were observed regarding the activity of the left hand, which is interpretable because the left hand serves no specific purpose on a road without curves.

The results show a significantly higher workload on each of the six items of the NASA TLX for the TP versus the NTP session. Among the 17 self-report measures, the largest effects ( $|d_z| > 2.0$ ) of NTP versus TP were observed for the time-related measures (i.e., not enough time, feeling of hurry, time pressure, and temporal demand). Thus, our time pressure manipulation was successful in the sense that participants in the TP condition drove faster and experienced a greater feeling of hurry, time pressure, and temporal demand than in the NTP condition.

Consistent with Hypothesis 2, participants exhibited physiological reactions that represent an increase of sympathetic arousal. Statistically significant differences were observed for each of the physiological measures, except for the mean respiration amplitude and the mean HRV. The mean blink rate decreased, while the mean pupil diameter, mean respiration rate, and mean heart rate increased from the NTP to the TP session. Additionally, drivers sat slightly (but statistically significantly) closer to the steering wheel in the TP session compared to the NTP session. Table 3 further shows that the session-averaged horizontal gaze variance and percentage road center were not significantly different for the TP session compared to the NTP session. The time spent gazing at the in-vehicle clock increased when participants drove in the TP session compared to the NTP session, most likely because the clock contained task-relevant information in TP condition.

The comparisons of physiological responses between the NTP and TP session had a medium effect size ( $d_z = 0.5$ ) for the mean blink rate and a large effect size for the mean pupil diameter ( $d_z = 0.9$ ). These effect sizes were comparable to the effect sizes of the vehicle control measures shown in Table 3.

Correlation coefficients between the NTP and TP sessions are shown in Table 3. Correlations were about 0.5–0.6 for the vehicle control measures and about 0.8–0.9 for the physiological measures. Fig. 3 illustrates the correlation coefficient between the NTP and TP sessions for the mean speed (left), mean blink rate (center), and mean pupil diameter (right). Statistically significant effects of the time pressure manipulation are visible in all three figures. Furthermore, Fig. 3 signifies that the differences between individuals are substantially larger than the effects within individuals due to time pressure.

### 3.2. The relative validities of the physiological measures

A correlation matrix for the within-subject difference between the NTP and TP sessions is shown in Table 4 and Table S.1. This correlation matrix shows a positive manifold among the mean speed, maximum speed, SDLP, mean steering speed, throttle variance, mean pupil diameter, and the mental demands item from the NASA TLX. Thus, the mean pupil diameter exhibits relative validity with respect to driving performance measures and self-reported mental workload.

Several of the correlations listed in Table 4 are illustrated in Fig. 4. The correlations of the pupil diameter and mean speed (left), pupil diameter and mental demands (NASA TLX) (center), and pupil diameter and heart rate (right) are depicted. The figures show that an increase in pupil diameter was moderately associated with an increase in driving speed, heart rate, and mental demands (NASA TLX). For example, Fig. 4 (right) shows that people who showed a large increase in mean heart rate generally also showed a large increase in mean pupil diameter.

### 3.3. The effects of time pressure during traffic scenarios

#### 3.3.1. Physiological signals versus traversed distance along the route

Fig. 5 shows an overview of 11 selected measures as a function of traveled distance in the NTP and TP sessions. This figure illustrates the difference between the NTP and TP session for the various types of scenarios along the route (see Table 2, for an overview of the traffic scenarios).

Consistent with Table 3 and Hypothesis 1, drivers in the TP session drove with higher average speeds and throttle positions than they did in the NTP session. However, this was not the case during the car following scenarios, where the participants were held up by a lead car that was driving at constant speed. It can also be seen that participants braked harder

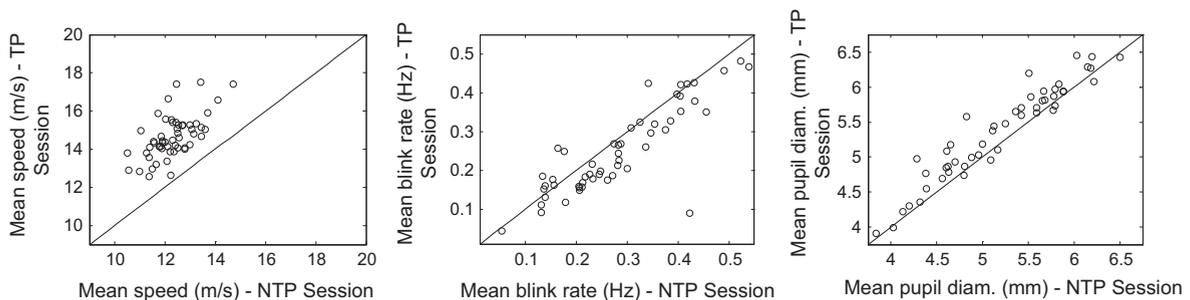


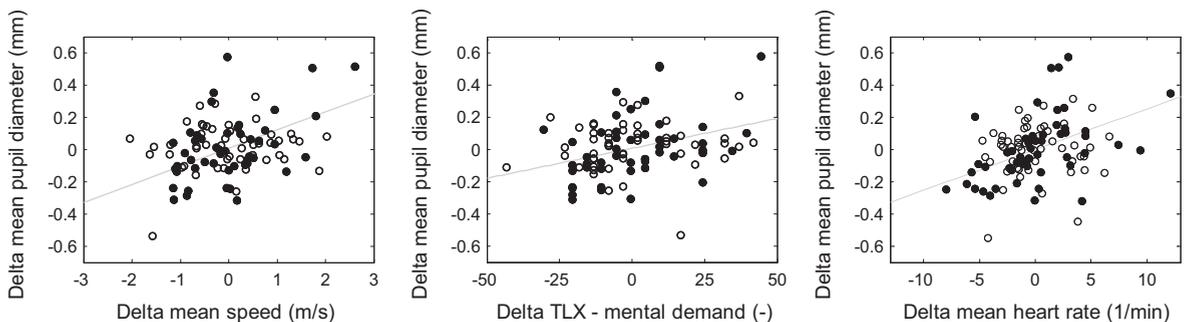
Fig. 3. Correlation between mean speed (left,  $N = 54$ ), blink rate (center,  $N = 54$ ), and pupil diameter (right,  $N = 50$ ) between the No time pressure (NTP) and Time pressure (TP) sessions. The correlation coefficients are shown in Table 3.

**Table 4**

Pearson correlation matrix ( $N = 54$ ) for driving performance, physiological, and self-reported workload measures. Correlations per measure were determined by taking the difference between the time pressure (TP) and no time pressure (NTP) sessions.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Mean speed (m/s)															
2. Max speed (m/s)	<b>.39</b>														
3. SDLP (m)	<b>.43</b>	.13													
4. Mean steering speed (deg/s)	<b>.56</b>	<b>.39</b>	<b>.66</b>												
5. Throttle variance (0–0.25)	<b>.60</b>	<b>.57</b>	<b>.32</b>	<b>.51</b>											
6. Mean acc. right hand ( $m/s^2$ )	<b>.29</b>	<b>.33</b>	<b>.31</b>	<b>.48</b>	<b>.35</b>										
7. Mean acc. right foot ( $m/s^2$ )	<b>.45</b>	<b>.36</b>	<b>.35</b>	<b>.48</b>	<b>.55</b>	<b>.48</b>									
8. Mean pupil diameter (mm)	<b>.36</b>	.26	<b>.37</b>	<b>.39</b>	<b>.29</b>	.14	.20								
9. Mean blink rate (1/s)	-.06	.07	.21	.06	-.05	.09	.01	<b>-.34</b>							
10. Percentage clock (%)	-.15	-.02	-.04	.10	-.13	.06	-.06	.00	-.23						
11. Percentage dials (%)	-.23	<b>-.47</b>	-.22	<b>-.28</b>	<b>-.36</b>	-.11	<b>-.27</b>	.13	<b>-.49</b>	.26					
12. Hor. gaze variance ( $deg^2$ )	.04	.01	<b>.37</b>	<b>.34</b>	.02	.15	.06	-.05	<b>.30</b>	.17	-.10				
13. Mean heart rate (1/min)	.04	<b>.34</b>	.06	.18	.26	.15	.18	<b>.41</b>	-.01	-.01	-.13	.10			
14. Mean respiration rate (1/min)	.21	<b>.28</b>	.03	.15	<b>.29</b>	.10	.04	<b>.40</b>	-.11	-.02	.13	.05	.21		
15. TLX mental demand (0–100)	.23	.19	<b>.28</b>	<b>.40</b>	<b>.28</b>	-.11	.15	<b>.49</b>	-.09	.00	-.05	.10	.12	.18	

Note: Correlations of magnitude greater than .27 correspond to  $p < 0.05$  and are in boldface.



**Fig. 4.** Correlation between session differences of pupil diameter and mean speed (left,  $N = 50$ ), pupil diameter and mental demand (NASA TLX) (center,  $N = 50$ ), and pupil diameter and heart rate (right,  $N = 50$ ). Session differences between the Training (T) and No time pressure (NTP) sessions are indicated by unfilled markers and session differences between the Time pressure (TP) and NTP session are indicated by filled markers. Linear fits calculated from session differences between the TP and NTP session are shown as gray lines.

before intersections during the TP session than during the NTP session, which can be explained by their higher approach speed and their attempt to brake late in order to prevent time loss. Fig. 5 also shows that limb movement occurred particularly when approaching and leaving intersections, associated with accelerating, braking, and gear changing.

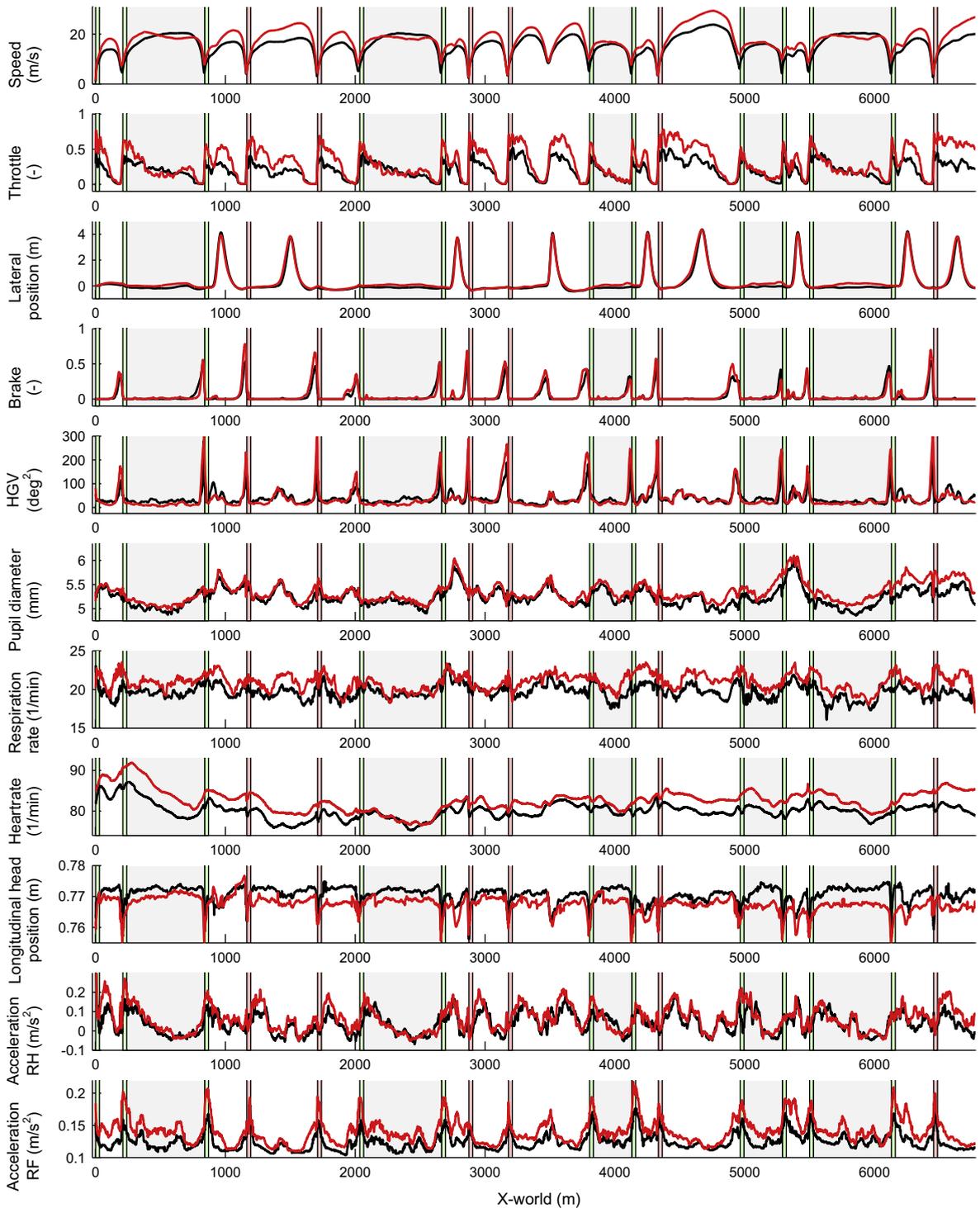
Consistent with Hypothesis 2 (effects on physiological measures), Fig. 5 shows an overall increase in pupil diameter, respiration rate, and heart rate during the TP session compared to the NTP session. Fig. 5 also shows a slightly more forward posture (indicated by a lower longitudinal head position). It can also be seen that the participants moved the head forward, on average about 1 cm, when approaching an intersection.

Regarding Hypothesis 3, several strategies can be observed. First, participants showed a higher (i.e., more to the left of the road) lateral position during car following for the TP session compared to the NTP session. This might represent a useful strategy to be able to change lanes quickly as soon as the left lane is free from traffic, or a previously learned strategy to signal to other road users that one is in a rush and wants to overtake the lead car (see e.g., Portouli, Nathanael, & Marmaras, 2014, for the communicative strategies that drivers use in traffic). Second, the increase of horizontal gaze variance (HGV) when approaching the intersections, which was most pronounced during the TP session, indicates that participants widened or accelerated their visual search. This behavior might represent an increased lookout, similar to the fact that participants adopted a more forward posture when approaching intersections.

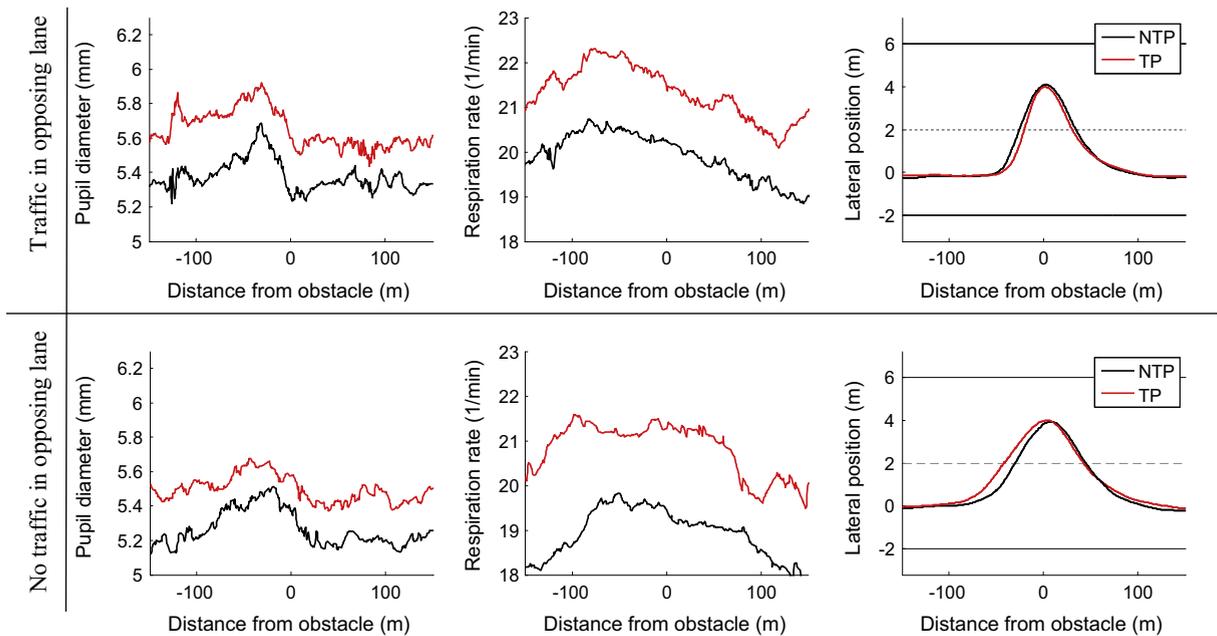
In the following sections, we zoom in and describe the distance-based effects for three scenarios: obstacle overtaking, intersection crossing, and car following.

### 3.3.2. Obstacle overtaking

Fig. 6 shows the pupil diameter, respiration rate, and lateral position for both the NTP and TP sessions during the obstacle overtaking scenarios. Consistent with Hypothesis 2, participants showed an increased mean pupil diameter when



**Fig. 5.** Means of 11 signals as a function of traveled distance for the No time pressure (NTP; black) and Time pressure (TP; red) sessions. The speed, lateral position, throttle position, and brake position were determined using a spatial sliding window of 4 m. The horizontal gaze variance (HGV), pupil diameter, respiration rate, heart rate, head position, and limb accelerations were determined using a temporal sliding window of 3 s. The intersections with and without traffic are indicated by green and red shading, respectively. Car following situations are indicated by gray shading and the overtaking maneuvers can be identified by lateral positions exceeding 2 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** Mean pupil diameter (left), mean respiration rate (center), and mean lateral position (right) for NTP (black) and TP (red) during overtaking maneuvers with traffic approaching in the opposing lane (top) and without traffic in the opposing lane (bottom). In the right two figures, the black lines indicate the lane boundaries and the dashed gray line indicates the road center line. The measures were averaged across all obstacle overtake maneuvers and participants. The measures were determined using a spatial sliding window of 0.5 m. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

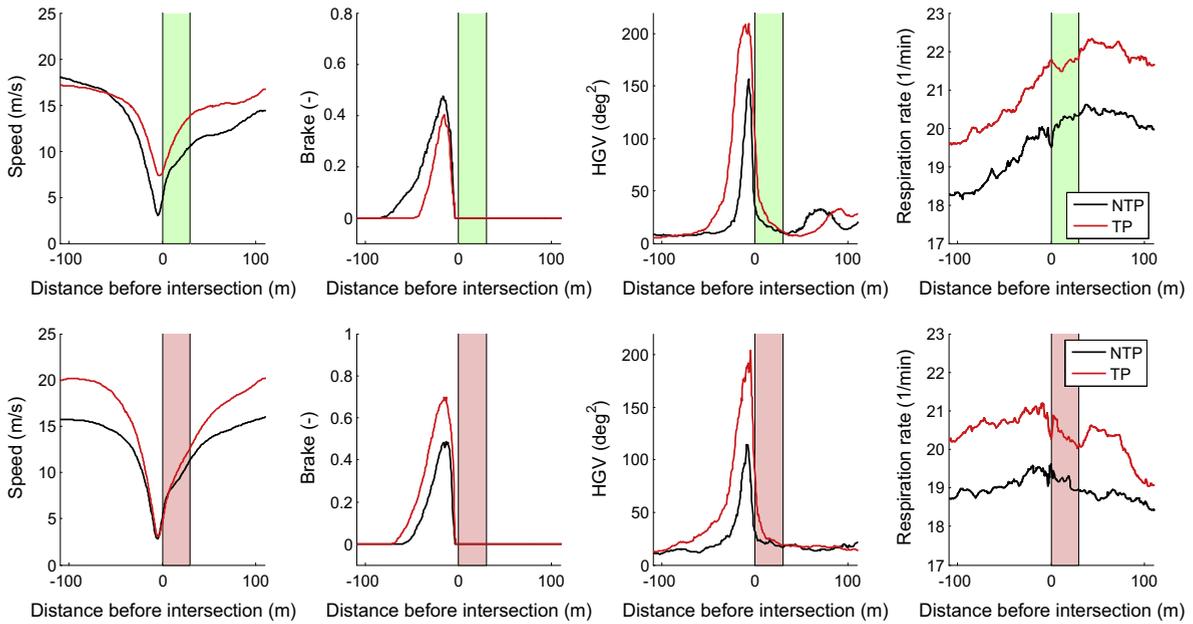
approaching the obstacle, both in the overtaking scenario with traffic in the opposing lane (top left figure) as well as in the scenario without traffic in the opposing lane (bottom left figure). The respiration rate shows an increase prior the overtaking maneuver and a decrease thereafter (middle two figures).

The lateral position shows that when traffic was present in the opposing lane, participants in the TP session initiated their overtaking maneuver *later* compared to the NTP session (right top figure). However, when no traffic was present in the opposing lane, the participants in the TP session initiated their overtake maneuver *earlier* compared to the NTP session (right bottom figure). In the context of Hypothesis 3, this can be interpreted as a strategy to complete the task as quickly as possible in a safe manner. That is, without traffic, it makes sense to change lanes early in order to minimize the traveled distance and to maximize the smoothness of travel.

### 3.3.3. Intersection crossing

Fig. 7 shows the mean speed, mean brake position, mean horizontal gaze variance, and mean respiration rate for both the NTP and TP sessions during the intersection-crossing scenarios. Consistent with Hypothesis 1 (manipulation check), TP resulted in an increased driving speed, increased intersection approach speed, and faster acceleration after crossing the intersection compared to the NTP session, both for the intersections with and without traffic. Consistent with Hypothesis 2 (physiological effects of time pressure), for both intersection types, the respiration rate was higher for the TP session than for the NTP session. A distinct pattern can be observed here, with the respiration rate rising upon approaching the intersection (see also Fig. 5, demonstrating a distance-based synchrony of the TP and NTP sessions for several of the physiological measures).

Drivers in the TP session braked later when there was no traffic on the intersection, and earlier when traffic was present on the intersection, compared to the NTP session. This strategy can be explained as follows: If the approach speed is higher and there is crossing traffic at the intersection, it makes sense to brake early, because one *has to* stop before the crossing traffic. However, if there is no traffic, then braking is not required and deceleration has a negative effect on the overall mean speed. The horizontal gaze variance increases in both intersection types during both the NTP and TP sessions, which indicates that participants scanned the intersection before crossing the intersection. Furthermore, participants in the TP session initiated their visual search earlier while approaching the intersection compared to the NTP session, as can be seen in the increasing horizontal gaze variance before the intersection for both intersection types. This altered visual scanning behavior when approaching intersections may be a strategy (Hypothesis 3) to acquire a maximal amount of visual information, in an attempt to minimize risk when crossing intersections with high speed.

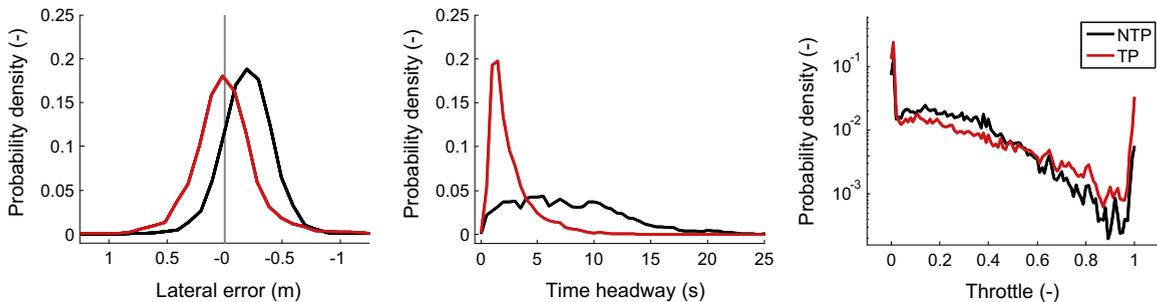


**Fig. 7.** Speed (far left), brake (left), horizontal gaze variance (right), and respiration rate (far right) before intersections without (top) and with traffic (bottom) on the intersection. Color shaded regions indicate the intersecting lane, with green and red corresponding to intersections without and with traffic, respectively. The measures were determined using a spatial sliding window of 0.5 m. Additionally, for each 0.5 m, the horizontal gaze variance was determined using a temporal window of 3 s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3.4. Car following

Fig. 8 shows the distribution of the lateral position, time headway, and throttle position for the NTP and TP sessions during the car following scenarios. During these scenarios, participants followed a lead car that had a constant speed. Fig. 8 (left) shows a probability distribution function indicating that, during the TP session, participants drove more toward the left of the lane than during the NTP session, possibly representing a strategy that prepares for overtaking or that signals to other road users that he/she is in rush (see also above). Fig. 8 (center) illustrates the smaller time headway adopted by participants in the TP session compared to participants in the NTP session. Fig. 8 (right) shows the throttle position for participants in both sessions. Participants in the TP session more often applied full throttle than participants in the NTP session. At first sight, this behavior seems to serve no functional purpose as the lead car’s speed was constant, but it may be a preparatory strategy allowing participants to overtake as soon as the traffic in the adjacent lane is free.

In Fig. 9, a heat map showing the gaze distribution during car following illustrates the increased gaze tunneling of drivers’ gaze. A significant difference in percentage road center ( $t(49) = 4.25, p < 0.001$ ) was found during the car following scenario between the NTP session ( $M = 57.9\%, SD = 14.3\%$ ) and the TP session ( $M = 66.7\%, SD = 16.9\%$ ). The reduced gaze variance during the car following scenarios is indicative of increased gaze tunneling during the TP session compared to the NTP session.



**Fig. 8.** Distributions of the lateral position (left), time headway (center), and throttle position (right, displayed on a logarithmic scale) during the car following scenarios. The distributions were determined by grouping the data across all participants in 0.1 m, 0.5 s, and 0.01 bins for the lateral position, time headway, and throttle, respectively.



**Fig. 9.** Heat map of gaze probability density during car following in the No time pressure (NTP; left) and Time pressure (TP; right) sessions, overlaid on a screenshot of the simulator display. Gaze distributions were determined by aggregating gaze data from car following sections of all participants in one-by-one degree bins and are shown on a logarithmic scale.

## 4. Discussion

This study explored the effects of time pressure on measures of driver physiology, driving performance, and vehicle control. We formulated three broad hypotheses: (1) When under time pressure, drivers show an increase of speed and an acceleration of control actions, (2) When under time pressure, drivers show increased signs of sympathetic arousal, that is, increased physiological activity, and (3) When under time pressure, drivers demonstrate various strategic behaviors that allow them to complete the driving task more effectively while minimizing the risk of crashing.

### 4.1. Hypothesis 1: Effects of time pressure on speed

Regarding the first hypothesis, it is concluded that the time pressure instructions clearly had the expected effect. Looking at Table 3, the four largest effect sizes between NTP and TP ( $|d_z| > 2.5$ ) among the 44 dependent variables were observed for (1) the task completion time itself, (2) the mean speed (which is highly correlated with the reciprocal of task completion time), (3) the self-reported time pressure, and (4) the self-reported temporal demand. These observations indicate that a driving simulator setup can elicit strong behavioral effects when drivers are exposed to a temporal constraint.

Various measures that are causally related to driving speed, such as throttle variance, activity of the right foot, maximum brake position, and mean absolute steering speed, were also higher for TP compared to NTP. These effects can be explained through classical mechanics. For example, when approaching an intersection with high speed and having to come to a standstill, a greater brake pedal pressure is required compared to when approaching with low speed. Similarly, when accelerating to high speed, a high throttle position is a prerequisite.

Another expected finding was that the lane keeping precision was poorer in the TP session compared to the NTP session. This indicates that a speed-accuracy tradeoff existed (cf. Szalma et al., 2008; Zhai et al., 2004). A reduction of lane keeping precision is also consistent with results from, for example, Engström, Johansson, and Östlund (2005), who found increased SDLP values when visual demands were increased by a secondary visual task.

### 4.2. Hypothesis 2: Effects of time pressure on physiological measures

Consistent with Hypothesis 2 and the stress model of Wickens et al. (2004), the time pressure ‘stressor’ resulted in increased physiological activity such as increased heart rate, increased respiration rate, increased pupil diameter, and decreased blink rate for participants in the TP session versus the NTP session. The strongest effects were observed for the pupil diameter, the respiration rate, and the heart rate. Our findings of heart rate and respiratory rate are in line with previous transportation research on the effects of secondary tasks during driving. For example, Mehler et al. (2009) found increased heart rates and respiration rates in 121 participants when performing an *n*-back mental task in a driving simulator compared to a control condition without secondary task. Our results regarding the pupillary response and blink rates are similar to the literature as well. For example, Recarte et al. (2008) found an increase in pupil diameter and a reduction of blink rate when drivers performed a secondary visual task.

Participants directed their gaze more at the lead car during the TP session than during the NTP session. Such gaze tunneling occurs when participants attend to their primary task and disregard secondary tasks (Crundall, Shenton, & Underwood, 2004; Hancock, 1989; Recarte & Nunes, 2003; Williams, 1988). In the present experiment, gaze tunneling might signal a strategy in which the participant focuses acutely on the car in front, explained by the closer following distance which required drivers to be more alert on the behavior of the lead vehicle.

Although the effects for the different physiological measures were mostly similar to each other and in the expected direction, each of these measures has unique strengths and weaknesses. For example, consistent with previous research in memory tasks and arithmetic tasks (e.g., Beatty, 1982; Klingner, 2010; Marquart & De Winter, 2015), pupil diameter has the advantage that it responds within a few tenths of second to changes in task demands, and that it can reach a peak dilation

of 0.5 mm in as little as 1 s. It should be noted, however, that fluctuations in pupil diameter might be confounded by environmental lighting and gaze direction (e.g., Beatty, 1982; Klingner, 2010). The heart rate has lower temporal sensitivity, and therefore is less suitable for assessing the effect of scenarios. Specifically, the mean inter-beat interval is 0.75 s, and it takes at least several beats to detect a change in heart rate (Jorna, 1992; Rowe, Sibert, & Irwin, 1998).

It is interesting that HRV, which has been said to be a valid index of time pressure (Nickel & Nachreiner, 2003), did not decline under TP. We believe that there are two main issues with the use of HRV. First, many different operationalizations of HRV exist (Task Force of the European Society of Cardiology & the North American Society of Pacing & Electrophysiology, 1996), such as frequency domain approaches, successive differences of inter-beat intervals, or average variability of inter-beat intervals (as employed in the present study). Second, HRV is difficult to interpret unless the task is constant with time. In our study, the task was dynamic, featuring various points along the route where the situation changed (e.g., car following, coming to a standstill). Thus, using heart rate variability for a task that itself varies as a function of time creates difficulties in interpretation.

One may argue that it is not surprising that time pressure elicited signs of sympathetic arousal. While this may be true, what is unique in our research is that we synchronized a large number of physiological measures with measures of driving performance and vehicle control. This allowed us to compare the differences between the NTP and TP sessions as a function of traveled distance along the route. Furthermore, we assessed the magnitude of inter-individual and found strong correlations between the two sessions ( $r > 0.8$ , see Table 3 and Fig. 3), indicating that the effects of time pressure should be interpreted as relative changes within individuals rather than changes on an absolute scale. Furthermore, we demonstrated the relative validities of the physiological measures. For example, people who showed a greater increase in mean speed were generally also those people who showed the greater increase in pupil diameter (Table 4).

#### 4.3. Hypothesis 3: Effects of time pressure on driving strategy

Consistent with Hypothesis 3 and the model of Maule and Hockey (1993), drivers adapted their driving strategies to the time constraint. For example, in the TP session, drivers drove more to the left of the right lane than in the NTP session, an effect that was particularly pronounced during car following. Presumably, drivers were maintaining a lateral position closer to the left lane in order to prepare for an overtaking maneuver. Another explanation is that participants drove to the left to signal to the lead car that they were in a rush.

A second change in strategy was observed when participants overtook obstacles and when crossing intersections. Specifically, in the TP session when no traffic was present in the opposing lane, participants made the overtaking maneuver earlier than in the NTP session. A similar effect could be seen in the intersection scenario, where participants in the TP session braked later compared to the NTP session when no traffic was present on the intersection, and braked earlier compared to the NTP session when traffic was present on the intersection. Presumably, participants in the TP session used these strategies to minimize the overall time to complete the session. Furthermore, at intersections, participants in the TP session adopted a more forward seating posture and showed greater gaze variance, possibly in an attempt to scan the intersection for oncoming traffic more rapidly before crossing it.

A third strategy was identified during car following, during which participants in the TP session showed a high throttle activity despite the fact that the lead car speed was constant. Note that some of these behaviors are nonfunctional in the driving simulator. For example, the other traffic did not adapt to the participant's behavior in any way (and so gestures or signaling did not have an effect). Collectively, these strategies under time pressure represent behaviors that may seem irrational, but serve the higher-order purpose to complete the task quickly yet safely.

#### 4.4. Implications of our research for driver assessment applications

The results of our experiment showed strong and statistically significant changes in physiological measures when drivers experienced time pressure. These findings provide support for the potential implementation of physiological measurements as estimators of driver's task demands (see also Brookhuis & De Waard, 2010; Mehler et al., 2009). The mean pupil diameter, mean heart rate, and mean respiration rate demonstrated a particularly strong effect as a function of time pressure. The vehicle-derived performance measures also showed strong effects of time pressure, but exhibited a strong context dependency. For example, during car following the participants' driving speeds were about equal to the speed of the lead car. Furthermore, our experiment illustrated that, on an absolute scale, within-subject effects of time pressure are small compared to between-subject differences. This phenomenon implies that changes in driver state can only be detected at the individual level (see also Brookhuis, De Waard, & Fairclough, 2003; Matthews, Reinerman-Jones, Barber, & Abich, 2014; Mulder, Dijksterhuis, Stuiver, & De Waard, 2009). That is, physiological measures have to be corrected for individual differences if they are to be used in real-time driver assessment applications.

#### 4.5. Limitations

Our experiment is affected by several limitations. First, the order of the NTP and TP sessions was not counterbalanced because the time constraint was determined on an individual basis. Thus, our protocol did not control for learning effects and other types of carryover effects. However, this limitation can be countered, because the majority of the dependent

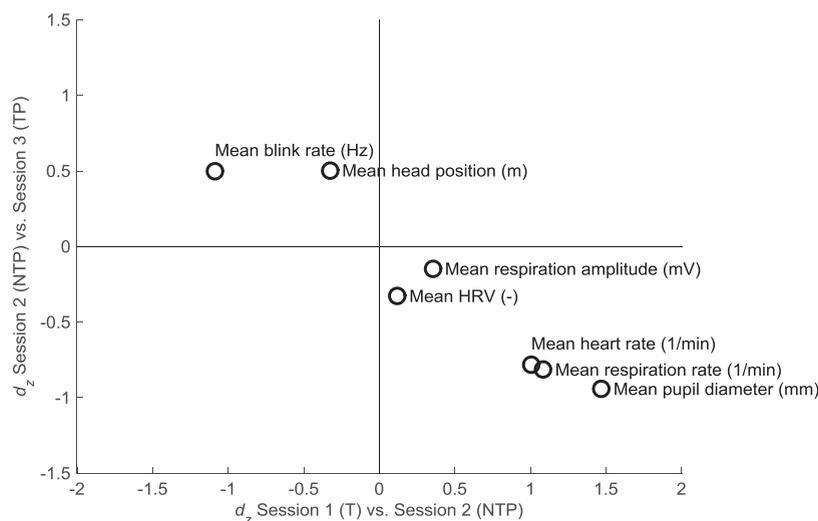
measures showed a *decreasing* trend from the training to the NTP session (which, indeed, can likely be attributed to learning and acclimation) but an *increasing* trend from the NTP to the TP session. For example, the mean pupil diameter was 5.38 mm, 5.19 mm, and 5.37 mm in the T, NTP, and TP sessions, respectively. Such a U-shaped pattern across the three sessions is apparent for all seven physiological measures, as illustrated in Fig. 10. This pattern of results suggests that the physiological response is not a methodological artifact caused by time-on-task.

A second limitation is that 28.6% of eye-tracker data had to be removed from our analysis. Missing eye-tracker data of around 30% are consistent with the literature (e.g., Ahlstrom, Victor, Wege, & Steinmetz, 2012). Because much of the data loss occurred at random events (e.g., due to eye blinks), no systematic error is expected in our results.

A third limitation is that it is unknown which mental or physical mechanisms have caused the observed physiological signals. It is likely that the effects in Table 3 are attributable at least partly to physical exertion. Indeed, the acceleration data of the limbs (Table 3) unequivocally indicate that participants were more physically active in the TP session than in the NTP session. This probably had an influence on the physiological outcomes, such as heart rate and respiratory rate, which are well known to be a function of physical activity. Moreover, Table 3 showed that the physiological measures exhibit a U-shaped pattern across the three sessions, while the self-reported time pressure exhibits a different pattern, with only a small effect between the training session and the NTP session and a very large effect between the NTP and TP session. This differential pattern suggests that the physiological measures do not capture time pressure *per se*. Indeed, different mental mechanisms might be at play, such as mechanisms associated with mental workload, frustration, ‘time stress’, anxiety, and arousal. We argue that it is impossible to uniquely identify these mechanisms and states based on the present physiological data (see also Cacioppo & Tassinari, 1990; Cacioppo, Tassinari, & Berntson, 2000). Taking pupil diameter for example, and setting aside issues of experimental control such as the fact that the pupil diameter is sensitive to environmental light conditions moderated by biological age (Näätänen, 1992; Watson & Yellott, 2012), it has been established that “any sensory occurrence—whether tactile, auditory, gustatory, olfactory, or noxious—evokes a pupillary reflex dilation”, and that “one should not assume that pupillary reflex dilations occur only to external sensory events, because emotions, mental processes, increases in intentional efforts, and motor output also produce systematic changes in pupillary diameter.” (Beatty & Lucero-Wagoner, 2000, pp. 145–146). In summary, our research showed that the time pressure manipulation (i.e., a time constraint and a virtual passenger urging to hurry up) had clear physiological effects, but it is not possible to reverse this causality and identify ‘time pressure’ as a unique cognitive construct from the physiological recordings. It is likely that other types of stressors, such as traffic complexity and secondary tasks, yield physiological effects that are indistinguishable from the effects that were observed in this study.

A fourth limitation is related to driving simulator validity. Driving simulators have been shown to provide measures that are strongly predictable of real world driving (Lee, Cameron, & Lee, 2003). Reimer (2009) demonstrated the relative validity of physiological measures recorded both in a fixed base driving simulator and during a field study. However, driving simulator validity remains an important limitation in our study, and more research is recommended to validate our findings on the road.

A fifth limitation is that our participants were recruited from a technical university campus, and may be assumed to have above average intelligence, spatial ability (Wai, Lubinski, & Benbow, 2009), and a specific interest in (driving simulator) technology. It has been argued that people in high-income societies, participants from university communities in particular, are not representative of the general population (Henrich, Heine, & Norenzayan, 2010).



**Fig. 10.** Scatter plot of the Cohen's  $d_z$  effect size of Session 1 (Training session, T) versus Session 2 (No time pressure session, NTP) and the Cohen's  $d_z$  effect size of Session 2 (NTP) versus Session 3 (Time pressure, TP). These results indicate that the measures of sympathetic arousal decreased from Session 1 to 2, but increased from Session 2 ( $r = -0.95$ ,  $p = 0.001$ ).

A sixth limitation is that our research focused exclusively on manual driving. In the foreseeable future, automated driving technologies will be introduced on the roads, a development that entails new types of psychological questions (De Winter et al., 2014; Fisher, Reed, & Savirimuthu, 2015; Young & Stanton, 2007). Specifically, the driving task is gradually changing from manual control into supervisory control, placing pressures on drivers to monitor both the environment and in-vehicle systems (Banks, Stanton, & Harvey, 2014; see also Warm, Parasuraman, & Matthews, 2008).

## Acknowledgments

We thank Green Dino BV, the Netherlands, for their technical and software support. The research was supported by Universidad EAFIT, the Dutch Ministry of Economic affairs through the projects “Driver Observation in Car Simulators” (HTASI09004-DrivObs), “Advanced Driver Vehicle Interface in a Complex Environment” (partner, RAAK PRO-3-08, 2011-2015, ADVICE), and by the Stichting voor de Technische Wetenschappen (Dutch Technology Foundation; STW), applied science division of the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (Netherlands Organisation for Scientific Research; NWO) and the Technology Program of the Ministry of Economic Affairs.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.trf.2016.06.013>.

## References

- Aarts, L., & Van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis and Prevention*, 38, 215–224.
- Addison, P. S. (2005). Wavelet transforms and the ECG: A review. *Physiological Measurement*, 26, R155–R199.
- Ahlstrom, C., Victor, T., Wege, C., & Steinmetz, E. (2012). Processing of eye/head-tracking data in large-scale naturalistic driving data sets. *IEEE Transactions on Intelligent Transportation Systems*, 13, 553–564.
- Backs, R. W., Lenneman, J. K., Wetzel, J. M., & Green, P. (2003). Cardiac measures of driver workload during simulated driving with and without visual occlusion. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 45, 525–538.
- Banks, V. A., Stanton, N. A., & Harvey, C. (2014). Sub-systems on the road to vehicle automation: Hands and feet free but not ‘mind’ free driving. *Safety Science*, 62, 505–514.
- Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, 91, 276–292.
- Beatty, J., & Lucero-Wagoner, B. (2000). The pupillary system. In J. Cacioppo, L. G. Tassinari, & G. Berntson (Eds.), *The handbook of psychophysiology* (2nd ed., pp. 142–162). Hillsdale, NJ: Cambridge University Press.
- Beck, K. H., Daughters, S. B., & Ali, B. (2013). Hurried driving: Relationship to distress tolerance, driver anger, aggressive and risky driving in college students. *Accident Analysis and Prevention*, 51, 51–55.
- Beck, K. H., Wang, M. Q., & Yan, A. F. (2012). Hurried driver dispositions: Their relationship to risky traffic behaviors. *American Journal of Health Behavior*, 36, 86–95.
- Benson, L., III, & Beach, L. R. (1996). The effects of time constraints on the prechoice screening of decision options. *Organizational Behavior and Human Decision Processes*, 67, 222–228.
- Birch, L., Juul-Kristensen, B., Jensen, C., Finsen, L., & Christensen, H. (2000). Acute response to precision, time pressure and mental demand during simulated computer work. *Scandinavian Journal of Work, Environment & Health*, 26, 299–305.
- Boiten, F. A., Frijda, N. H., & Wientjes, C. J. (1994). Emotions and respiratory patterns: Review and critical analysis. *International Journal of Psychophysiology*, 17, 103–128.
- Bongers, P. M., De Winter, C. R., Kompier, M. A., & Hildebrandt, V. H. (1993). Psychosocial factors at work and musculoskeletal disease. *Scandinavian Journal of Work, Environment & Health*, 19, 297–312.
- Brookhuis, K. A., & De Waard, D. (2010). Monitoring drivers’ mental workload in driving simulators using physiological measures. *Accident Analysis and Prevention*, 42, 898–903.
- Brookhuis, K. A., De Waard, D., & Fairclough, S. H. (2003). Criteria for driver impairment. *Ergonomics*, 46, 433–445.
- Cacioppo, J. T., & Tassinari, L. G. (1990). Inferring psychological significance from physiological signals. *American Psychologist*, 45, 16–28.
- Cacioppo, J. T., Tassinari, L. G., & Berntson, G. G. (2000). Psychophysiological science. In J. Cacioppo, L. G. Tassinari, & G. Berntson (Eds.), *The handbook of psychophysiology* (2nd ed., pp. 3–26). Hillsdale, NJ: Cambridge University Press.
- Cain, B. (2007). *A review of the mental workload literature (Report RTO-TR-HFM-121-Part-II)*. Toronto, Canada: Defence Research and Development.
- Cantin, V., Lavallière, M., Simoneau, M., & Teasdale, N. (2009). Mental workload when driving in a simulator: Effects of age and driving complexity. *Accident Analysis and Prevention*, 41, 763–771.
- Cnossen, F., Rothengatter, T., & Meijman, T. (2000). Strategic changes in task performance in simulated car driving as an adaptive response to task demands. *Transportation Research Part F: Traffic Psychology and Behaviour*, 3, 123–140.
- Cœugnet, S., Miller, H., Anceaux, F., & Naveteur, J. (2013). How do time pressured drivers estimate speed and time. *Accident Analysis and Prevention*, 55, 211–218.
- Cœugnet, S., Naveteur, J., Antoine, P., & Anceaux, F. (2013). Time pressure and driving: Work, emotions and risks. *Transportation Research Part F: Traffic Psychology and Behaviour*, 20, 39–51.
- Collinson, J. (2014). *A9 average speed cameras and HGV 50mph pilot monitoring – “before” market research*. Retrieved from [http://a9road.info/uploads/publications/A9\\_Average\\_Speed\\_Cameras\\_and\\_HGV\\_50mph\\_Pilot\\_Monitoring\\_-\\_Before\\_Market\\_Research.pdf](http://a9road.info/uploads/publications/A9_Average_Speed_Cameras_and_HGV_50mph_Pilot_Monitoring_-_Before_Market_Research.pdf).
- Conover, W. J., & Iman, R. L. (1981). Rank transformations as a bridge between parametric and nonparametric statistics. *The American Statistician*, 35, 124–133.
- Cooper, P. J. (1997). The relationship between speeding behavior (as measured by violation convictions) and crash involvement. *Journal of Safety Research*, 28, 83–95.
- Crundall, D., Shenton, C., & Underwood, G. (2004). Eye movements during intentional car following. *Perception*, 33, 975–986.
- Crundall, D. E., & Underwood, G. (1998). Effects of experience and processing demands on visual information acquisition in drivers. *Ergonomics*, 41, 448–458.
- De Craen, S. (2010). *The X factor. A longitudinal study of calibration in young novice drivers*. Doctoral dissertation: Delft University of Technology.
- De Groot, S., De Winter, J. C. F., López-García, J. M., Mulder, M., & Wieringa, P. A. (2011). The effect of concurrent bandwidth feedback on learning the lane keeping task in a driving simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 53, 50–62.

- De Groot, S., De Winter, J. C. F., Wieringa, P. A., & Mulder, M. (2009). An analysis of braking measures. In *Exploiting the possibilities of simulators for driver training* (pp. 4–12). The Netherlands: Delft. Retrieved from [http://repository.tudelft.nl/assets/uuid:893379c9-0e8c-43d8-9f57-06149a778183/2013.11.07\\_DeGroot.pdf](http://repository.tudelft.nl/assets/uuid:893379c9-0e8c-43d8-9f57-06149a778183/2013.11.07_DeGroot.pdf).
- De Waard, D. (1996). *The measurement of drivers' mental workload*. Doctoral dissertation. Haren, The Netherlands: University of Groningen.
- De Winter, J. C. F., Happee, R., Martens, M. H., & Stanton, N. A. (2014). Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence. *Transportation Research Part F: Traffic Psychology and Behaviour*, 27, 196–217.
- Dijksterhuis, C., Brookhuis, K. A., & De Waard, D. (2011). Effects of steering demand on lane keeping behavior, self-reports, and physiology. A simulator study. *Accident Analysis and Prevention*, 43, 1074–1081.
- Edland, A., & Svenson, O. (1993). Judgment and decision making under time pressure: Studies and findings. In O. Svenson & A. J. Maule (Eds.), *Time pressure and stress in human judgment and decision making* (pp. 83–101). New York, NY: Plenum Press.
- Elander, J., West, R., & French, D. (1993). Behavioral correlates of individual differences in road-traffic crash risk: An examination of methods and findings. *Psychological Bulletin*, 113, 279–294.
- Elvik, R., Christensen, P., & Amundsen, A. (2004). *Speed and road accidents. An evaluation of the power model* (TØI Report 740/2004). Oslo: Institute of Transport Economics (TOI).
- Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8, 97–120.
- Evans, L., & Wasieleski, P. (1982). Do accident-involved drivers exhibit riskier everyday driving behavior? *Accident Analysis and Prevention*, 14, 57–64.
- Fisher, M., Reed, N., & Savirimuthu, J. (2015). Misplaced trust? *Engineering & Technology Reference*. <http://dx.doi.org/10.1049/etr.2014.0054>.
- Hancock, P. A. (1989). A dynamic model of stress and sustained attention. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 31, 519–537.
- Hancock, P. A., & Szalma, J. L. (Eds.). (2008). *Performance under stress*. Aldershot: Ashgate.
- Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139–183). North-Holland: Elsevier Science.
- Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Sciences*, 33, 61–83.
- Ivancic, K., & Hesketh, B. (2000). Learning from errors in a driving simulation: Effects on driving skill and self-confidence. *Ergonomics*, 43, 1966–1984.
- Jorna, P. G. (1992). Spectral analysis of heart rate and psychological state: A review of its validity as a workload index. *Biological Psychology*, 34, 237–257.
- Klingner, J. M. (2010). *Measuring cognitive load during visual tasks by combining pupillometry and eye tracking*. Doctoral dissertation: Stanford University.
- Klingner, J., Kumar, R., & Hanrahan, P. (2008). Measuring the task-evoked pupillary response with a remote eye tracker. In *Proceedings of the 2008 Symposium on Eye Tracking Research & Applications* (pp. 69–72).
- Kramer, A. F. (1991). Physiological metrics of mental workload: A review of recent progress. In D. L. Damos (Ed.), *Multiple-task performance* (pp. 279–328). London: Taylor & Francis.
- Lajunen, T., Karola, J., & Summala, H. (1997). Speed and acceleration as measures of driving style in young male drivers. *Perceptual and Motor Skills*, 85, 3–16.
- Lee, H. C., Cameron, D., & Lee, A. H. (2003). Assessing the driving performance of older adult drivers: On-road versus simulated driving. *Accident Analysis and Prevention*, 35, 797–803.
- Marquart, M., & De Winter, J. C. F. (2015). Workload assessment for mental arithmetic tasks using the task-evoked pupillary response. *PeerJ Computer Science*, 1, e16.
- Martinussen, L. M., Lajunen, T., Møller, M., & Özkan, T. (2013). Short and user-friendly: The development and validation of the Mini-DBQ. *Accident Analysis and Prevention*, 50, 1259–1265.
- Matthews, G. (2002). Towards a transactional ergonomics for driver stress. *Theoretical Issues in Ergonomics Science*, 3, 195–211.
- Matthews, G., Reinerman-Jones, L. E., Barber, D. J., & Abich, J. (2014). The psychometrics of mental workload multiple measures are sensitive but divergent. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 57, 125–143.
- Maule, A. J., & Hockey, G. R. J. (1993). State, stress, and time pressure. In O. Svenson & A. J. Maule (Eds.), *Time pressure and stress in human judgment and decision making* (pp. 83–101). New York, NY: Plenum Press.
- McKenna, F. P. (2005). *Why do drivers break the speed limit? Behavioral research in road safety 2005: Fifteenth seminar*. London: Department for Transport. Retrieved from <http://www.bv.transports.gouv.qc.ca/mono/0996518.pdf>.
- Mehler, B., Reimer, B., Coughlin, J. F., & Dusek, J. A. (2009). Impact of incremental increases in cognitive workload on physiological arousal and performance in young adult drivers. *Transportation Research Record: Journal of the Transportation Research Board*, 2138, 6–12.
- Miller, J. G. (1960). Information input overload and psychopathology. *American Journal of Psychiatry*, 116, 695–704.
- Mulder, L. J. M., Dijksterhuis, C., Stuiver, A., & De Waard, D. (2009). Cardiovascular state changes during performance of a simulated ambulance dispatchers' task: Potential use for adaptive support. *Applied Ergonomics*, 40, 965–977.
- Näätänen, R. (1992). *Attention and brain function*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Nickel, P., & Nachreiner, F. (2003). Sensitivity and diagnosticity of the 0.1-Hz component of heart rate variability as an indicator of mental workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 45, 575–590.
- Organisation for Economic Co-operation & Development (2006). *Young drivers: The road to safety*. Paris, France: OECD.
- Owsley, C., Stalvey, B., Wells, J., & Sloane, M. E. (1999). Older drivers and cataract: Driving habits and crash risk. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 54, M203–M211.
- Palinko, O., Kun, A. L., Shyrovok, A., & Heeman, P. (2010). Estimating cognitive load using remote eye tracking in a driving simulator. In *Proceedings of the 2010 symposium on eye tracking research & applications* (pp. 141–144).
- Parker, D., Reason, J. T., Manstead, A. S. R., & Stradling, S. G. (1995). Driving errors, driving violations and accident involvement. *Ergonomics*, 38, 1036–1048.
- Portouli, E., Nathanael, D., & Marmaras, N. (2014). Drivers' communicative interactions: On-road observations and modelling for integration in future automation systems. *Ergonomics*, 57, 1795–1805.
- Prado Vega, R., Van Leeuwen, P. M., Vélez, E. R., Lemij, H. G., & De Winter, J. C. F. (2013). Obstacle avoidance, visual detection performance, and eye-scanning behavior of glaucoma patients in a driving simulator: A preliminary study. *PLOS ONE*, 8, e77294.
- Recarte, M. A., & Nunes, L. M. (2000). Effects of verbal and spatial-imagery tasks on eye fixations while driving. *Journal of Experimental Psychology: Applied*, 6, 31–43.
- Recarte, M. A., & Nunes, L. M. (2003). Mental workload while driving: Effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied*, 9, 119–137.
- Recarte, M. A., Pérez, E., Conchillo, Á., & Nunes, L. M. (2008). Mental workload and visual impairment: Differences between pupil, blink, and subjective rating. *The Spanish Journal of Psychology*, 11, 374–385.
- Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual tunneling. *Transportation Research Record: Journal of the Transportation Research Board*, 2138, 13–19.
- Rendon-Velez, E., Horvath, I., & Van der Vegte, W. (2012). A pilot study to investigate time pressure as a surrogate of being in haste. In *Proceedings of the Ninth International Symposium on Tools and Methods of Competitive Engineering* (pp. 393–406).
- Riener, A., Ferscha, A., & Matscheko, M. (2008). Intelligent vehicle handling: Steering and body postures while cornering. In U. Brinkschule, T. Ungerer, C. Hochberger, & R. G. Spallek (Eds.), *Architecture of computing systems—ARCS 2008* (pp. 68–81). Berlin: Springer.
- Robert, G., & Hockey, J. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology*, 45, 73–93.
- Rogers, S. D., Kadar, E. E., & Costall, A. (2005). Gaze patterns in the visual control of straight-road driving and braking as a function of speed and expertise. *Ecological Psychology*, 17, 19–38.

- Rothengatter, T. (1988). Risk and the absence of pleasure: A motivational approach to modelling road user behavior. *Ergonomics*, 31, 599–607.
- Rowe, D. W., Sibert, J., & Irwin, D. (1998). Heart rate variability: Indicator of user state as an aid to human-computer interaction. In *Proceedings of the SIGCHI conference on human factors in computing systems, Los Angeles, CA* (pp. 480–487).
- Sivak, M. (1996). The information that drivers use: Is it indeed 90% visual? *Perception*, 25, 1081–1089.
- Szalma, J. A., Hancock, P. A., & Quinn, S. (2008). A meta-analysis of the effect of time pressure on human performance. In *Proceedings of the human factors and ergonomics society 52nd annual meeting* (pp. 1513–1516).
- Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Circulation*, 93, 1043–1065.
- Taubman-Ben-Ari, O., Mikulincer, M., & Gillath, O. (2004). The multidimensional driving style inventory—Scale construct and validation. *Accident Analysis and Prevention*, 36, 323–332.
- Tran, C., & Trivedi, M. M. (2010). Towards a vision-based system exploring 3d driver posture dynamics for driver assistance: Issues and possibilities. In *IEEE intelligent vehicles symposium (IV)* (pp. 179–184).
- Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., et al. (1979). *Tri-level study of the causes of traffic accidents (Report DOT HS 805 099)*. Washington, DC: National Highway Traffic Safety Administration.
- Van der Hulst, M., Rothengatter, T., & Meijman, T. (1998). Strategic adaptations to lack of preview in driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 1, 59–75.
- Van Galen, G. P., & Van Huygevoort, M. (2000). Error, stress and the role of neuromotor noise in space oriented behavior. *Biological Psychology*, 51, 151–171.
- Van Leeuwen, P. M., Gómez i Subils, C., Ramon Jimenez, A., Happee, R., & De Winter, J. C. F. (2015). Effects of visual fidelity on curve negotiation, gaze behavior and simulator discomfort. *Ergonomics*, 58, 1347–1364.
- Van Leeuwen, P. M., Happee, R., & De Winter, J. C. F. (2013). Investigating the effect of a visual search task for simulator-based driver training. In *Proceedings of the 7th international driving symposium on human factors in driver assessment, training and vehicle design, Bolton Landing, NY* (pp. 425–431). Retrieved from [http://drivingassessment.uiowa.edu/sites/default/files/DA2013/Papers/065\\_vanLeeuwen\\_0.pdf](http://drivingassessment.uiowa.edu/sites/default/files/DA2013/Papers/065_vanLeeuwen_0.pdf).
- Van Leeuwen, P. M., Happee, R., & De Winter, J. C. F. (2014). Vertical field of view restriction in driver training: A simulator-based evaluation. *Transportation Research Part F: Traffic Psychology and Behaviour*, 24, 169–182.
- Veltman, J. A., & Gaillard, A. W. K. (1996). Physiological indices of workload in a simulated flight task. *Biological Psychology*, 42, 323–342.
- Victor, T. W., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8, 167–190.
- Vogel, K. (2003). A comparison of headway and time to collision as safety indicators. *Accident Analysis and Prevention*, 35, 427–433.
- Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101, 817–835.
- Warm, J. S., Parasuraman, R., & Matthews, G. (2008). Vigilance requires hard mental work and is stressful. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 50, 433–441.
- Watson, A. B., & Yellott, J. I. (2012). A unified formula for light-adapted pupil size. *Journal of Vision*, 12, 1–16.
- Wells, P., Tong, S., Genderton, B., Grayson, G., & Jones, E. (2008). *Cohort II: A study of learner and new drivers. Main report (Report No. 81)* (Vol. 1) London, UK: Transport Research Laboratory, Department for Transport.
- Wickens, C. D., Lee, J. D., Liu, Y., & Gordon-Becker, S. E. (2004). *An introduction to human factors engineering* (2nd ed.). Upper Saddle River, NJ: Pearson Prentice Hall.
- Wientjes, C. J., Grossman, P., & Gaillard, A. W. (1998). Influence of drive and timing mechanisms on breathing pattern and ventilation during mental task performance. *Biological Psychology*, 49, 53–70.
- Wikman, A. S., Nieminen, T., & Summala, H. (1998). Driving experience and time-sharing during in-car tasks on roads of different width. *Ergonomics*, 41, 358–372.
- Williams, L. J. (1988). Tunnel vision or general interference? Cognitive load and attentional bias are both important. *The American Journal of Psychology*, 101, 171–191.
- Wright, P. (1974). The harassed decision maker: Time pressures, distractions, and the use of evidence. *Journal of Applied Psychology*, 59, 555–561.
- Young, M. S., & Stanton, N. A. (2007). What's skill got to do with it? Vehicle automation and driver mental workload. *Ergonomics*, 50, 1324–1339.
- Zhai, S., Accot, J., & Woltjer, R. (2004). Human action laws in electronic virtual worlds: An empirical study of path steering performance in VR. *Presence: Teleoperators and Virtual Environments*, 13, 113–127.