IS ELECTRIC VEHICLE DRIVERS' COGNITIVE WORKLOAD INCREASED BY ECO-DRIVING FEEDBACK IN THE FACE OF RANGE ANXIETY?

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July 08, 2021

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In collaboration with the BMS lab

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Abstract

The introduction of electric vehicles is a way to reduce the high contributions of the transport sector to CO2 emissions. Eco-driving feedback is often employed to reduce range anxiety in electric vehicles, but can also affect cognitive workload. Increases in cognitive workload pose safety risks when they interfere with driving. In the current study, effects of range anxiety and eco-driving feedback on cognitive workload are investigated. For this, 23 participants holding a driver's license took part in a VR-simulated experiment. They drove for five minutes in each of the four conditions. These were divided into low range (LR) and high range (HR) situations and depending on whether efficiency feedback was shown (marked by adding /F to the condition). This resulted in the conditions of HR/F, LR/F, HR, and LR. After each condition, levels of range anxiety and cognitive workload were measured. Range anxiety and cognitive workload were strongly correlated (r=.66). Cognitive workload was significantly higher for the conditions in which eco-driving feedback was shown. Eco-driving feedback did not moderate the effect of range anxiety on cognitive workload. These findings inform the design of in-vehicle information systems in electric vehicles. Future research should investigate ways to reduce effects on cognitive workload.

Keywords: Cognitive Workload, Driving Simulator, Eco-driving Feedback, Efficiency Gauge, Electric Vehicle, In-Vehicle Information System, Range Anxiety

1. Introduction

As global warming is a growing concern, preventive actions are taken. It is widely recognised that the average atmosphere temperature rises due to anthropogenic activities, i.e. human influences (Powell, 2017). Electric vehicles (EVs) have the potential to reduce negative anthropogenic effects on the environment (European Parliament, 2019; Trinomics BV, 2018). However, a disadvantage of EVs is their limited range and the resulting anxiety of not reaching one's destination (Eisel et al., 2016). Eco-driving advice may be given to EV drivers to alleviate this anxiety (Eisel et al., 2016; Rauh et al., 2017). Despite the proven effectiveness of feedback on eco-driving behaviour and reduced anxiety, providing continuous feedback poses a safety risk as it can increase drivers' cognitive workload (Benedetto et al., 2014; Jamson et al., 2015; Lansdown et al., 2004). In the current study, it is investigated whether range anxiety and eco-driving feedback influence the level of cognitive workload in a simulated EV driving situation.

1.1 Potential of Electric Vehicles

Minimising anthropogenic effects on global warming poses challenges especially to the transport sector, which contributes nearly 30% to the EU's total CO2 emissions, thus being the sector with the highest CO2 emissions (European Environment Agency, 2020; European Parliament, 2019). Road transportation contributes 72% to transport emissions with passenger cars making up most of all transportation emissions with 60.7% (European Parliament, 2019). One promising way to reduce CO2 emissions in road transportation is by replacing fuel cars with EVs (European Parliament, 2019; Trinomics BV, 2018). As EVs are partially, i.e. plug-in hybrid electric vehicles (PHEV) or fully, i.e. battery electric vehicles (BEV), electrically powered, they do not emit greenhouse gases in electric mode. Powering EVs increasingly from renewable sources – as is planned in the future - further improves the eco-friendliness of EVs as compared to conventional vehicles (European Parliament, 2019). Despite the recent growth in sales to 10.5% in 2020, the market share is still considered too low for the desired environmental effects (European Alternative Fuels Observatory, 2020; Trinomics BV, 2018). Multiple studies indicate that limited range and resulting expected range constraints is considered a key drawback of EVs (Egbue & Long, 2012; Haddadian et al., 2015; Noel et al., 2019). Therefore, in increasing EV popularity, limited range and ways of dealing with this have to be considered.

1.2 Range Anxiety

Drivers may experience psychological discomfort due to the limited distance range of their EV, commonly labelled as "range anxiety" (Noel et al., 2019). Rauh et al. (2015) describe range anxiety as a "stressful experience of a present or anticipated range situation, whereby the range resources and personal resources available to effectively manage the situation (e.g., increase available range) are perceived to be insufficient" (p. 178). Stress can be divided into the four main facets of cognition, emotion, behaviour, and physiology. An example of expressing range anxiety along these four aspects of stress are concerns about not reaching one's destination, fear or nervousness as a result of such concerns, looking at range displays more frequently and adapting one's driving style, and a heightened heart rate, respectively (Rauh et al., 2015). Thus, range anxiety is a form of stress experienced on cognitive, emotional, behavioural, and physiological dimensions.

Rauh's et al. (2015) notion of range anxiety is derived from Lazarus and Folkman's (1984) Transactional Model of Stress which proposes that individuals make two forms of appraisal before responding to a potentially stressful situation. As a primary appraisal, an individual interprets it as a threat and/ or challenge to determine whether the situation poses implications for their well-being. If this is the case, the person then assesses whether coping options are available to deal with the situation in a process labelled as secondary appraisal. The individual assesses the situation according to expectations relating to their self-efficacy and in how far the situation can be controlled. The interaction between these two appraisals influence the experienced stress level. To conclude, range anxiety can be conceptualised as the stress response resulting from primary and secondary appraisal of range situations.

The degree of experienced range anxiety depends on multiple factors. Franke et al. (2016) found that tolerance of low range and trustworthiness of range estimation systems are critical factors influencing range anxiety. Range estimation systems reflecting the degree of uncertainty in range predictions by giving broad rather than precise range predictions are considered more trustworthy and prevent aggressive driving in critical range situations (Jung et al., 2015). Bingham et al. (2012) suggest that energy consumption is over 30% higher for aggressive driving styles as compared to moderate driving. Saving energy is not only eco-friendly, but also helps EV drivers to use their range efficiently (Franke et al., 2016). Furthermore, range anxiety may be increased in critical range situations, i.e. when driving with limited resources (Jung et al., 2015). Next to helping drivers make better use of the range, i.e. by adopting an eco-driving style, ways of dealing with range anxiety and its impact on driving have to be addressed.

1.3 Eco-Driving Feedback

To alleviate range anxiety, EV drivers may receive coping information on how to save energy, i.e. driving eco-friendly. Rauh et al. (2017) found that providing instructions on how to drive energy efficiently, before and during driving via phone contact with the experimenter improves secondary appraisal of the range situation. Continuous feedback can be given through in-vehicle information systems (IVISs). Eisel et al. (2016) used IVISs presenting drivers with a navigation system, charging points, and a range gauge. As a result, critical range situations were perceived as less threatening and challenging.

The form in which this feedback is given has implications for its acceptance, effectiveness, and the safety of the driver (Fricke & Schießl, 2011; Jamson, 2015; Jung et al., 2015). Fricke and Schießl (2015) found that for promoting eco-friendly driving, a simple colour-coded display showing the momentary consumption rate was preferred over other visualisations of IVISs. Furthermore, continuous visual feedback has a greater effect on eco-driving than haptic feedback (Jamson et al., 2015). To conclude, visual and continuous real-time feedback is most efficient in promoting an eco-driving style and can assist drivers in dealing with their EVs' range.

1.4 Cognitive Workload

Despite alleviating range anxiety and promoting eco-efficient driving, visual feedback of IVISs may increase driver's cognitive workload. In this paper, the definition of Wickens (2002) was adopted which describes cognitive workload as the relation between resource demands of a task and resource supply capacities of the operator. Wickens' (2002) Multiple Resource Theory models how simultaneous tasks may interfere with one another. Whilst some tasks can be performed next to each other with little interference, tasks that share the same processing resources cause mutual interference by occupying workload capacities that are needed for both tasks. This effect is accentuated for more difficult tasks, e.g. driving on a crowded highway while looking at a map. IVISs usually use the same workload capacities as driving, therefore potentially causing interference (Wickens, 2002). Thus, Multiple Resource Theory explains how IVISs and driving may interfere with one another due to shared processing resources.

Multiple studies found potential interferences of IVISs with driving through added cognitive workload. Jamson et al. (2015) observed that drivers looked at the dashboard display more often when it presented feedback on eco-driving performance. Interference is also reflected in drivers' subjective cognitive workload measured using the NASA-TLX as they reported increased mental, physical, and temporal demands as well as more effort and frustration when driving with visual feedback (Jamson et al., 2015). In line with this, Benedetto et al. (2011) observed an interference effect of an IVIS requiring visual and manual capacities on multiple measures of objective and subjective cognitive workload. In a study of Lansdown et al. (2004), higher cognitive workload on the NASA-TLX led to reduced driving performance, indicated by reduced speed, reduced headway to the front vehicle, and greater brake pressure. To conclude, visual feedback affects cognitive workload and interferes with the driving task which reduces driving performance. Thus, IVISs may increase drivers' cognitive workload and thereby pose a safety risk.

However, IVISs can be designed in a way that does not affect cognitive workload or with the potential to relieve it. Using an IVIS design based on ergonomic principles, Birrell and Young (2011) found that eco-driving feedback provided by the IVIS led to the desired driving behaviour and did not have an effect on drivers' subjective cognitive workload. These results suggest that designing IVISs through an ergonomic design process can lead to eco-friendly driving behaviour with little to no added effect on cognitive workload. Additionally, Hancock and Verwey (1997) suggest that adaptive IVISs can prevent information overload by presenting information when workload demands are low through in-vehicle and real-time estimation of visual workload. Thus, if IVIS are designed to be adaptive or with respect to ergonomic principles, increases in cognitive workload can be reduced or eliminated.

1.5 Current Study

The use of IVISs to mitigate range anxiety and potential to increase cognitive workload have become apparent. Whether range anxiety affects subjective cognitive workload as well was investigated. In critical range situations, cognitive workload demands may be particularly high due to increased range anxiety (Jung et al., 2015). Lazarus and Folkman's (1987) Transactional Model of Stress suggests that control expectancies and self-efficacy mitigates stress appraisals. Similarly, receiving coping information, e.g. eco-driving feedback, after appraising a situation as stressful, may mitigate the effect of range anxiety on cognitive workload. Therefore, cognitive workload demands due to range anxiety may be alleviated by providing eco-driving feedback.

The current study investigated how range anxiety and eco-driving feedback relate to subjective cognitive workload. Further, it was tested whether eco-driving feedback reduces cognitive workload under higher range anxiety. First, it is expected that perceived range anxiety and subjective cognitive workload are positively correlated. Second, subjective cognitive workload is expected to be significantly higher in conditions in which eco-driving feedback is given than in those without eco-driving feedback. Third, eco-driving feedback is suggested to moderate the relationship between perceived range anxiety and subjective cognitive workload. This would mean that the effect of range anxiety on cognitive workload is different when efficiency feedback is given. Eco-driving feedback is expected to mitigate the effect of range anxiety on cognitive workload.

2. Methods

The experiment was conducted as part of a bigger project. Therefore, not all measurements related to the current study. Each participant took part in four experimental conditions. The sequence of conditions was the same for every participant, starting with a high range condition including an efficiency gauge (HR/F), followed by low range including efficiency gauge (LR/F), high range excluding efficiency gauge (HR), and low range excluding efficiency gauge (LR), respectively.

2.1 Participants

In total, 23 participants took part in the study of which 20 were psychology and communication science students recruited via Sona-systems, a cloud-based participant management software. The others were recruited using opportunity sampling, i.e. drawn from the personal network of the researchers. To take part in the study, participants were required to be at least 18 years old, own a drivers' licence, not to be pregnant, and have no known tendency to get motion sick. Furthermore, participants could not participate when they had visual impairments that they could not compensate for by wearing contact lenses. Due to the VR glasses, participants who were normally wearing corrective glasses, were asked to wear contact lenses. No participants had to be excluded from the experiment. Of all participants, 14 were female, eight male, and one non-binary, with an age range from 18 - 29, a mean of 21.4, and a standard deviation of 2.4. Further, 17 were German, four Dutch, and two had another nationality. Prior to the start of the study, the simulated driving tasks and questionnaire was approved by the BMS ethics committee of the University of Twente.

2.2 Materials

A high fidelity driving simulator was used with VR equipment. Participants were asked to fill in a questionnaire including two scales to report levels of cognitive workload and range anxiety after each simulated driving task and to provide some demographic data prior to the study.

2.2.1 Hardware

Participants were presented with the virtual environment via a Varjo VR-2 headset and operated the virtual car using a Logitech G920 Driving Force steering wheel including pedals. In accordance with most electric vehicles on the market, the simulated car used an automatic gearbox. Participants only had to steer and use the accelerator pedal as well as the braking pedal. An adjustable Playstation seat was mounted on a Next Level Racing frame together with the pedals and steering wheel (Figure 1).

Figure 1

Driving Simulator Setup

2.2.2 Software

An Alienware Windows 10 computer was used to run the experimental setup. The headset was tracked and calibrated with SteamVR. Varjo was used to calibrate the participants' eyes and record their screen including a gaze dot. The driving simulation was programmed and run in Unity (2019.2.21f1). Assets used for the simulation include the Fantastic City Generator (Figure 2), intelligent Traffic System (iTS), Vehicle Physics v1 by NWH, and Logitech Gaming SDK.

The virtual environment showed a city road system consisting of buildings, trees, directional signs, and four way roads with integrated traffic lights as well as other simulated vehicles. Most of the buildings were high or skyscrapers. One subway was integrated into the environment. Next to other vehicles including cars, vans, and busses, no bicycle drivers or pedestrians were simulated. The traffic was moderate and did not change in amount over the course of the experiment. The weather was constantly clear. Next to directional signs, no other road signs were shown in the environment. Figure 2 shows a photo of the city built using the Fantastic City Generator.

Figure 2

Virtual Driving Environment

2.2.2.1 Car Interior. Participants were seated in a four-seater Sedan car. Interior as well as exterior mirrors were not functional in the simulation used for the experiments due to time constraints. The dashboard behind the steering wheel was adapted from a common combustion vehicle's one and consisted of three displays providing feedback updated in real-time (Figure 3). On the right, a speedometer was shown ranging from 0 to 260 km/h and indicating the current speed with which the participant was driving. A colour-coded battery indicator was shown in the middle of the dashboard. During two high range situations, i.e. the HR and HR/F conditions, the battery was green and displayed 80% of full capacity at the start of the simulated scenarios (Figure 3). In the other two situations, i.e. the LR and LR/F conditions, the battery was red and displayed a charge of 20% (Figure 4).

Figure 3

Dashboard With Efficiency Gauge and High Battery Status in the HR/F Condition

Figure 4

Dashboard With Efficiency Gauge and Low Battery Status in the LR/F Condition

The battery level dropped slightly over the course of each condition based on time. On the left, an efficiency gauge was shown indicating the extent to which participants were driving eco-friendly. A needle indicated the current driving efficiency on a circular display fading from green on the left side over yellow on top to red on the right side. Efficiency was calculated by constancy of speed. Momentary speed values were compared to each other; the higher the difference in speeds - and thus speed of acceleration - the lower was the displayed efficiency. Therefore, the needle moved to the red zone on the right during times of fast acceleration and braking. The needle stayed in the green zone on the left when speed was held constant or during slow acceleration or braking. Thus, the constantly updating efficiency gauge reflected the momentary eco-friendliness of the participants' acceleration and braking behaviour. The efficiency gauge was only present in the HR/F and LR/F conditions; a non-functional display was shown in the HR and LR conditions. Figure 5 shows the driver's view on the dashboard when seated in the HR condition.

Figure 5

Dashboard Without Efficiency Gauge and High Battery Status in the HR Condition

2.2.3 Routes

Participants were verbally instructed to follow one of four predetermined routes (Appendix A). Per condition, one of the four routes was randomly picked for verbal navigation. As soon as the participant started driving, a timer of five minutes was started. Instructions were given by the researchers and kept as short as possible e.g. "Turn left at the next intersection." After five minutes of driving, participants were asked to stop at the next possible - by the researcher determined - position on the route, e.g. "we are done with this round, please stop after this turn." Therefore, participants were driving roughly five to six minutes in every condition. Routes were alternated after each condition so participants did not drive the same route twice.

2.2.4 Tasks

Participants were presented with four consecutive driving scenarios. Before the first condition (HR/F), participants were explained the dashboard, i.e. speedometer, battery, and efficiency gauge. They were instructed to drive as they normally would and under consideration of traffic laws. Prior to each condition, a researcher picked a route and instructed the participants as described under 2.2.3. Participants were not given any speed restrictions. The simulation was stopped after the participant stopped the car.

Prior to the LR/F and LR conditions, participants' attention was drawn to the low battery display. Participants were told that they would have 2 km left to drive. Additionally, a researcher told them that it would be possible for them to run out of battery, which some participants before them had indeed experienced. They were instructed to drive as they normally would under these conditions. This was done to induce more range anxiety during the two low range conditions. After giving these LR/F and LR specific instructions, participants were instructed following the same procedure as before.

2.2.5 Questionnaire

All questions were answered in an online form which participants were asked to open at the beginning of the experiment and go back to after each driving condition. The scales presented below were filled out after each condition. These were introduced with "The following are some questions in regard to your driving experience with the simulator." As the current study was part of a larger project, one additional questionnaire was administered after each condition that is not included here.

2.2.5.1 PASA. The Primary Appraisal Secondary Appraisal (PASA) questionnaire is based on the Transactional Model of Stress and is used to measure perceived range anxiety (Gaab, 2009; Lazarus & Folkman, 1984; Rauh et al., 2015). Prior to the start of the experiment, the PASA was translated from German to English and back by two researchers proficient in German and English independently (Appendix B). Forward translation, i.e. translation from German into English, was performed by an English native speaker proficient in German, whilst a German native speaker proficient in English translated the questionnaire back into German. The researchers oriented themselves on the procedure of forward-backward translation (WHO, 2016 as cited in Toma et al., 2017). Forward-backward translation has been found to be a suitable translation method and has been used to translate other questionnaires in the past (Lee et al., 2018; Toma et al., 2017). The PASA is composed of 4 subscales making up a total of 16 items. The first two subscales, threat and challenge, measure primary stress appraisal, whereas the other two subscales, self-confidence in one's abilities and control expectancies, measure secondary stress appraisal. Items were formulated in the form of statements to which participants responded to on a 6-point Likert scale ranging from *Strongly disagree* (1) to *Strongly agree* (6). Mean scores of each subscale and all items in total were computed. This questionnaire was administered first after each driving condition.

2.2.5.2 NASA-TLX. The NASA Task Load Index (NASA-TLX) is a questionnaire assessing subjective cognitive workload and is composed of six subscales, namely mental demand, physical demand, temporal demand, performance, effort, and frustration. The NASA-TLX was the second one administered after driving, directly following the PASA questionnaire. Participants were asked to rate each of the six scales from *Very low* (0) to *Very high* (100) in steps of five points. Scores below 50 indicate low cognitive workload demands, whereas scores above 50 indicate high ones. For this study, the subscales of the NASA-TLX were averaged without prior comparisons of each item's importance as is originally the case. This modification is known as the raw TLX and is used to facilitate replicability. The resulting score is a mean of the six subscales and lies between 0 and 100 (Grier, 2016).

2.3 Design

For this study, a 2 (low vs high range situation) x 2 (efficiency feedback presented vs no efficiency feedback presented) within-subjects design was chosen. The independent variables were range indicated by battery level and the presence of the efficiency gauge. The dependent variables were perceived range anxiety as measured by the PASA questionnaire and subjective cognitive workload as measured by the NASA-TLX.

2.4 Procedure

The driving simulator of the BMS lab of the University of Twente was used. In line with local preventive COVID-19 measures, all present people were wearing a face mask, at least one window of the simulator room was open during the entire time of the experiment, and no more than three people stayed in the room at a time. At least one, but mostly two researchers were present per participant. All equipment of the driving simulator was disinfected prior to the arrival of each participant. The experiment took roughly 90 minutes for each participant.

Upon arrival, the participant and acting researchers filled in a consent form on compliance with COVID-19 regulations. After entering the simulator room, participants were explained the procedure of the experiment and offered to sit down in the driver's seat. If needed, they were instructed in adjusting their seat to a comfortable distance to the pedals. The researchers informed the participant about the possibility of experiencing motion sickness in which case they could pause or end the experiment without consequences. Participants were asked to open an online form on which they gave informed consent and provided some demographic information about themselves. A researcher explained the general set-up and functions of the simulator. For hygienic purposes, participants were handed an eye cover and hairnet.

The participant was helped with putting on the VR headset and adjusting it to a comfortable and secure position. Afterwards, a researcher started the simulation in Unity and adjusted the virtual viewpoint to the participant's preference matching their position in the physical set-up. For this, the participant was asked for confirmation or whether their position in the virtual car had to be adjusted. Thereby, the researcher also ensured that the participant was able to see both the dashboard and the road when sitting as they normally would.

Before the experiment started, participants were allowed to familiarise themselves with the simulation by driving around without interference by the researcher. Participants took roughly five to ten minutes to get used to the simulator, after which they let the researchers know that they were ready to start with the experiment. After the test drive, participants were asked whether they were feeling motion-sick and offered a break and some water. Before starting the experiment, participants were asked to perform an eye-tracking calibration with the VR headset. This entailed following a dot on the VR screen with their eyes. Then, the experiment started and participants completed the driving task as described under 2.2.4. The screen was recorded in all experimental conditions.

After each experimental condition, the VR headset was taken off and participants filled in the next part of the online questionnaire, including the PASA and NASA-TLX, after every condition. They were offered a small break between the first and second as well as third and fourth conditions. A longer break was offered after the first two conditions so participants could drink some water and go to the restroom. Before each consecutive condition, the eye-tracking was calibrated and the participant had to be positioned in the car again. After completion of all four conditions and respective questionnaires, participants could pose questions or make remarks and were thanked for their participation.

2.5 Data Analysis

SPSS v25.0 including PROCESS 3.0 (Hayes, 2018) were used for data analysis. At first, descriptives and frequencies of participant demographics were computed. For the analysis of PASA and NASA-TLX scores, each condition was treated as an individual data entry. After restructuring the dataset and recoding reverse items, the PASA subscales and total PASA score were computed following the procedure of Gaab (2009) described in Appendix C. Mean scores of the NASA-TLX items were computed for each participant and condition and added to a general cognitive workload measure. The hypothesised moderation effect of eco-driving feedback on the relationship between perceived range anxiety and subjective cognitive workload was analysed using Hayes' (2018) PROCESS. It was tested whether the conditions in which feedback was given have an influence on the relationship between PASA and raw TLX scores.

3. Results

Before restructuring the data, descriptive statistics of participants' demographics and scores on the PASA and NASA-TLX scales including their subscales were computed. With a mean of 35.91 (*SD* = 16.16) and a possible range of 0 - 100, raw TLX scores were generally low to moderate. As the PASA mean score was negative with -1.22 (*SD* = 1.35), secondary appraisals (M = 4.18, SD = 0.68) were generally higher than primary appraisals (M = 2.96, SD = 0.83) on the PASA subscales. Descriptive Statistics of all PASA and NASA-TLX subscales can be found in Table 1.

Table 1

Descriptive Statistics of NASA-TLX and PASA Scales

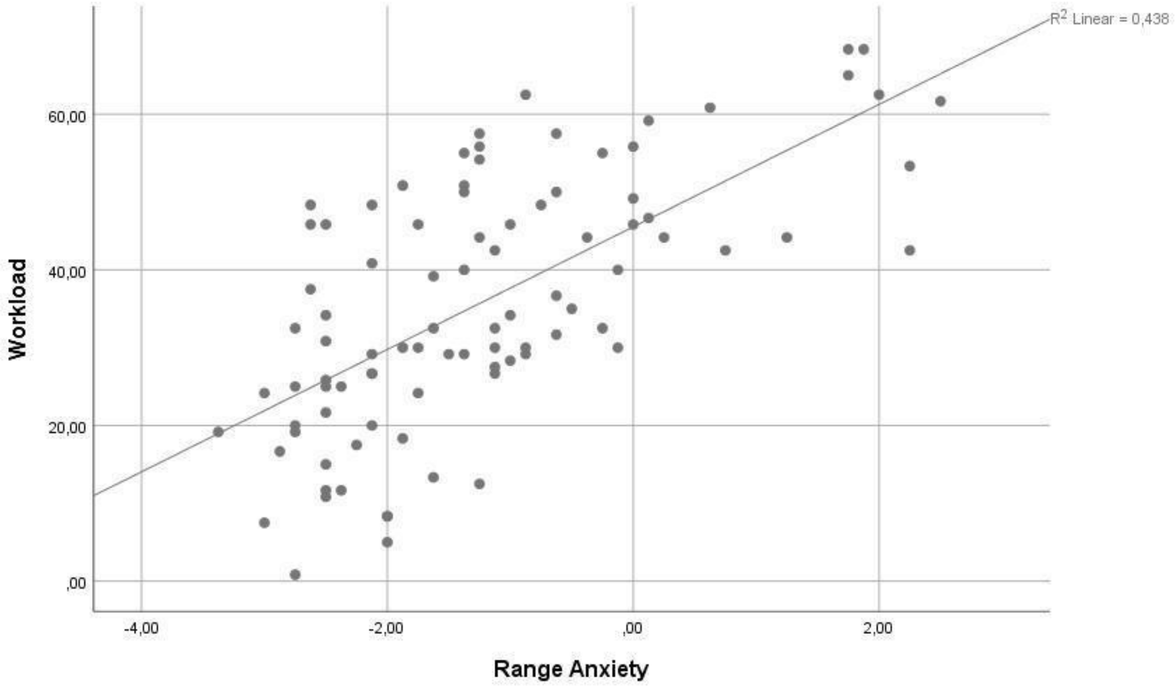
Scale	*M*	*SD*	Minimum	Maximum
raw TLX	35.91	16.16	0.83	68.33
Mental Demand*	49.67	25.62	0	100
Physical Demand	22.28	21.37	0	85
Temporal Demand	31.68	24.43	0	100
Performance	32.01	22.46	0	100
Effort	45.76	23.73	0	95
Frustration	35.11	27.43	0	100
PASA	-1.22	1.35	-3.38	2.50
Primary Appraisal	2.96	0.83	1.63	5.50
Threat	2.44	1.08	1.00	5.25
Challenge	3.49	0.70	2.00	5.75
Secondary Appraisal	4.18	0.68	2.13	5.25
Self-confidence in one’s abilities	4.03	0.77	1.75	5.50
Control expectancies	4.33	0.79	2.25	5.75

Note. n = 92 (*91), M = Mean, SD = Standard Deviation.

A Pearson correlation between PASA and raw TLX scores across all four conditions was run to examine the effect of perceived range anxiety on subjective cognitive workload. PASA and raw TLX scores were found to be significantly and strongly positively correlated, $r(91) = .66, p < .001$ (Figure 6). Thus, with increasing range anxiety, cognitive workload is also higher. To further investigate this effect, a t-test was run to compare the means of raw TLX score by battery level. No significant difference in mean cognitive workload scores in the low range and high range conditions the difference was found, $t(44) = -0.98$, $p = .33$. Thus, the correlation between PASA and raw TLX scores was not reflected in a significant difference in raw TLX mean scores for the range situations.

Figure 6

Scatterplot of PASA and Raw TLX Scores

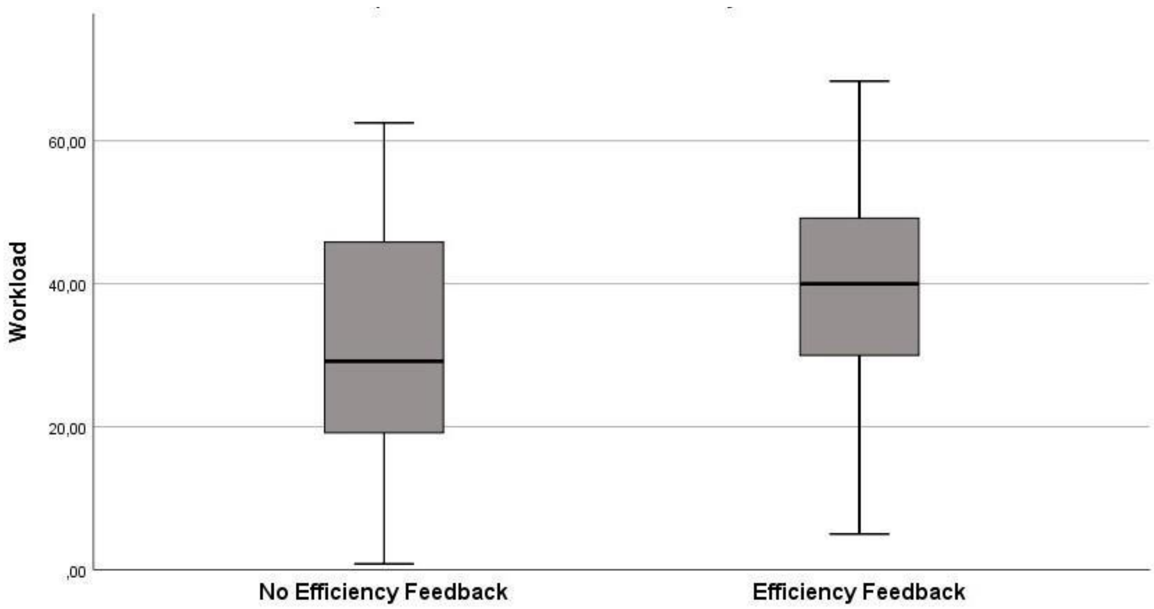


Further, Pearson correlations between the PASA and individual NASA-TLX item scores were run to identify relationships of the workload measures with range anxiety separately. This enhances replicability and comparability with studies using weighted NASA-TLX scores. A strong significant correlation was found for PASA scores and the frustration item, $r(92) = .60$, $p < .001$. Moderate significant correlations were found for PASA scores and the mental demand and temporal demand items as well as the reverse performance item with $r(91) = .52$, $p < .001$, $r(92) = .54$, $p < .001$ and $r(92) = .42$, $p < .001$, respectively. The correlation of PASA scores and physical demand was weak, $r(92) = .34$, $p < .001$. No significant correlation was found between PASA scores and the effort item, $r(92) = .17$, $p = .10$. Thus, the individual NASA-TLX items were differently correlated with PASA scores with no significant relationship for the effort item.

A t-test was performed to compare subjective cognitive workload scores depending on whether efficiency feedback was shown. Due to one missing raw TLX score, 90 out of the 92 data entries were compared. For the same reasons as done with the correlations, t-tests were run for each NASA-TLX item as well. As dependent variables, NASA-TLX item scores were compared by feedback and control conditions as the independent variable. Raw TLX scores were significantly higher for the feedback conditions ($M = 40.09$, $SD = 14.36$) as compared to the conditions in which no eco-driving feedback was given ($M = 31.70$, $SD = 17.09$), $t(44) = 4.25$, $p < .001$. As expected, raw TLX scores were higher in the conditions in which efficiency feedback was given than in the ones in which no efficiency gauge was present. Figure 7 illustrates the difference in raw TLX scores between conditions using boxplots.

Figure 7

Boxplots of Raw TLX Scores by Efficiency Feedback Conditions



Additionally, t-tests were run for each workload item individually to compare means of separate workload items depending on whether efficiency feedback was shown. Mental demand was significantly higher in the feedback conditions (M = 12.24, SD = 4.29) than the control conditions (M = 9.60, SD = 5.73), $t(44) = 4.08$, $p < .001$. Participants also rated frustration significantly higher in the conditions in which efficiency feedback was given (M = 8.85, SD = 5.33) than in those, in which no efficiency feedback was shown (M = 7.20, SD = 5.71), $t(45) = 3.23$, $p = .002$. For temporal demand, the efficiency conditions were rated significantly higher (M = 8.50, SD = 5.06) than control conditions (M = 6.17, SD = 4.46), $t(45) = 3.60$, $p < .001$. In the efficiency conditions, participants also rated effort significantly higher (M = 11.24, SD = 4.21) as compared to the control conditions (M = 9.07, SD = 5.04), $t(45) = 2.52$, $p = .02$. Physical demand was also significantly higher in the feedback conditions (M = 6.00, SD = 4.24) than the control conditions (M = 4.91, SD = 4.28) as well, $t(45) = 2.30$, $p = .03$. The difference was not significant for the reversed performance item, $t(45) = 1.00$, $p = .32$. In conclusion, differences in item mean scores depending on whether efficiency feedback was shown were found for all NASA-TLX items except the item performance.

A moderation analysis was run with efficiency feedback as the moderator on the effect of range anxiety on cognitive workload. Efficiency feedback was not found to moderate the relationship between PASA and raw TLX scores as the interaction effect with a coefficient of -.50 was not significant (p = .79). Thus, the direction or strength of the correlation between PASA and raw TLX scores was not significantly different depending on whether efficiency feedback was shown.

To conclude, perceived range anxiety and eco-driving feedback both had a positive effect on cognitive workload, but eco-driving feedback did not moderate the effect of range anxiety on cognitive workload.

4. Discussion

The aim of the current study was to identify the effects of perceived range anxiety and the provision of eco-driving feedback on driver's subjective cognitive workload. Range anxiety as well as eco-driving feedback increased subjective cognitive workload. Eco-driving feedback did not interact with range anxiety to moderate the relationship between range anxiety and cognitive workload. These findings are in line with the first two hypotheses stating that range anxiety and eco-driving feedback individually increase subjective cognitive workload. However, the third hypothesis, i.e. eco-driving feedback moderates the effect of range anxiety on cognitive workload, was not confirmed.

4.1 Range Anxiety and Cognitive Workload

It was found that perceived range anxiety has a strong effect on subjective cognitive workload. According to the Multiple Resource Theory of Wickens (2002), this indicates that range anxiety and cognitive workload while driving occupy the same processing resources i.e. cognitive appraisal of the remaining driving range interferes with the processing demands of driving. As Lansdown et al. (2004) found that interference with driving in terms of cognitive workload demands reduced driving performance, experiencing range anxiety poses safety risks. Considering the Transactional Model of Stress, range anxiety may increase cognitive workload as it results from cognitive appraisals (Lazarus & Folkman, 1984). By appraising a situation as stressful, dealing with range anxiety implicates increased cognitive workload which can reduce safety.

The correlations of range anxiety and cognitive workload items were particularly strong for the frustration, temporal demand, mental demand, and performance items. This indicates that range anxiety particularly interferes with these aspects of cognitive workload while driving. When experiencing range anxiety, drivers may feel more frustrated and rushed, consider driving more mentally demanding, and think their driving performance suffers.

The current study did not find a significant relationship between the range situation and cognitive workload, which means that range itself does not predict cognitive workload demands. In contrast, previous research found that levels of range anxiety are higher in critical range situations (Franke et al., 2016; Jung et al., 2015). However, there are more factors than range that influence range anxiety. The current finding supports previous literature identifying range as less important in predicting range anxiety than personal characteristics such as tolerance of low range, experience with EV driving, and trust in the EV's range estimation system (Franke et al., 2016; Rauh et al., 2015). In conclusion, cognitive appraisal of range situations influenced cognitive workload while the situation itself did not.

4.2 Eco-Driving Feedback and Cognitive Workload

In line with the original expectations, drivers' cognitive workload was increased when eco-driving feedback was given. This indicates that, as proposed by Wicken's (2002) Multiple Resource Theory, using eco-driving feedback and driving share the same processing resources. The current findings confirm previous results showing that eco-driving feedback increases cognitive workload (Benedetto et al., 2011; Jamson et al., 2015). However, eco-driving feedback did not have a significant effect on perceived performance in the current study, which was different in the study of Jamson et al. (2015). Allison et al. (2020) did not find a significant effect of eco-driving IVISs on performance either, but identified main effects for mental demand and effort. Some of the workload items may be more relevant for driving than others. In this study, the strongest differences in perceived cognitive workload were found for mental and temporal demand as well as frustration.

The current efficiency gauge is similar to effective and liked IVISs in previous studies (Fricke & Schießl, 2011; Jamson et al., 2015). However, the efficiency gauge in the current study affected cognitive workload. As previously shown by Birrell and Young (2011), IVISs do not necessarily increase cognitive workload if they are designed according to ergonomic principles which was not the case for the current efficiency gauge. This may explain why eco-driving influenced cognitive workload in the current study.

4.3 Range Anxiety, Eco-Driving Feedback, and Cognitive Workload

Counter to expectations, eco-driving feedback did not moderate the effect of range anxiety on cognitive workload. This means that eco-driving feedback does not help drivers deal with their range anxiety in a way that reduces cognitive workload. Particularly when experiencing higher range anxiety, when eco-driving feedback should help drivers cope with it, cognitive workload was high. Since previous studies found that higher cognitive workload is linked to lower driving performance, the additional impact of eco-driving feedback on cognitive workload even under high range anxiety, poses a safety risk (Jamson et al., 2015; Lansdown et al., 2004). Musabini et al. (2020) found that an extensive IVIS in EVs can reduce expressions of range anxiety on its behavioural and physiological dimensions. These findings may not hold true for the effect of range anxiety on cognitive workload and for an IVIS reduced to the provision of efficiency feedback. To conclude, providing eco-driving feedback using an efficiency gauge may not be a sufficient coping resource to deal with range anxiety.

4.4 Practical Implications

Range anxiety is a phenomenon that EV drivers experience more frequently than drivers of combustion vehicles. Due to its strong effect on cognitive workload, ways have to be identified to mitigate this effect as well as range anxiety itself. Assisting EV drivers to cope with their limited range, e.g. through IVISs providing eco-driving feedback can mitigate range anxiety (Eisel et al., 2016; Franke et al., 2016; Musabini et al., 2020).

As the current study found that the efficiency gauge increases cognitive workload and does not mitigate the effect of range anxiety on cognitive workload, it did not add value in this respect. Due to safety risks, eco-driving feedback should be given in a form that does not lead to cognitive overload and thereby interfere with driving (Jamson et al., 2015; Lansdown et al., 2004). To minimise interference with driving, haptic feedback may be preferred (Jamson et al., 2015; Wickens, 2002) or the current efficiency gauge may be adapted to ergonomic principles (Birrell and Young, 2011). Generally, the prioritised goal in the design of eco-driving IVISs should be safety in terms of preventing cognitive overload instead of effectiveness in promoting eco-driving (Jamson et al., 2015; Lansdown et al., 2004). In the current study, the tested efficiency gauge did not lead to strong increases in workload, which indicates that cognitive overload due to the efficiency gauge is unlikely. Thus, it may be used as an eco-driving IVIS. However, it should be further researched whether it interferes with the driving task and thus potentially risks safety in a real EV.

Furthermore, as eco-driving feedback did not reduce the effect of range anxiety on cognitive workload, other factors have to be found or IVISs designed to decrease this effect when range anxiety occurs. As a way to cope with range anxiety, Lundström and Bogdan (2012) propose an IVIS estimating the required average efficiency with which EV drivers have to drive to complete their predetermined route. Such an IVIS is a promising tool next to eco-driving feedback to help drivers deal with range anxiety.

4.5 Strengths and Limitations

The VR-Simulator is in continuous development and the study was conducted in a limited time frame which gave rise to some limitations.

4.5.1 VR-Simulator and Driving Experience

One limitation relates to the fact that the simulated car did not perfectly reflect a real EV. As the simulator incorporated a combustion vehicle that was adapted to look and behave like an EV, some parts did not completely resemble those of an EV. In a real EV, the dashboard may look more complex or has a different setup. Furthermore, multiple participants reported the steering wheel as well as gas and braking pedals to be too sensitive. Some said this made it difficult to drive eco-efficiently. The oversensitivity of the pedals also hindered full immersion into the environment for some as it seemed unrealistic to them. This means that drivers may interact differently with eco-driving feedback in real EVs due to different dashboard setups and easier regulation of speed.

In addition, the effect of eco-driving feedback on the relationship between range anxiety and cognitive workload may be different in a real driving situation. Moreover, eco-driving feedback may reduce the effect of range anxiety on cognitive workload when it is easier to adjust one's driving style, i.e. in a real EV. Thus, the current findings relating to the efficiency gauge need to be replicated in a real EV, to confirm the current findings that the efficiency gauge increases cognitive workload and does not add value in terms of managing cognitive workload due to range anxiety.

Strengths of the simulator were that the vehicle responded to user input as a real automatic car would. The efficiency gauge was programmed in a way that mimics visualisations of driving efficiency in EVs well. Participants got used to the simulator quickly during the test condition, which means they experienced little difficulties with the simulator. Furthermore, the participants did not report high levels of motion sickness while driving. Thus, motion sickness did not influence their driving experience much.

4.5.2 Methodology

A confounding factor is the within subjects design with conditions always following in the same order. Range anxiety and/ or cognitive workload levels may have been influenced by previous conditions, thus confounding the actual effects of the conditions on these two variables. To exclude this possibility, a between subjects design may be chosen or the order of conditions randomised.

Cognitive workload was assessed subjectively after each condition. This means that variations in cognitive workload over the course of the scenario are lost. Furthermore, participants may not be fully aware of cognitive workload demands or cannot recall these afterwards as established in a review comparing measures of subjective and objective cognitive workload (Paxion et al., 2005). Situational fluctuations can be assessed by measuring cognitive workload continuously in real-time, e.g. using eye-tracking (Ahlstrom & Friedman-Berg, 2006; Hayhoe, 2004, Paxion et al., 2004). In a study of Ahlstrom and Friedman-Berg (2006), blink duration and pupil dilation revealed cognitive workload demands not reflected in retrospective ratings. Additionally, Hayhoe (2004) points out that eye-tracking is unobtrusive, i.e. it does not interfere with the driving task. Therefore, some information regarding cognitive workload may have been lost due to the use of a retrospective subjective measure instead of an objective real-time instrument such as eye-tracking.

A strength of assessing cognitive workload using the NASA-TLX is that the results can be easily compared across studies. The NASA-TLX is established as a thoroughly validated and reliable measure of subjective cognitive workload (Grier, 2016). In the current study, raw TLX scores were used to facilitate replicability of findings. If other studies computed cognitive workload scores on the NASA-TLX differently, the results can be compared to the reported individual item scores.

4.6 Further Research

The current study may inform future research on eco-driving systems and ways to mitigate cognitive workload as well as range anxiety's effect on it. Next to continuing research on ways to prevent range anxiety, factors can be investigated that potentially reduce its effect on cognitive workload. A different IVIS may be able to moderate the effect of range anxiety on cognitive workload. A promising example is an IVIS helping EV drivers cope with range anxiety by estimating how efficient they need to drive to reach their destination (Lundström & Bogdan, 2012). Environmental factors like weather and temperature may be taken into account in this estimation as well to facilitate accurateness of prediction (Donkers et al., 2020; Lundström & Bogdan, 2012). Influences of this kind of IVIS on cognitive workload should be investigated and weighed against its mitigation of the effect of range anxiety on cognitive workload. For this, the relationship of trustworthiness of a system to the IVIS's effect on cognitive workload may also be investigated. This would add to existing literature on trustworthiness of various range estimation systems and the relationship to driving styles (Franke et al., 2016). Research on the effect of various IVISs on cognitive workload informs the design of future IVISs that take into account safety considerations. Finding ways to decrease range anxiety or its effect on cognitive workload helps to increase the safety of future EVs.

Additionally, the current study could be replicated in an altered form that minimises its limitations. The sample could be extended to include people of various age groups. In a student sample, experience with EVs is likely to be lower as compared to older age groups. As Rauh et al. (2015) found that experienced BEV drivers experience less range anxiety, it is expected that range anxiety levels are lower in a sample with a more varied or older age group. A between-subjects design may be chosen with a larger sample size or randomised order of conditions to account for learning effects. Further, a future study could investigate the effect of range anxiety on real-time objectively measured cognitive workload to account for momentary fluctuations and subconscious cognitive workload demands using eye-tracking measurements (Ahlstrom & Friedman-Berg, 2006; Hayhoe, 2004, Paxion et al., 2004). This way, situational peaks in cognitive workload may also be determined to identify workload critical situations that need to be avoided. As a simulator cannot completely mimic the experience of driving a real car in which drivers may experience different levels of range anxiety and cognitive workload, IVISs should be tested in a real EV to confirm results of simulator studies.

4.7 Conclusion

Considering the potential of EVs to ameliorate the eco-friendliness of the transport sector, the influence of EV-specific factors such as range anxiety and eco-driving feedback on EV drivers' cognitive workload have to be dealt with. In the current study, the effects and relationship between eco-driving feedback and range anxiety on EV drivers' cognitive workload were investigated. Eco-driving feedback and range anxiety both affected cognitive workload. Further, eco-driving feedback did not mitigate the effect of range anxiety on cognitive workload. To conclude, eco-driving feedback should be given in a form that does not impact driving through increased workload and other ways to reduce the effect of range anxiety on cognitive workload have to be found to prevent overload.

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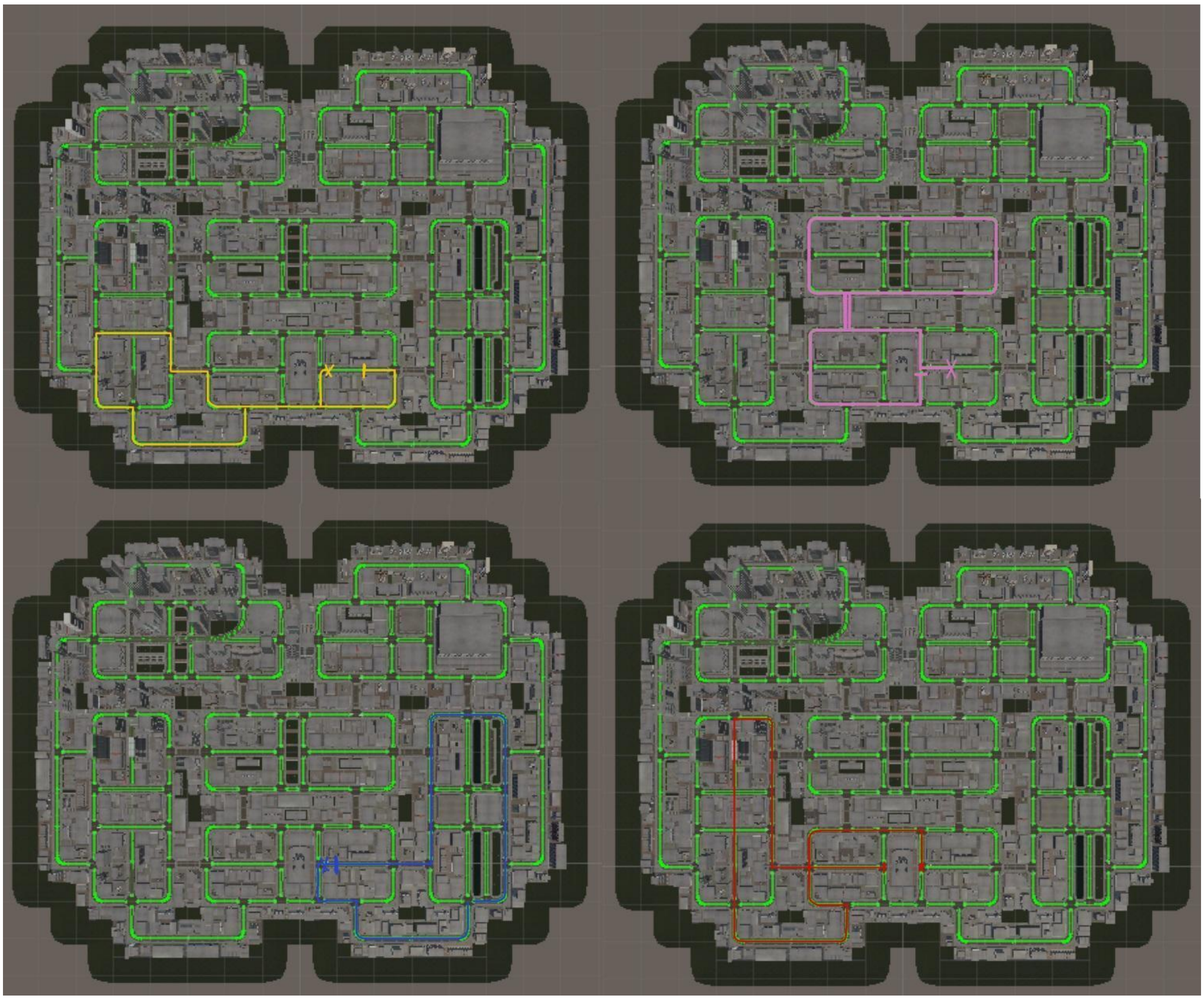
Appendices

Appendix A

Routes

Figure 8

Maps of The Driving Environment Showing The Four Predetermined Routes



Appendix B

PASA translated into English adapted from Gaab (2009)

1. I do not feel threatened by the situation.

2. The situation is of relevance for me.

3. In this situation, I know what I can do.

4. It is mostly dependent on me whether I can manage the situation.

5. The situation is uncomfortable for me.

6. The situation leaves me unbothered.

7. I do not know at all what I should do now.

8. Through my behaviour I can protect myself the best against failure.

9. I do not feel uneasy because the situation is not a threat to me.

10. The situation is not a challenge to me.

11. In this situation I can think of many alternatives how to act.

12. I can determine much of what happens in this situation myself.

13. This situation scares me.

14. This situation challenges me.

15. For this situation I can think of many solutions.

16. When I manage the situation, it is because of my effort and my personal involvement.

Appendix C

Calculation of PASA Scales adapted from Gaab (2009)

Reversed items:

1, 6, 7, 9, 10

Primary scales:

Threat: 1, 5, 9, 13

Challenge; 2, 6, 10, 14

Self-confidence in one's abilities: 3, 7, 11, 15

Control Expectancies: 4, 8, 12, 16

Secondary scales:

Primary Appraisal: (Threat + Challenge) / 2

Secondary Appraisal: (Self-confidence in one's abilities + Control Expectancies) / 2

Tertiary Scale:

PASA: Secondary Appraisal - Primary Appraisal