Bachelor Thesis

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Tools of the future, anxiety of the past? Looking at the influence of an eco-feedback display on range anxiety within a simulated electric vehicle

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Abstract

While the range of electric vehicles (EVs) has steadily increased over time, range anxiety remains an issue commonly experienced by drivers. Range anxiety can be described as the fear to become stranded due to an empty battery. This anxiety is influenced by the user's ability to cope with range anxiety inducing situations, their preferred amount of range when going for a drive, and the resources they have available to increase their range. A way to increase the drivers' coping skills is by encouraging their eco-driving behavior. Eco-driving behavior encompasses the behaviors that prolong range, these behaviors include driving slowly, using stop and go driving to utilize the EVs regenerative braking, and accelerating moderately. Encouraging this behavior can be done using an eco-feedback display that informs the driver of how efficiently they are driving. To study the effect of such a display on range anxiety participants underwent four conditions. Each participant underwent a high and a low range anxiety condition, first with the eco-feedback display present and afterwards without the eco-feedback display. Each condition was followed by a questionnaire from which the resulting range anxiety scores, range buffer values, and driving style indicators were examined. An analysis of variance showed that the eco-feedback display had no effect on the experienced range anxiety. However, an analysis of variance showed that setting a range buffer was associated with range anxiety and the eco-feedback display. Where the eco-feedback display led to higher range buffers with low range anxiety and low range buffers with high range anxiety. While the opposite occurred without the eco-feedback display.

Keywords: Range Anxiety, Electric Vehicles, Eco Feedback Display.

Introduction

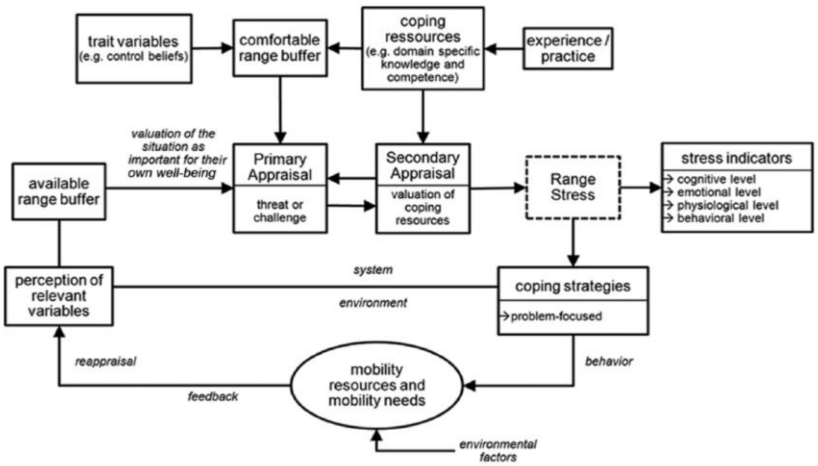
While the ambitious target of the European Commission regarding emission-free passenger transport by 2050 is highly reliant upon the electrification of mobility, diffusion of electric vehicles (EVs) within the EU has been marginal (Biresselioglu et al., 2018). Many barriers regarding the uptake of EVs, ranging from commercial to individual and technical to societal, have been identified and examined (Biresselioglu et al., 2018; Haddadian et al., 2015). One that is prominent among individuals is the problem of limited driving range. While this range has significantly increased over the past years with the average new EV model in Europe having a range of 314 km, running from 95 km to as high as 750 km, and 85% of car trips already being achievable with a single charge, range anxiety persists ("EV Database", 2021; Melliger et al., 2018). This is partially caused by users tending to overestimate their range needs, deeming the range to be insufficient. This results in a large barrier for uptake and contributes to the psychological phenomena of range anxiety (Bonges & Lusk, 2016; Franke et al., 2012; Zaunbrecher et al., 2015). Ecological driving can help reduce energy consumption, allowing users to utilize more of the EVs available range (Araque et al., 2018; Bingham et al., 2012). Several in-vehicle information systems (IVIS) providing eco-feedback have been examined and found to be effective in encouraging eco-driving behavior (Perelló-March et al., 2019). However, limited research is available on the effects of such tools on range anxiety. Therefore, the current study examines the effect of a simulated IVIS providing eco-feedback on the experienced range anxiety.

Range Anxiety

Range anxiety is the fear of becoming stranded due to an empty battery. This can occur both during a drive or prior to driving (Lundström et al, 2012). Franke et al. (2012) elaborated upon this concept by dividing the notion of range into several components, the most relevant being the comfortable range. This is the actual used range between charges, or lowest remaining range status while still comfortable. It is when this comfortable range is not met and users enter or anticipate entering a critical range situation that range anxiety or everyday range stress (ERS) occurs (Franke et al., 2016).

Figure 1

Range anxiety framework (Rauh et al., 2015)



Rauh et al. (2015) conceptualized this range anxiety within a framework (Figure 1). In this framework the driver appraises the situation through primary and secondary appraisal. Depending on the users' coping resources and range buffer, these appraisals can lead to an increase or decrease within the experienced range anxiety. It is stated that when the available range buffer does not meet the comfortable range buffer the user will primarily appraise the situation as a threat and/or challenge. Then, if coping resources are found to be insufficient the situation will be appraised again, by the secondary appraisal, as a threat and stress will occur. If coping resources and strategies are thought to be sufficient the situation will be seen as challenging and less threatening, leading to a reduction in stress. In turn, higher availability of coping resources also influences the comfortable range buffer, causing disrepancies between available and comfortable range buffer to decrease. The way a user utilizes these coping resources is called their coping startegy and equates to the users' ability to maximize the available range. It was found that experienced drivers are better in this regard due to their eco-driving abilities which increase range (Rauh et al., 2015). Thus, the current study aims to utilize this framework to examine range anxiety through participant's appraisals and seeing what effect an eco-feedback tool could have upon this and the range buffer.

A way for users to increase range would be through practicing eco-driving behavior. Since EVs have energy saving advantages with low average speeds and frequent stops, but decrease in efficiency with fast, erratic driving, stimulating energy saving would allow for less wasted range (Yuan et al., 2015; Araque et al., 2018). Rauh et al., (2015) demonstrated that this eco-driving behavior already occurs in experienced drivers, who in turn experience less range anxiety due to this being a coping strategy that they can utilize in critical range situations. By narrowing the gap between comfortable range buffer and available range buffer through eco-driving it is thought that range anxiety will decrease, as users have better coping strategies to utilize the available range in critical range situations and in turn will appraise the situation as less threatening (Rauh et al., 2015).

Eco-driving displays

One way to improve coping strategies would be through eco-driving behavior, as this can increase range and therefore partially alleviate range anxiety. The ecological driving behaviors in EVs differ from those within internal combustion engine vehicles (ICEVs) and therefore drivers must adjust and learn how to utilize them to increase range. Several possibilities have been researched to support this learning process. Neumann et al. (2015) suggest additional interfaces within the display to inform drivers of their energy consumption and by proxy the range prolonging factors and propose that this could be beneficial for both experienced and inexperienced drivers. Hibberd et al. (2015) have found visual displays using color gauges to be effective for energy saving, however mostly focused on comparisons with haptic and audio-feedback. In a comparable study, Perelló-March et al. (2019) found a visual display to be most effective for energy saving. Considering that the energy saving properties of these displays are due to the increased coping skills of the driver, displays such as these should be effective in their ability to stimulate and inform drivers about energy-saving behavior and therefore decrease range anxiety. This leads to the first hypothesis; drivers experience less range anxiety when an eco-feedback display is provided, compared to when no eco-feedback display is provided (H1).

Comfortable range buffer

According to the framework proposed by Rauh et al. (2015) it can also be seen that the coping strategies influence the comfortable range buffer, which influences the primary appraisal.

This buffer is the minimum remaining range with which users still feel comfortable driving the EV (Franke et al., 2012). Franke et al. (2012) proposed that this buffer is proportional to the car's range, with users willing to utilize 80% of the EVs resources. Furthermore, this buffer can vary with regards to the trip distance, with longer trips requiring more range buffer but less proportionally in comparison to shorter trips. Yuan et al. (2018) found that a 10 km trip requires 6.43 km buffer on average, a 30 km trip requires 14.93 km buffer, and a 60 km trip requires 16.20 km buffer. Thus, as trip distance increases, the more stable and proportionally smaller, in accordance with the trip length, the range buffer becomes.

Surprisingly, in the same paper they found that driving experience was positively correlated to the range buffer and therefore negatively related with range anxiety. This goes against the findings of Franke and Krems (2013) who saw a small decrease in range buffer with increased experience. Therefore, the current literature is indecisive regarding the relation between range anxiety, experience, and the effect of the range buffer upon both. Considering that the effect of experience upon the range buffer is mediated through the available coping resources, it is expected that eco-driving behavior should influence the range buffer. This leads to the second hypothesis; The driver's preferred range buffer is smaller with the eco-feedback display, compared to when no eco-feedback display is provided (H2).

Driving Style

As previously mentioned, eco-driving is a driving style that has been characterized in both ICEVs and EVs by their increased fuel efficiency and reduced emissions in comparison to normal and aggressive driving styles (Bingham et al., 2012; Fonseca et al., n.d.). There are several factors that are of importance to determine the driving style: driving speed, speed oscillations, frequency, and intensity of acceleration and deceleration, timing of gear shift changes, and the stop factor, which is the time taken below 2 km prior to stopping (Alvarez et al., 2015; Brundell-Freij & Ericsson, 2005; Donkers et al., 2020; Fonseca et al., n.d.). This list is not exhaustive as many factors influence the driving style that are beyond the scope of the current study. Additionally, since the current study examines an EV, the gear shift changes and stop factor are not of interest due to the automatic engine and regenerative breaking that would allow for shorter stop times to be of value. Thus, eco-driving within this context will be focused on speed, speed oscillations, and acceleration and deceleration rates. Since the eco-feedback display utilized is intended to incentivize eco-driving behaviors it is expected that the presence of the display will lead people to exhibit an eco-driving style. This leads to the third hypothesis; participants will employ an eco-driving style with the eco-feedback display, while employing an aggressive driving style without the eco-feedback display (H3).

In short, the current study aimed to answer the question: Does an eco-feedback display influence experienced range anxiety within a simulated EV in comparison to a no-feedback display? Several expectations have been drawn from the literature. First, we explored whether range anxiety differs with an eco-feedback display as opposed to a no eco-feedback display. It is expected that drivers experience less range anxiety when an eco-feedback display is provided, compared to when no eco-feedback display is provided (H1). Secondly, we investigated whether the comfortable range/range buffer differs with an eco-feedback display as opposed to a regular display. It is expected that the driver's preferred range buffer is smaller with the eco-feedback display, compared to when no eco-feedback display is provided (H2). Lastly, we inspected whether the driving style differs with the eco-feedback display as opposed to a regular display. It is expected that participants will employ an eco-driving style (as indicated by lower speed, less speed oscillations, and lower acceleration) with the eco-feedback display, while employing an aggressive driving style when no eco-feedback display is provided (H3).

Method

Participants

The current study employed a convenience sample of 23 University of Twente students. All participants with recorded data were able to complete the study, thus no one has been excluded from the final sample. Fourteen of the participants were female (60.9%), eight were male (34.8%), and one was non-binary (4.35%). Most respondents were German (N=17, 73.9%), followed by Dutch (N=4, 17.4%), with two respondents of other nationalities, namely Luxembourgish and Romanian (N=2, 8.66%). The ages ranged between 18 and 29 (*Mage*=21.4 years old, *SDage*=2.42, 53.3% female, 45.7% male). Recruitment was done through a university study recruitment system and through private channels of the researchers. Several requirements were stated up-front, these included the need for a driver's license, being above the age of 18, having no visual impairments, not being (potentially) pregnant, and not being prone to motion sickness. Additionally, it was required to have sufficient English skills. The study was approved by the Ethics Committee of the BMS faculty at the University of Twente.

Materials and Apparatus

A VR environment was used with several hardware and software components which are elaborated upon below. To measure the dependent variables a questionnaire and output from the simulation was utilized. Each participant participated in four conditions with different routes, these conditions were preset differently and described below.

Hardware

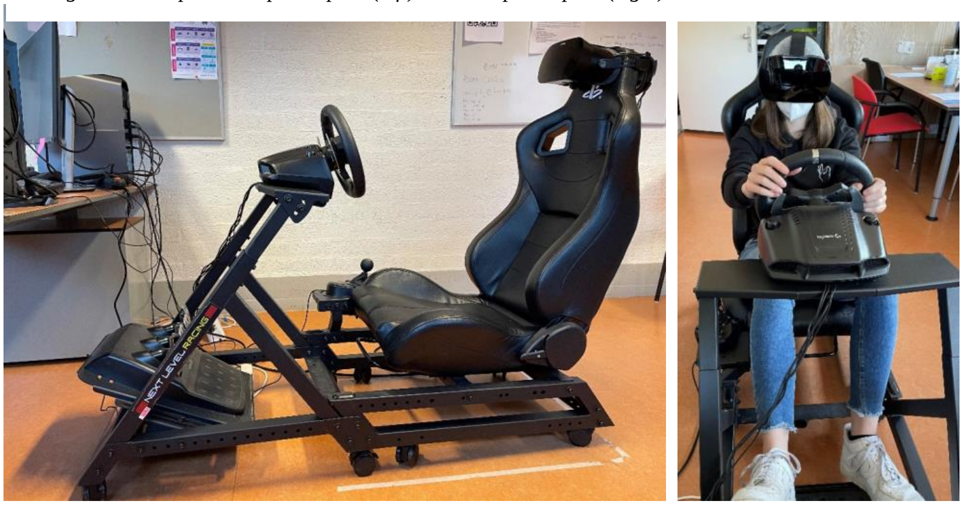
A racing game chair was used for participants to be seated in. This chair was from the Playstation brand and was placed upon a metal frame from Next Level Racing. The seating was adjustable in distance from the wheel and pedals by a metal bar underneath the seat. By a crank on the side, the sitting angle could be changed. The steering wheel and pedals were part of the Logitech G920 Driving Force and were attached to the same Next Level Racing frame. Thus, participants were able to be seated within the gaming chair and adjust their position to comfortably reach the pedals with their feet and steering wheel with their hands. The set up included gear shifts and a clutch pedal, however since the current study examined electric vehicle driving these were not utilized. Leaving participants with usage of the gas and brake pedal and the steering wheel. Chair set-up with and without participant can be seen in Figure 2.

The Varjo VR-2 was the virtual reality headset used in this study. It had an adjustable strap on the top to adjust it in height on the participant's head and a twistable button on the back which allowed for tightening or loosening the straps. Two buttons on top of the glasses allowed the participant to interact with the software. The glasses required two base-stations to be set-up within the room. These base-stations made sure that the participant would be positioned correctly within the software as they would in the actual room by tracking the movement of the glasses.

The Logitech G920 Driving Force and Varjo VR-2 glasses were connected to an Alienware computer which ran all further software. A single monitor was connected to the computer.

Figure 2

Gaming chair set-up without participant (left) and with participant (right)



Software

The Varjo glasses included their own software which allowed for easy calibration and checking whether participants viewed the scene correctly. To run the simulation SteamVR needed to be running as well, which could be done through the room set-up menu in the Varjo software. Unity version 2019.2.21f1 was the game engine used for the simulation. Within the simulation the Fantastic City Generator was used to generate a city which can be seen in Figure 3. The city resembled an American city with large flats, several tunnels, bridges, 4-lane roads, and many intersections and turns creating a block-like structure. All intersections featured stoplights and besides the roads, sidewalks were included with trees and sometimes patches of greenery. The iTS – Intelligent Traffic System was used to spawn other traffic unto the road. This traffic included busses, pick-up trucks, and regular cars of different models. Additionally, an output module was used within the simulation to collect data on the participant's driving. This included measures such as the speed, average speed, acceleration, steering angle, brake, and gas values per in game frame, resulting in about 60 values per second for each measurement all combined in an excel file per participant, per condition.

Figure 3

City environment within the simulator

For the handling of the vehicle within Unity, Vehicle Physics was employed which was connected to the input from the Logitech controllers and translated this to the participant's driving in-game. The Vehicle Physics were set up to simulate an electric vehicle, thus no gear shifting was necessary and only the break and gas pedal had any influence on driving besides the steering wheel.

The dashboard contained two programmed components and a regular speedometer. First, the eco-feedback tool consisted of a dial much like a speedometer. This dial ranged from green to red, green being efficient, red being inefficient, as can be seen on the left side of the dashboards in Figure 4. Efficiency was calculated as the participant drove and was based on the driver's speed consistency. This consistency was calculated through taking the average of the speed difference every 20 frames. Thus, if a participant sped up from 0 km/h to 20 km/h within a second, the dial would turn to the red side, decreasing back to the green area as the participant's speed stabilized.

Figure 4

Car dashboard low range anxiety (left) and high range anxiety (right)

The second component was the battery gauge which displayed the remaining battery percentage left. These were pre-programmed to be 80 or 20 percent according to each condition and colored green or red accordingly. This can be seen in the middle bars in Figure 4, the high battery level on the left and the low battery level on the right. The battery gauge was set to decrease steadily over time, thus the battery level at the end of the 5-minute drive would be decreased by approximately 10% as indicated by a lower bar. The battery color did not change within conditions as these were pre-set. Lastly, a speedometer was present which displayed the speed of the driver, as can be seen on the right in Figure 4 on the right of both displays.

Measurements

The Primary Appraisal Secondary Appraisal (PASA) questionnaire was used to measure range anxiety. The PASA is a 16-item questionnaire with answers being on a 6-point Likert scale ranging from totally disagree (1) to totally agree (6). It included statements such as: I do not feel threatened by the situation, this situation is uncomfortable for me, this situation challenges me, and more. It has previously been found to be a reliable measure for range anxiety and provided the benefit of being able to differentiate between primary and secondary appraisal (Franke et al., 2016). The primary and secondary appraisal are measured through 4 subscales that make up the questionnaire. The two subscales 'threat' and 'challenge', measure the primary appraisal, oppositely the two subscales 'self-confidence in one's abilities' and 'control expectancies' combine to measure secondary appraisal. As there was no applicable English version of the PASA available, the forward-backward translation method as was completed by two native Germans and the final translation can be found in Appendix A. This method has been recommended by the WHO and has been found to be robust within other translated questionnaires ("WHO | Process of translation and adaptation of instruments", 2021; Lee et al., 2018).

"Which range buffer do you set yourself, below which you would not be willing to drive the EV anymore (except in exceptional circumstances)?" was asked to measure the participants' self-set range buffer. This question was previously used by Franke et al, (2012) to indicate range buffers and was used to provide insight into what participants would set as a range buffer for themselves. Additionally, the minimum comfort range for different length trips was asked as can be seen in Appendix A. The questions asked for the minimum comfort range remaining in a 10 km trip, 30 km trip, and 60 km trip. Each question had 5 answer options available, each indicating the range left in the tank, starting with the distance of the trip itself and remaining answers adding 7.5 km to each previous answer. Except for the 10 km trip, here the answers differed with 2.5 km. These questions were taken from Yuan et al. (2018) and are utilized here to find range buffer percentages and differences.

For the driving style indicators, the output module within the unity simulation was used. The speed and acceleration values were taken from these to find average speed, speed variance, and average acceleration per condition as these are measures commonly used to indicate aggressive driving behavior when the values are higher or eco-driving behavior when these values are lower and were readily available from the simulation (Alvarez et al., 2015; Brundell-Freij & Ericsson, 2005; Donkers et al., 2020; Fonseca et al., n.d.).

Conditions and Routes

There were 4 different conditions, always administered in the same order; 1. Low range anxiety with feedback, 2. High range anxiety with feedback, 3. Low range anxiety without feedback, 4. High range anxiety without feedback. The low range anxiety conditions utilized the high battery percentage of 80% range or 8 km with a green battery bar as can be seen in Figure 4 on the left. The low range conditions utilized the low battery percentage with 20% range or 2 km left with a red battery bar as can be seen in Figure 4 on the right. Conditions with feedback utilized the eco-feedback display as seen on the left of the dashboards in Figure 4. No-feedback conditions resulted in the removal of the eco-feedback display and participants instead saw the regular built-in gear shift display as can be seen in figure 5.

Figure 5

Car dashboard without eco-feedback tool

Four routes were created for the four different conditions (Appendix B). These were picked at random for each condition by the researcher, ensuring that no route was driven twice. Routes allowed for approximately five to seven minutes of driving to ensure the five-minute time limit would be reached. To monitor this, a five-minute timer was set before the participant drove the route. Turns were kept to a minimum to minimize motion sickness and each route used the same starting point. The route was described verbally, and instructions were given as clearly as possible e.g., “at the next intersection, turn right”. When the time was reached the researcher would ask the participant to stop at a convenient place e.g., “we are done for now, please stop at the following stop light.”.

Design

The current study is part of a larger study carried out with 4 researchers. The study at hand utilized a within-subjects 2x2 factorial design. The first independent variable is the eco-feedback tool, which has two levels: with and without. The second independent variable is range anxiety, consisting of the levels high and low. This resulted in four different conditions per participant. Dependent variables include the PASA range anxiety scores, range buffer values, and driving style category based on speed, speed oscillations, and acceleration and decelerations.

Procedure

Considering the study was conducted in April and May of 2021, COVID-19 measures needed to be taken to ensure the safety of the participants and researchers. Prior to participants entering, windows would be opened for extra ventilation. All persons were required to wear a facemask, disinfect their hands, sign a COVID-19 document. Participants further needed to wear a VR-mask and hairnet to avoid direct contact with the glasses. All objects used by the participants were disinfected prior to use.

Prior to testing, the VR glasses were calibrated when the base stations had moved or were not used for a longer time. This was done through the Varjo room calibration, which opened SteamVR to set the glasses' height. Afterwards, Unity could be started up and the student number would be filled in for the output file.

Upon arrival, participants had to comply to the corona measures. Afterwards they were requested to scan a QR code, read the informed consent, and fill out the first part of the questionnaire on their phone. Subsequently, participants were seated and were asked to adjust the seating to their liking. A general explanation of was given about the simulation. They were informed that they would be driving an electric vehicle and would use only the gas and brake pedals. A warning regarding the car sensitivity and a short explanation of what could be seen on the dashboard was given (The eco-feedback tool (if present), a battery bar, and a speed gauge). Then, the VR glasses were placed on the participant's head and adjustments were made until comfortable.

After this, the simulation was started and participants were asked to close their eyes as the researcher placed them into the car correctly, asking whether the participant felt comfortable with the positioning and adjusting when necessary. When positioned, the participant was asked to do a test drive that spanned three to five minutes to ensure familiarity with the driving sensation. Participants were asked after some time whether they feel familiar and if they were positive the test drive was ended. They were asked about feeling any motion sickness before proceeding further.

If the test drive was successful and the participant felt good to continue, the experimental drives began. For each drive, the participants' position needed to be adjusted. Each participant was told to drive as they normally would, considering the situation. If they were in a low range condition, they were told that the current range was 2 km and that they might not be able to finish the drive as other participants experienced this as well. This was done to maximize the stress upon the participant. The participant drove in each situation for 5 minutes with the researchers giving verbal directions according to the assigned routes (Appendix B). After each drive, the participant was requested to take off the VR glasses and fill out the PASA and range buffer questions. After this they would continue with the next condition and fill out the questionnaire again. Between the first and last two drives participants were given an elongated break if they so desired.

Data Analysis

Data Preparation

Box plots and histograms were created for each tested variable to determine normality and remove extreme outliers. For the self-set range buffer questions one participant needed to be removed as their scores were a far outlier from the rest. Some participants missed output of the driving speed indicators which were coded as missing values.

Firstly, the PASA included directions on recoding and combining scores into an ultimate stress score and can be subdivided into primary and secondary appraisal scores as well as further subcategories. The subscales threat, challenge, self-confidence in one's abilities, and control expectancies were calculated by the sum of their respective questions. Primary appraisal was the threat and challenge scores summed and divided by two. Secondary appraisal the self-confidence in one's abilities and control expectancies combined and divided by two. The ultimate stress score was the primary appraisal score minus the secondary appraisal score (Gaab, 2009).

The range buffer scores were classified as the self-set range buffer and the multiple-choice categories. 'Km' or 'kilometer' descriptions were removed to treat these values as numeric. The multiple-choice answer category answers were recoded to represent the actual distance participants chose as their remaining range.

The driving style indicators were calculated from the Excel file resulting in the average speed, speed oscillations as given by the SD in speed, and average acceleration. All zero values up to the first value larger than zero were removed to account for the idle time while positioning the participant. Averages and standard deviations were computed within Excel and entered in

SPSS per condition by participant manually. Acceleration values were made absolute to take deceleration into account as well.

Analyses

To conduct this manipulation check, the high and low range PASA stress scores were converted to long format, thus each participant had two high RA scores and two low RA scores, disregarding the eco-feedback condition. A paired samples t-test was conducted to see whether the different range anxiety situations led to higher or lower range anxiety.

A two-way repeated measures ANOVA was conducted with the RA condition, eco-feedback condition (IVs) and the PASA stress scores (DV). To run this analysis, the wide format had to be utilized with the four different PASA stress score measures representing each condition.

A paired t-test was conducted to examine the difference within self-determined range buffer scores (DV) between the eco-feedback conditions (IV). Here the long format was utilized, where data was restructured for the range buffer scores. To gain scores for with and without feedback conditions, the two scores for each condition were averaged into one. For each trip length, a paired t-test was conducted. This was chosen over an ANOVA as significant differences would be present between the trip length categories since the answer categories differ greatly from each other.

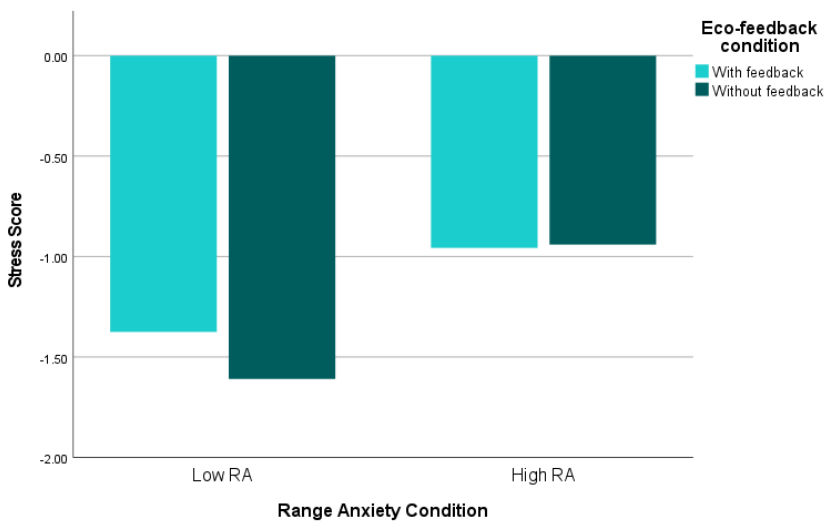
Lastly, A repeated measure one-way MANOVA was done to test for differences between driving style indicators between eco-feedback conditions. Data was transformed into long format by restructuring the data around the feedback condition, doubling the participant’s entries.

Results

Prior to hypothesis testing, a manipulation check was carried out to see whether the high and low range anxiety situations did increase anxiety levels. The paired t-test revealed that there was a significant difference in PASA stress scores between the high RA condition and the low RA condition, $t(45) = 2.56$, $p < .01$, indicating that the range anxiety manipulation had the expected effect. Overall, the obtained PASA stress scores ranged from -3.37 to 2.50 from a possible -5.00 to 5.00. Low numbers signifying no stress and higher numbers signifying stress ($M = -1.22$, $SD = 1.35$). On average participants were 0.54 points more stressed in the high RA condition in comparison to the low RA condition ($r = .42$, 95% CI [0.12, 0.97]).

Figure 4

Stress by range anxiety and eco feedback, lower scores indicating less stress



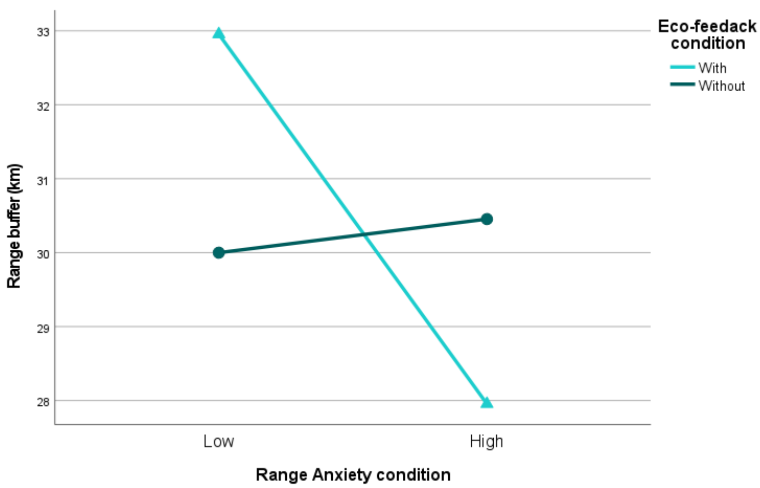
For the first hypothesis a two-way repeated measures ANOVA was run with the 2 IV's being the RA condition and the eco-feedback condition, the DV being the PASA stress scores. The analysis showed that there was no significant main effect of range anxiety condition on stress score, $F(1, 22) = 4.0$, $p = .06$, $\eta_p^2 = .15$, indicating that participants did not experience a significant difference in range anxiety depending on the range condition. Furthermore, the main effect of the eco-feedback condition upon the participant's stress was also not significant, $F(1,22)$

= 0.61, p = .44, η_p^2 = .03). Lastly, the interaction effect of the RA condition and feedback condition also proved to be non-significant, F(1,22) = 0.88, p =.36, η_p^2 = 0.88). Participants had the highest stress scores in the High RA no-feedback condition (M = -.94, SD = 1.63) followed closely by the High RA feedback condition (M = -.96, SD = 1.16). The low RA conditions experienced lower stress, with-feedback was seen to be more stressful (M = -1.38, SD = 1.18) than no-feedback (M = -1.61, SD =1.36). This is visualized in Figure 6.

A paired samples t-test was conducted to find a difference between the self-described range buffer in the eco-feedback condition in comparison to the one without. The paired samples t-test showed no significant difference between these conditions, t(43) = .15, p = .88). A two-way ANOVA was conducted to further investigate the difference within the self-described range buffer between all conditions, considering both range and eco-feedback condition. This test confirmed the earlier findings that there was no significant main effect of feedback condition upon the range buffer, F(1,21) =.02, p = .89, η_p^2= .001).

Figure 5

Range buffer in kilometers by range anxiety and eco-feedback condition



Additionally the RA condition had no significant main effect, F(1,21) = .81, p = .38, η_p^2 = .04. However, the interaction effect of both conditions was large and significant, F(1,21) = 5.7, p

= .03., $\eta_p^2 = .21$). Thus, the difference between range buffers was large between range conditions when feedback was present, but small when feedback was not present as can be seen in Figure 7.

Since a base measurement of the self-set range buffer was made, this average (*M*=68.41 km) was compared to the overall average of range buffers with conditions (*M*=33.34 km). A One-sample t-test was conducted and found a significant difference between the base range buffer and overall average of range buffers within conditions, $t(22) = 2.7$, $p = .01$. Indicating that participants had set a higher range buffer for themselves before driving.

Apart from the self-set range buffer, the multiple-choice range buffer questions were also analyzed. A paired t-test was conducted for each trip length question (10, 30, and 60 km) to find differences in these between the feedback and no-feedback conditions. For the 10 km trip length, no significant difference was found between range buffer scores in the feedback and without conditions, $t(21) = .34$, $p = .74$. For the 30 km trip length, there was no significant difference found between range buffer scores in the feedback and without feedback conditions; $t(22) = .75$, $p = .46$. Lastly, range buffer scores for the 60 km trip length similarly showed no significant difference between feedback without feedback conditions; $t(22) = .88$, $p = .39$.

Lastly, the third hypothesis was analyzed based on eco-feedback condition and driving style categorization. Driving style was indicated by the standard deviation of speed, average speed driven, and average acceleration. The one-way repeated measures MANOVA showed that there was no significant difference for the driving style indicators between the feedback and no feedback condition, $F(3,36) = .45$, $p = .72$, Wilk's $\Lambda = 0.96$) indicating that the presence of feedback had no influence upon driving style.

Discussion

The aim of this study was to see whether the utilization of an eco-feedback display influences experienced range anxiety within a simulated EV in comparison to a no-feedback display. We examined whether drivers experienced less range anxiety with than without the tool in both high and low range anxiety situations. We examined the influence of the eco-feedback display on range anxiety, range buffer, and driving style. The results show that eco-feedback has no significant effects on these aspects but can be seen to have a combined effect with range anxiety upon the range buffer. The results are discussed in detail per hypothesis below.

Range anxiety and feedback

Contrary to the expectations based on Neumann et al. (2015) and Rauh et al., (2015), no significant effect of the eco-feedback display on experienced range anxiety was found. While participants were more stressed during the high range anxiety condition, their stress was not affected by the feedback display. Yet in the low range anxiety condition the presence of the feedback display resulted in higher stress scores in comparison to no-feedback. This may be due to participants finding the feedback more distracting when the information is not necessary in a non-stressful situation. This would corroborate the findings of Beloufa et al., (2014) in which participants spent more time looking at an eco-driving display in a low range anxiety situation when compared to a high range anxiety situation. However, since the difference was non-significant, further research would be needed.

Range buffer and feedback

The effect of range anxiety upon the range buffer was inconclusive from the literature, Yuan et al. (2018) and Frank and Krems (2013) provided opposing relationships between these. It was expected that the range buffer to be smaller when eco-feedback was present based on the influence this would have upon the experienced range anxiety. The current study found that neither range anxiety nor the eco-feedback display in themselves led to a difference in self-set range buffers. However, when considering both conditions together it showed significant differences within the self-set range buffer. The range buffer difference was large when feedback was present, being set higher in the low range anxiety condition and lower in the high range anxiety condition. While only a small difference was present when no feedback was presented. Within the framework of Rauh et al., (2015) the decrease in range buffer in the high range anxiety with feedback condition could be attributed to a reappraisal in resources such as coping skills. Since the low range anxiety situation does not result in a threat situation, the coping skills are not used and thus the range buffer is not reappraised resulting in the higher range buffer. Additionally, the higher range buffer may be due to extra stress the feedback causes in low range situations, causing a negative reappraisal of the range buffer. This would explain why the no-feedback low range anxiety condition has a lower range buffer. The high range condition then results in a slightly higher range buffer, possibly due to the additional stress.

Additionally, the self-set range buffer was also asked for before the participants drove. This was intended to be used as a baseline, however it turned out to be much higher than the range buffers participants gave during the conditions. A significant difference was found between this score when compared to the average of the range buffers of the conditions. Overestimation of range needs has been commonly mentioned as a barrier to wide EV acceptance (Bonges & Lusk, 2016; Franke et al., 2012; Zaunbrecher et al., 2015). These findings corroborate this overestimation and suggest that it may be related to whether the participant drove recently.

Furthermore, the trip distance range buffer questions from Yuan et al., (2018) were examined. Per trip length differences between the feedback and no-feedback condition were tested. No significant differences were found from these questions. The same trend of increasing range buffer as trip distance increases was found with one exception being the 60 km trip length without feedback. Here the range buffer was 4.2 km in comparison to the 15.7 km with feedback. This difference was not significant, but the sudden downward trend without feedback is peculiar. The other questions did not differ much which may indicate a more stable range buffer when exact trip lengths are given.

Driving styles and feedback

No significant differences were found between the driving indicators and feedback conditions. This was contrary to the findings of Perelló-March et al. (2019) and Beloufa et al., (2014) who did find people to adhere to more eco-driving behaviors when feedback was presented. This calls into question whether this simulated eco-feedback tool is an effective method of stimulating eco-driving behaviours, which may be due to simulation inaccuracies.

Limitations

Considering the large number of technologies, applications, and steps that were required for the successful collection of data, several issues may have influenced the results.

Firstly, the driving simulator is an ongoing project of the BMS lab. The current research team proposed to calculate efficiency through speed constancy, allowing for smooth transitions of the needle on the gauge which had not previously been possible. This, however, lacks complexity as it did not consider the regenerative breaking and other factors relevant to energy saving. Additionally, the gauge could still appear erratic as it quickly shifted to the red area when a participant would brake. This could have impacted the results as participants may not have trusted the gauge to give them accurate feedback, found it to be distracting, or were unable to discern which behavior the gauge would count as efficient. Furthermore, the simulation was very sensitive, leading to faster than usual braking. This might have influenced driving style outputs due to the fast accelerations.

The procedure was quite error prone as many preparations needed to be done and instructions needed to be given to the participants verbally. The SONA ID needed to be entered before each condition, if this was forgotten output was missing for a condition. Map reading and seeing where participants were driving would sometimes lead to a missed turn or surprising the participant with the need to turn sharply. Moreover, all conditions were done order due to time constraints. This leads to time being a confounding factor, with participants perhaps being more accustomed to driving the EV after the first couple of conditions. All of these may have influenced the data and made the experiment less standardized.

Further research

For future research utilizing VR to simulate driving and researching an eco-feedback tool it would be recommended to use a newer version of Unity and accordingly vehicle physics. This would improve the car handling and could allow participants to feel more immersed. It would also be suggested to seek an accurate way to model efficiency as this could increase reliability upon it and may influence coping strategies related to range anxiety. Both changes may also improve realism and thus generalizability to real life situations. Procedurally, a way to map directions within the simulation may be better to reduce mistakes that could be made by the researcher and improve autonomy of the driver.

Further research could look more closely at the relationship between the range buffer, coping skills, and range anxiety. As current literature is inconclusive on the relationship between range buffer and range anxiety more data would be beneficial (Yuan et al.,2015; Frank & Krems, 2013). The current study showed interaction between the range buffer and eco-feedback tool upon range anxiety, by looking at coping skills more generally rather than an eco-feedback tool, it could build upon the existing framework as proposed by Rauh et al., (2015). From the current study it was also seen that the range buffer can be quite pliable, while it has commonly been thought of as set. Seeing whether such changes remain over a longer time could be useful to see if it could be used to change people's common overestimation of needed range.

Not much is known about driving styles and range anxiety. While the current study was unable to find significant differences between the driving style indicators, more data and output may lead to different results. Ideally this would be done in a real life setting to ensure realistic car handling and more accurately experienced range anxiety due to the immersion. However, simulation improvements could make this better. More insight into the relationship between driving styles and range anxiety could provide further reasons to increase efforts into decreasing range anxiety. Consequently, an accurate feedback tool could be utilized here as well to see whether it could moderate the relationship and provide a possible solution.

Lastly, it would be beneficial to ask participants what the eco-feedback tool is promoting them to do. This would give further insight into the learning process and whether participants understand what the behavior the eco-driving behavior the tool is promoting them to perform is. Further qualitative research into what users would desire from such a tool could be beneficial in designing a user-friendly assistance tool.

Conclusion

The current study aimed to answer the question whether an eco-feedback display influences experienced range anxiety within a simulated EV in comparison to a no-feedback display. This was further examined by researching differences in range buffers and driving style indicators. This was done through a 2x2 experimental design, with participants experiencing two levels of range anxiety (high and low) and two levels of eco-feedback (with or without) within the simulated electric vehicle. No significant effects were found of an eco-feedback display on range anxiety. However, a significant difference was found within self-set range buffers under influence of both range anxiety and the eco-feedback display. Here the eco-feedback display led to higher range buffers with low range anxiety and low range buffers with high range anxiety. While the opposite occurred without the eco-feedback display. These results indicate that this eco-feedback tool does not result in lower range anxiety and does not increase eco-driving behavior. This may be due to simulation inaccuracies, but further research is needed.

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Appendix A

Questionnaires

PASA Final translation

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. This 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 behavior 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.

Range buffer

- Minimum comfort range remaining in a 10 km trip: 10 km 12.5 km 15 km 17.5 km 20 km

- Minimum comfort range remaining in a 30 km trip: 30 km 37.5 km 45 km 52.5 km 60 km
- Minimum comfort range remaining in a 60 km trip: 60km 67.5km 75km 82.5km 90km

Appendix B