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MEASURING THE PERCEPTION OF COMFORT IN ACCELERATION VARIATION USING ELECTROCARDIOGRAM AND SELF-RATING MEASUREMENT FOR THE PASSENGERS OF THE AUTOMATED VEHICLE

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Abstract

While the fully automated vehicle (AV) has been the future of the automotive industry, there is uncertainty regarding how the vehicle will be operating. This study aims to investigate the feeling of comfort in terms of experienced motion sickness for the AV passengers when exposed to two different automated test rides. Two sessions were performed on the real road using an instrumented vehicle. The first session was a defensive automated test ride (DATR) with relatively low acceleration forces. The second session was an assertive automated test ride (AATR) with stronger acceleration forces. Electrocardiogram (ECG) and self-rating questionnaires were used to investigate the relation between them when given forces variation. Statistically significant ($p<0.05$) increases were found when comparing the before and after self-rating motion sickness score for the AATR, whereas no statistically significant ($p<0.05$) increases were found for the DATR. For the discomfort rating, the level of perceived comfort remained almost constant throughout DATR. Whereas for the AATR, an approximately linear increase in the feeling of discomfort was found. The physiological variations (ECG) could not accurately predict the subjective comfort based on the statistical analysis results. The linear regressions suggest that forces resulted from driving should be kept as low as possible to improve the AV riding experience.

Keywords: Acceleration variation, Automated vehicle, Comfort, Passenger.

1. Introduction

It is not known how a fully automated vehicle (AV) is going to operate or drive. But fundamentally, a fully AV is a robotic vehicle with various sensors that can drive by itself. Therefore, it is predicted that human users or passengers inside the vehicle can make the journey more productive. However, since the passengers do not have to drive, and likely engage in activities other than driving, the unpredictable changes in acceleration are predicted to cause physical and mental discomfort to them. Comfort is highly influenced by expectation from the user [1], and in the context of a riding vehicle, comfort is highly related to the acceleration's rate and/or deceleration, jerk (the first derivative of acceleration), and seating type [2].

In this paper, we focus on physical comfort and discomfort related to abrupt changes in acceleration that will lead to motion sickness. Humans are susceptible to motion sickness (MS) when exposed to low-frequency longitudinal and lateral accelerations within the range of 0.1-0.5 Hz [3]. These kinds of motion occur when a vehicle is being driven on a suburban environment with stop-and-go traffic, and when the geometry of the roadways is winding and curved. Therefore, it is interesting to discover what will happen to the AV passenger's level of MS when subjected to low-frequency motions. Especially when they are no longer deal with driving task and engaging in future preferences of a non-driving related task (NDRT) such as playing games and reading [4-6].

When engaging in NDRTs, the occupants will be passive passengers who lose the controllability from the perspective of the user [7]. According to Elbanhawi et al. [8], this loss introduces the need for reassessing passenger comfort criteria for future AV development. Thereby, prior work found that passengers typically have significantly different perspectives with regards to comfort and safety than drivers do [9]. Passengers are unable to foresee and anticipate the vehicle's direction of motion [10, 11]. Hence, it can potentially cause conflicts between the physical and psychological variation components. AV's passengers are likely to develop MS because of three reasons; the lack of control over the direction of motion, the inability to anticipate the direction of motion, and the mismatched inputs between the vestibular and visual system [10, 11]. Sivak and Schoettle [12] estimates that about 12% of American adults are expected to experience moderate MS in future AV, whereas this would be the case for about 17% of the Indians. Hence, MS is a possible threat to the overall acceptance of AV's and that it is one of the key factors that potentially affect the perception of comfort in a negative way. Therefore, this study assumed and treated the feeling of MS as an extreme form or level of discomfort.

Human comfort and its perception can be assessed by subjective (e.g., by using self-rating questionnaires) and by objective evaluation (e.g., physiological measures). The perception of comfort was supposed to be observable at the psychological (i.e., subjective) as well as the physiological (i.e., objective) level. The reasons for using the physiological measurements to measure MS are twofold. First, its ability to obtain a continuous recording of one's physiological state. Hence, allow the experiment to be done without the need to stop and collect the data [13]. Secondly, the physiological measurements offer a quantitative view of the measurement of MS. The physiological measurements can be analysed together with the subjective measurement for a complete understanding of what happened to comfort level during the presence of MS.

Physiological measurements have been used in the past to investigate the severity of MS experienced by a human. Heart rate variability (HRV) analysis was an attractive method because it is non-invasive, pain-free, economic, and simple to apply [14]. HRV can be analysed using both time- and frequency-domain analysis. The frequency-domain analysis includes an analysis of the power spectral density (PSD). In the past, PSD was usually calculated by an algorithm called the Fast Fourier Transform (FFT). Recent research has also focused on autoregressive modelling (AR) for PSD calculation [14].

Based on previous research, there are challenges in the development of AVs. One of these challenges is to create a better AV riding experience. This study focuses on one particular aspect of this AV riding experience, namely the perception of the comfort of AV passengers in terms of the feeling of MS. Thereby, comfort due to physical causes (i.e., variation in forces resulting from driving exerted on the passenger's body) was of particular interest. It was hypothesised that stronger forces result in more AV passenger discomfort indicated by higher experienced MS. It was decided to use psychological (i.e., self-rating measurements) and physiological measures (i.e., HRV) to study the perception of comfort. Thereby, it was hypothesised that physical variations (i.e., variation in forces) are related to both psychological and physiological variations. Therefore, an on-road experiment was organised in which the physical variations were controlled in the sense of having two different test rides conditions.

2. Methodology

2.1. Test vehicle

The test vehicle was provided by the Department of Industrial Design of the Eindhoven University of Technology (TU/e). A Renault Espace was transformed into an instrumented car to make it a suitable test vehicle for AV driving scenarios and has been used for prior researches on AV riding experience [15]. The vehicle is equipped with a built-in accelerometer and electrocardiogram (ECG) sensors for the participants. All the data captured and synchronised in a data acquisition device (DAQ). The vehicle's interior was adjusted to simulate an AV riding experience for an SAE's Level 5 automated vehicle [16]. One may refer to [15] for further explanation of the test setup.

The Driver Wizard technique was used to simulate the AV riding experience. This technique is introduced by Baltodano et al. [17] for simulating automated vehicles on open public roads. In this method, the subjects were told that they are interacting with a computer system through an interface whereas the Driver Wizard is concealed (see Fig. 1). Since the vehicle is still operated by a human driver (Driver Wizard), there is a need for consistent driving to maximise the validity of the experiment data across subjects. Therefore, the Driver Wizard is helped by a device, which is called the Automatic Acceleration and Data controller (AUTOAccD). This device has been developed to guide the Driver Wizard to accomplish selected accelerations (see Table 1) [18].

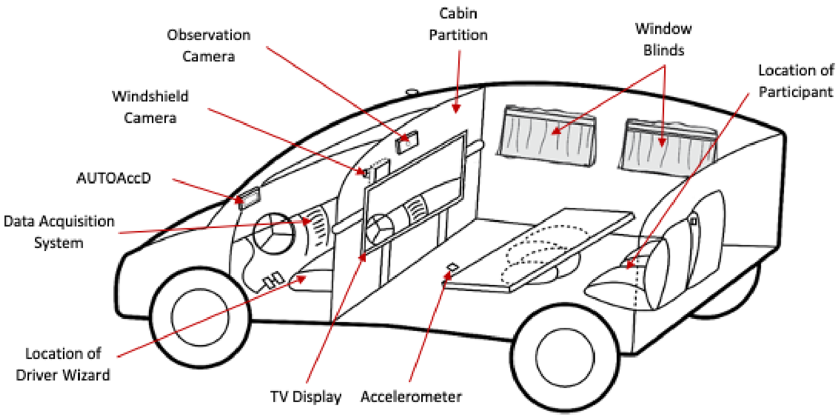

Fig. 1. Test setup interior layout.

2.2. Approach

The study consisted of two test rides conditions, in which two AV's driving styles, defensive and assertive automated driving style were tested. These two automated driving styles are characterised by typical ranges of acceleration, as shown in Table 1. They have been proved and used in previous studies on AV riding experience (e.g., [6, 19]).

Table 1. Ranges of acceleration for defensive and assertive AV driving styles in tri-axial directions, 1.00 g = 9.81 (m/s²).

Type of acceleration	Defensive automated driving style	Assertive automated driving style
Longitudinal acceleration	0.14 g to 0.25 g	0.25 g to 0.50 g
Longitudinal deceleration	- 0.14 g to - 0.33 g	- 0.33 g to - 0.76 g
Lateral acceleration	0.15 g to 0.42 g	0.42 g to 0.54 g
Vertical acceleration	0.00 g to 0.16 g	0.16 g to 0.66 g

Every participant was required to participate in both experimental conditions. A within-subjects design is also highly recommended for ECG recording, primarily because of inter-individual variations and complex interaction influencing HRV [20]. During both experimental conditions, participants were instructed to start playing a simple game (Angry Birds®) on a tablet, as soon as they noticed the car started moving. They were asked to keep playing the game as long as the vehicle was driving. Participants were instructed to stop playing as soon as the car was parked again.

Both experiment sessions were organised on the campus of the TU/e, Netherlands. Since the assertive automated driving style included higher longitudinal velocities than the defensive automated driving style, a longer distance was travelled within the same time frame.

2.3. Participant

Fourteen healthy volunteers (4 females, 10 males), all students at the TU/e, Netherlands participated in the study, the average age was 23.5 years (SD = 3.8, minimum = 19, maximum = 31 years).

Three participants did not have a driving license, whereas eleven participants did own a driving license (driving experience > 2 years; N = 10). Nine participants indicated they do between one and five hours' sport every week; five participants do even more than five hours. The average BMI of the fourteen participants was 20.9 (SD = 1.4). The majority of participants (N = 9) drink less than one consumption of alcohol per week, five drink between two and seven consumptions. With regards to the consumption of caffeinated drinks (coffee, tea, energising drinks, etc.), twelve participants drink less than one consumption per day while only two participants drink more than one consumption daily. All of the selected participants indicated that they do not smoke.

The Motion Sickness Susceptibility Questionnaire (MSSQ) was used to measure the participant's susceptibility to MS [21]. The mean MSSQ score across the fourteen subjects was 4.68 out of 54.00 (SD = 5.45) with the minimum recorded value of 0.00 and maximum recorded value of 18.00. The selected participants are under the 25th percentile (i.e., low susceptible to MS).

2.4. Consistency of AV test ride

Vehicle dynamics data (i.e., velocities and accelerations) were collected to measure the consistency of the test rides sessions performed by the Driver Wizard. The calculation of Motion Sickness Dose Value (MSDV) was applied based on [22] as shown in the following equation:

$$\mathrm{MSDV} = \sqrt{\int_0^T [a_w(t)]^2 \, dt} \tag{1}$$

where a_w is the root mean square of the acceleration that has been weighted with frequency-weighing and T is the exposure period to the motion. MSDV can be calculated individually in each of the three axes (longitudinal, lateral, and vertical).

The LabVIEW DIAdem Toolkit was used to filter the acceleration data and to calculate the MSDV. The analogue acceleration data first have to be converted into SI units (i.e., expressed in m/s²). Then the software uses the digital Savitzky-Golay filter to detect and filter out noise from the data [23]. These adjusted data were then used to obtain acceleration data that are expressed in terms of root mean square (r.m.s.). The r.m.s. data were obtained by converting the adjusted (i.e., de-noised) acceleration data into frequency weighted accelerations in x-, y-, and z-direction. The data expressed in r.m.s. then have to be squared before they were integrated over the total exposure time. The final result, then, is the MSDV value quantifying the dose value in the longitudinal, lateral, and vertical direction, respectively, expressed in $\mathrm{ms}^{-1.5}$.

2.5. Subjective Measurement

Since MS should be viewed as a multidimensional construct, a questionnaire able to assess multiple dimensions - i.e., the Motion Sickness Assessment Questionnaire (MSAQ) [24]. It consists of sixteen statements that are related to one of four dimensions (i.e., Gastrointestinal, Central, Peripheral, and Sopite). Gastrointestinal relates to sick to stomach and queasy symptoms, Central relates to faint-like and lightheaded symptoms, Peripheral relates to clammy and sweaty symptoms, and Sopite relates to tired and drowsy symptoms [24]. An overall MS score is obtained by calculating the percentages of total points scored.

Another subjective measure done on a one-minute base was implemented to avoid the known issues of retrospective evaluation. That means that subjects would be asked how uncomfortable they were feeling after every minute of driving. For the "discomfort rating", it was decided to use a unipolar rating scale since it was aimed at investigating varying levels of the same concept (i.e., the feeling of discomfort). For unipolar scales, it is known that five scale units are acceptable [25]. This resulted in a 5-point Likert unipolar scale answering the question, *"How uncomfortable are you feeling right now?"*; 1 = not uncomfortable at all, 2 = slightly uncomfortable, 3 = moderately uncomfortable, 4 = very uncomfortable, 5 = extremely uncomfortable. Participants were instructed to give their rating every minute during the test ride by showing the appropriate number of fingers to the observation camera that was mounted on the partition inside the vehicle concealed (see Fig. 1).

2.6. Objective Measurement

Electrocardiogram (ECG) was recorded from three pads attached to the participant's body using the chest placement method suggested by Shaffer and Combatalade [26]. These pads were connected to the Analog Devices AD8232 single-lead HR monitor. After recording the data, the National Instruments LabVIEW Biomedical Toolkit software was used for further analysis, both in the time and the frequency domain. The software typically extracts the time and frequency domain parameters from the data recorded by the ECG sensors. Once these parameters are extracted from the data, the software returns a clear overview of the different time and frequency domain analyses and their values during the specified measurement intervals. For the frequency domain analysis (i.e., analysis of the LF/HF ratio), the data from autoregressive modelling (AR) analysis with a model-order of 16 were used.

3. Result

3.1. Consistency of the test rides

The mean, standard deviation, and coefficient of variation (CoV = SD/Mean) of the motion sickness dose values (MSDVs) produced by the Driving Wizard for the 13 participants for the two driving sessions indicated high reliability and consistency as were shown in Table 2. The results indicate that the same MSDVs were generated to the participants for both defensive and assertive driving sessions. Furthermore, the generated mean MSDV for the assertive automated driving session was substantially higher than the mean for the automated defensive driving session, as was hypothesized for this study. For the statistical analysis, IBM's SPSS software was used, and the effect sizes were calculated through the G*Power software [27].

Table 2. Mean, standard deviation (SD), and coefficient of variation (CoV) for MSDV in the triaxial direction for the entire driving sessions.

	Defensive Driving Sessions			Assertive Driving Sessions		
	Mean (ms$^{-1.5}$)	SD	CoV (%)	Mean (ms$^{-1.5}$)	SD	CoV (%)
MSDV_x	4.685	0.424	9.051	13.064	0.875	6.670
MSDV_y	7.001	1.061	15.155	12.846	1.009	7.855
MSDV_z	6.338	0.540	8.520	6.613	0.358	5.414

3.2. Subjective rating - MSAQ

Wilcoxon signed-rank tests (WSRTs) were performed on the pre-and post-MSAQ data to check if the setup induced any MS symptoms to all the participants for both driving sessions (see Table 3 for descriptive statistics of the MSAQ).

The WSRTs determined that there was no statistically significant increase, neither in the total MSAQ score nor in the scores of the four constructs for the defensive driving session (see Table 4). For the assertive driving session, however, the same test revealed that, apart from the Peripheral construct, statistically significant increases were found when comparing the pre- and post-MSAQ score.

Table 3. Pre- and post-MSAQ scores with mean and standard deviation for both defensive and assertive driving sessions.

Construct	*Defensive automated driving session*				*Assertive automated driving session*			
	Pre-MSAQ		Post-MSAQ		Pre-MSAQ		Post-MSAQ	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Gastrointestinal	14.88	9.28	16.27	10.44	14.48	5.89	31.55	18.42
Central	13.65	6.15	12.70	3.19	13.81	5.73	21.27	13.35
Peripheral	17.20	12.03	12.96	3.48	17.72	9.87	18.78	14.99
Sopite	19.44	11.53	19.64	18.98	17.26	7.72	26.00	13.94
Total MSAQ	16.07	8.29	15.38	7.89	15.57	5.36	24.55	12.56

Table 4. Results of a Wilcoxon signed-rank test of the MSAQ scores for the after-before comparison of the two experiments (G = Gastrointestinal, C = Central, P = Peripheral, S = Sopite).

	Defensive automated driving session				Assertive automated driving session			
	Median increase	z	p	Cohen's d	Median increase	z	p	Cohen's d
G	0.00	0.85	0.39	0.14	13.9	2.71	0.01**	1.05
C	0.00	- 0.82	0.41	0.19	4.44	2.14	0.03*	0.64
P	0.00	- 1.08	0.28	0.39	0.00	0.34	0.73	0.08
S	0.00	- 0.73	0.46	0.01	6.94	2.27	0.02*	0.72
Total	0.00	- 0.28	0.78	0.09	5.90	3.05	0.00**	0.82

**$p < 0.01$, *$p < 0.05$

3.3. Subjective rating - Discomfort rating

A unipolar 5-point rating scale measured the assessment of participant level of perceived comfort, and the descriptive statistics are shown in Table 5.

Table 5. Average discomfort ratings per minute for the defensive and assertive driving sessions. (Comfort Rating with 5-point scale; 1 = not uncomfortable at all, 5 = extremely uncomfortable).

Time	Defensive automated driving session			Assertive automated driving session		
	Mean	SD	N	Mean	SD	N
1st Minute	1.40	0.70	10	1.25	0.62	12
2nd Minute	1.33	0.65	12	1.58	0.79	12
3rd Minute	1.46	0.52	13	1.82	0.87	11
4th Minute	1.33	0.49	12	2.09	1.04	11
5th Minute	1.64	0.75	14	2.33	1.23	12
6th Minute	1.58	0.79	12	2.31	1.03	13
7th Minute	1.42	0.67	12	2.46	1.20	13
8th Minute	1.46	0.66	13	2.69	1.44	13
9th Minute	1.62	0.77	13	2.92	1.32	13
10th Minute	1.46	0.66	13	2.45	1.37	11

For the defensive automated driving session, the level of perceived comfort remained almost constant throughout driving. In contrast, for the assertive automated driving session, an approximately linear increase in the feeling of discomfort was found. The results of the comfort rating suggest that the defensive automated driving session with lower forces exerted on the body was rather not perceived as uncomfortable. The assertive automated driving session, however, resulted in exposure to stronger forces and vibrations. As a consequence, it seems that the longer people were exposed to these stronger forces, the more uncomfortable they were feeling. To compare the severity of the perceived comfort between the two driving sessions, the differences between the means of the comfort rating where compared. A Wilcoxon-signed rank test showed that, especially during the last five minutes of driving, participants were significantly feeling more uncomfortable during the assertive automated driving session than during the defensive assertive automated driving session (see Table 6). The fourth minute (4th) was the first time instance at which a significant difference between the two driving sessions was found. Therefore, the analysis of ECG data, discussed next, focused on the specific period between the fourth (4th) and tenth minute (10th).

Table 6. Wilcoxon's signed-rank test for differences in subjective discomfort.

	The median increase between defensive and assertive automated driving sessions	z	p	Cohen's d
1st Minute	0.00	-0.82	0.41	0.23
2nd Minute	0.00	0.71	0.48	0.34
3rd Minute	0.00	1.34	0.18	0.47
4th Minute	0.50	2.06	0.04*	0.84
5th Minute	1.00	1.51	0.13	0.64
6th Minute	0.00	1.89	0.06	0.78
7th Minute	1.00	2.23	0.03*	1.00
8th Minute	1.00	2.39	0.02*	0.99
9th Minute	1.00	2.55	0.01*	1.13
10th Minute	0.50	2.06	0.04*	0.83

*$p < 0.05$

3.4. Objective rating - Heart rate & LF/HF Ratio

For the heart rate (HR) measurement, the analysis began with the inspection of the boxplot. Three (3) outliers were found that were more than 1.5 box-lengths from the edge of the box. It was found that these outliers did not influence the results, so they were kept in the analysis. The descriptive statistics of the HR data in beats per minute (bpm) are shown in Table 7. The mean HR baseline values pre- and post- for both driving sessions appeared to be almost the same. HR seemed to increase during driving minute 4th to 10th). Thereby, it is observed that HR increased to a higher level during the assertive automated driving session than during the defensive automated driving session.

A one-way repeated measures ANOVA was performed to determine whether there were statistically significant differences in mean HR value over the three phases for the two driving sessions. HR was found to be statistically significant different over the phases of the defensive automated driving session (F (2,26) = 10.3, p = 0.001, partial η^2 = 0.442) as well as for the assertive automated driving session (F(2,26) = 12.0, p < 0.001, partial η^2 = 0.481).

Table 7. The mean and standard deviation (SD) for the heart rate data in beats per minute (bpm) for both the driving sessions.

Automated driving session	Experiment phase	Heart rate (bpm)	
		Mean	SD
Defensive (N=14)	Pre-experiment	107.86	23.38
	During-experiment	126.82	14.09
	Post-experiment	104.14	21.18
Assertive (N=14)	Pre-experiment	106.07	27.27
	During-experiment	131.41	7.70
	Post-experiment	103.29	27.50

A paired-sample t-test was then used to determine whether there was a statistically significant difference in the mean score of HR values during the three phases for the participants when exposed to the defensive and assertive automated driving sessions (see Table 8). No statistically significant mean difference was found between the driving sessions with regards to any of the phases during the experiment. The baseline conditions (pre- and post-experiment) did not show any statistically significantly different, implying that participants exhibited the same rest conditions before and after both driving sessions.

Table 8. Paired-samples t-test results for mean HR values during the three phases of the two experiments.

Experiment phase	Defensive automated driving session		Assertive automated driving session		t	p	Cohen's d
	Mean	SD	Mean	SD			
Pre-experiment	107.86	23.38	106.07	27.27	-0.34	0.74	0.07
During-experiment	126.82	14.09	131.41	7.70	1.56	0.14	0.38
Post-experiment	104.14	21.18	103.29	27.50	-0.19	0.85	0.03

Inspection of the boxplot revealed three outliers that were more than 3.0 box-lengths from the edge of the box and were disregarded for further analysis. The descriptive statistics are shown in Table 9. A one-way repeated measures ANOVA was performed to determine whether there were statistically significant differences for the low frequency (LF) component over the high frequency (HF) component of the heart rate variability (LF/HF) throughout the three phases. The value of LF/HF was found to be statistically significantly different over the three phases for the defensive automated driving session (F (2,20) = 4.66, $p = 0.022$, partial $\eta^2 = 0.318$). For the assertive automated driving session, a Greenhouse and Geisser epsilon ($\varepsilon = 0.538$) was used to correct the one-way repeated measures ANOVA. LF/HF was not statistically significantly different over the three phases of the assertive automated driving session (F (1.075,10.75) = 1.599, $p = 0.227$, partial $\eta^2 = 0.138$).

A paired-samples t-test was then used to determine whether there was a statistically significant mean difference between LF/HF for the defensive and the assertive automated driving session. The results of this test are shown in Table 10. It can be observed that LF/HF was statistically significantly lower before the assertive session compared to the defensive session. However, no clear conclusions can be drawn concerning the during-experiment phase.

Table 9. Descriptive statistics of the ratio of LF/HF data.

Automated driving session	**Experiment phase**	**LF/HF ratio**	
		Mean	**SD**
Defensive (N = 11)	Pre-experiment	0.94	0.35
	During-experiment	0.60	0.20
	Post-experiment	0.85	0.28
Assertive (N = 11)	Pre-experiment	0.72	0.20
	During-experiment	0.68	0.18
	Post-experiment	1.04	0.91

Table 10. Paired-samples t-test results for LF/HF.

Experiment phase	**Defensive automated driving session**		**Assertive automated driving session**		**t**	**p**	**Cohen's d**
	Mean	**SD**	**Mean**	**SD**			
Pre-experiment	0.94	0.35	0.72	0.20	-2.89	0.02*	0.73
During-experiment	0.60	0.20	0.68	0.18	0.87	0.41	0.40
Post-experiment	0.85	0.28	1.04	0.91	0.69	0.50	0.24

**Statistically significant at the level* $p < 0.05$

3.5. Correlations between participants' subjective & objective measurements

A linear regression established that the discomfort rating subjects gave during the last five minutes of driving could statistically significantly predict their Motion Sickness

Assessment Questionnaire (MSAQ) score, F (1,26) = 77.06, $p < 0.001$ and discomfort rating accounted for 74.80% of the explained variability in MSAQ score, with adjusted $R^2 = 0.74$. The regression equation was: Predicted MSAQ score = 0.22 + 9.78 x (discomfort rating during driving) and is graphically shown in Fig. 2. Additionally, Pearson's product-moment correlation was run to assess the relationship between subjective comfort and the four constructs of MSAQ. The result is shown in Table 11 and implies that the more discomfort passengers were experiencing, the more they tended to develop feelings of MS. This finding appears to support the initial assumption that MS can be seen as an extreme level of discomfort.

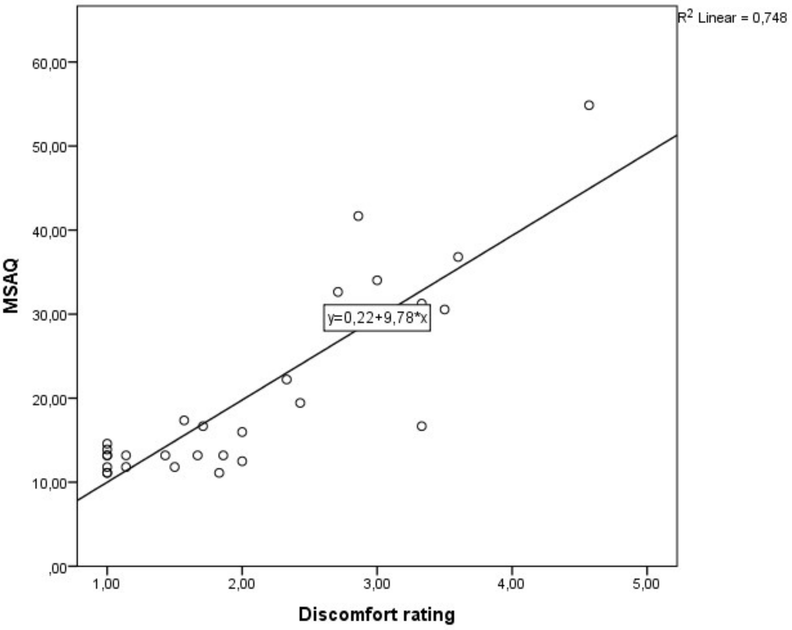

Fig. 2. Linear regression of MSAQ and subjective feeling of comfort during driving sessions.

Table 11. Results of Pearson's correlation of subjective comfort and MSAQ constructs.

	Correlation coefficient r	p
MSAQ score	0.865	$< 0.001^{**}$
Gastrointestinal score	0.834	$< 0.001^{**}$
Central score	0.803	$< 0.001^{**}$
Peripheral score	0.503	0.006^{**}
Sopite score	0.627	$< 0.001^{**}$

***Statistically significant at the* $p < 0.01$ *level;*

A linear regression established that HR measured during driving could not statistically significantly predict participants' subjective feelings of comfort, F (1,26) = 0.602, $p = 0.445$, and HR accounted for 2.30% of the explained variability in discomfort rating, with adjusted $R^2 = -0.015$. The regression equation was:

Predicted rating = 3.72 - 0.013 x (HR). A linear regression established that LF/HF could not statistically significantly predict participants' subjective feelings of comfort, F (1,26) = 3.28, p = 0.082, and LF/HF accounted for 11.20% of the explained variability in discomfort rating, with adjusted $R^2 = 0.078$. However, p-values in the range $0.05 < p < 0.10$ are considered approaching significance. So, there seems to be a trend towards a statistically significant prediction of subjective feeling of comfort by LF/HF. The regression equation was: predicted rating = 0.815 + 1.86 x (LF/HF). Additionally, a Spearman's rank-order correlation was run to assess the relationship between LF/HF and the rating of discomfort, and the result indicated that the correlation coefficient of 0.384 with $p < 0.044$.

Although a linear regression established that LF/HF could not statistically significantly predict participants' subjective feelings of comfort, a statistically significant moderate positive relationship between LF/HF and subjective feeling of comfort was found (*rs* (26) = 0.384, $p < 0.05$). It can be concluded that the relationship between LF/HF and subjective comfort is not particularly strong. Therefore, LF/HF might not precisely predict the discomfort rating during driving.

4. Discussion

Prior work has reported the effectiveness of lower driving forces (i.e., a defensive AV driving style) in terms of users' perceived pleasantness, enhancing the AV riding experience (e.g., [28, 29]. However, the relation between subjective and objective (physiological) data in the assessment of the perception of comfort was not investigated. Other researchers did consider physiological measures to investigate perceived AV diving comfort but did not test the perception of comfort in a public-road AV driving scenario (e.g., [30, 31].

This study focused on the relation between psychological (subjective) and physiological (objective) responses to physical variations (i.e., variations in acceleration driving forces) to study the perception of comfort for AV passengers. Although the recruited sample has lower susceptibility to MS, as concluded from the relatively low MSSQ scores, a significant increase in the subjective feeling of MS resulting from the assertive AV driving style was found. This increase in MSAQ as per the results of previous studies on MS of AV occupants [6] as well as studies on visual flow in virtual motion [32] and MS [33].

Besides, this study (with N = 14 participants) indicates that the defensive AV driving style did not significantly influence the passengers' subjective perception of comfort. For the assertive session, however, it was found that the feeling of MS (discomfort) grew almost linearly concerning exposure time. Thereby, the results showed significant differences in subjective discomfort during the second and last half of driving, when comparing the data of the assertive to the data of the defensive session.

The initial assumption that the feeling of MS can be treated as an extreme level of discomfort was supported by the results of a correlation and linear regression between subjective comfort and MSAQ. It is speculated that MS and subjective comfort can still be treated as two different constructs when investigating AV riding experience. However, both constructs appear to be significantly related to each other. This might be useful for future work, as it allows for concluding on the perception of comfort when, for example, only MS data are available. Knowing that the tested sample had relatively high levels of tolerance in terms of MS and discomfort, the current findings of significant increases in discomfort and feelings of MS might also be of interest for future work. The results imply that even people with no or little previous experience of MS may develop feelings of sickness during AV driving, mainly when the AV drives according to an assertive driving style.

Although increases in HR were observed when comparing the assertive to the defensive AV driving style, they were not statistically significant. Previous research, however, found that increases in HR resulted from either an increase in sympathetic modulation or a decrease in parasympathetic modulation. These increases in HR were found to be related to nausea and vomiting resulting from exposure to nauseagenic motion. (e.g., [34, 35]). For the research under consideration, it was noted that increases in feelings of MS were found significant, though still relatively low, implying that none of the participants experienced severe MS. This might explain the not significant increase in HR when comparing the assertive to the defensive session. The result of the LF/HF ratio did not show statistically significant differences between the sessions. Previous work, however, found that LF/HF is suitable for detecting long-lasting stress events, and so long-lasting discomforting events [31]. Besides, exposure to lower (1.8 Hz) as well as higher vibrations (6.0 Hz) is found to decrease vagal activity (HF) and to increase LF/HF [36]. The current experiment seemed not to cause excessive amounts of stress. Thereby, the LF/HF ratio was decreased during exposure, suggesting that sympathetic activities seemed to reduce. The discomforting event appeared not to last long enough to detect significant changes in LF/HF, which might be different in case of higher susceptibility to MS.

When considering the correlation and linear regression between physiological responses and subjective comfort, it was observed that the subjective comfort could not be predicted based on the HR data. Therefore, it is speculated that variations in HR do not mimic the subjective perception of comfort accurately enough. For future work, this implies that for a given physical variation, HR is somewhat not reliable to predict the resulting psychological variation. Also, with regards to the relationship between subjective comfort and LF/HF, a linear regression did not reveal a significant relationship. Although a significant positive correlation between subjective comfort and LF/HF was found, this correlation was assumed to be not strong enough to draw definite conclusions. This might also be because no severe feelings of MS were reported. Previous work successfully found that LF/HF increased with the rating of MS [37] and that increases in LF (n.u.) relate to increasing nausea (e.g., [38] which corresponds to gradual sympathetic activation [39].

The current findings, however, extend those of [40], who did not observe significant changes in HRV and HR in subjects who did not complain about MS after watching a movie with oscillating pictures. In general, the regressions and correlations between HRV parameters and subjective comfort indicate that it might not be useful also to measure the physiological variation resulting from physical variation to predict subjective comfort. This contradicts the hypothesis that physical variation would lead to specific variations in the physiology that accurately mimic psychological variation. Thereby, however, it is noted that GSR could alternatively be used as a measure for physiological variation since prior work found that GSR is a promising measure in assessing intense discomforting events [31, 41].

Finally, it could also be noted that the two experiment sessions consisted of only ten minutes of driving for each session. Future work might also investigate the effects of forces generated during AV driving when exposure to these forces is spread over a more extended period, e.g., one hour of driving. The experiment sessions were also organised on the TU/e campus, which is a slightly urbanised environment with only cobblestone roads. Therefore, it might also be worthwhile to assess the aforementioned physical boundaries at higher vehicle speeds as well as in other environments and on other types of road surfaces.

5. Conclusions

Although the assessment of MS experience revealed that the sample group was not susceptible to MS, the assertive AV driving style resulted in significant increases in the feeling of MS. Thereby, a correlation and linear regression confirmed the initial assumption that MS can be treated as an extreme level of discomfort.

HRV analysis revealed no significant changes when comparing the two experimental sessions. HR results indicated an increase during the assertive session compared to the defensive session. However, it turned out that this increase was not significant, which was also the case for the relation between HR and subjective comfort. The LF/HF ratio also did not show significant changes when comparing the two experimental sessions.

The results of this study suggest that further development of full AVs should consider the effects of strong forces that are exerted on the passenger's body. AV driving is promoted as a mobility solution that allows for involvement in non-driving tasks such as reading. To be perceived as comfortable, the findings of this report suggest that AV driving styles should be such developed, that forces exerted on the passenger's body are kept low. This will probably improve the AV riding experience and reduce the likelihood of discomfort, such as MS.

Future research should look at the level of comfort especially the effects of motion sickness when the passenger of an AV in performing other non-driving related tasks such as watching a movie or reading when travelling in an automated mode. In addition, the effects of different geometric landscape of the road for example, suburban and winding roads, should be also be considered. Another factor that can be studied is the role of visual stimuli in the driving environment. In this case, subjects were isolated entirely from the physical environment the vehicle was driving in. This implies that the obtained results apply for those passengers who do not have any kind of behavioural information about the vehicle or ability to look outside. It is speculated that either or both of these stimuli might increase the levels of tolerance, but future research should investigate whether that is the case or not.

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