Experiments On Motion Sickness Repeatability And Hypersensitivity For Autonomous Vehicles

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Abstract For motion sickness modeling on an individual level, it is important for individual sickness responses to be repeatable, however no study has yet investigated repeatability. In addition to this, complex phenomena such as hypersensitivity are still poorly understood. The paper aims to address both points. In the present study participants were seated at the back of a Toyota Prius. All external vision was blocked, providing only an internal view of the car. The drive consisted of a slalom of 0.2 Hz with a lateral acceleration of 0.4 G force for the passenger. In total sixteen participants first underwent a three minute standing sway test, followed by a thirty minute exposure to the sickening motion, after which a subsequent hypersensitivity round was performed. During the drive the head acceleration and head roll were recorded and the motion sickness of the participant was quantified using the misery scale (MISC). A factor of 3.7 times larger MISC rate was observed for the hypersensitivity round compared to the first motion exposure. This shows the robustness of hypersensitivity. In addition to this, median variation in the intra-individual sickness response was a factor 5.75 smaller than the group variation. This shows consistent individual responses to sickening stimuli, which is promising for future modeling efforts. Finally the α value after analyzing the standing postural sway is Pearson correlated with the MISC rate and is found to be -0.4 (p=0.0142). This supports Stoffregen's theory of postural stability for inertial motions, a point which was never validated. However, the head accelerations as well as the head roll during the drive did not show significant correlation with MISC rate. This implies that movements of the head while driving do not relate to the susceptibility of an individual to motion sickness.

Introduction

With the rise of autonomous vehicles, a change in the nature of travelling occurs. Driving from one place to another will include reading a book or working on an electronic device. The problem that occurs is that people who do not have their eyes fully on-road will get more easily motion sick {1}, which overrules the utility and usefulness of autonomous vehicles in the first place. Therefore it is profitable to increase understanding of what motion sickness is, which may allow for novel ways of increasing user comfort and friendliness of autonomous cars. If a model could predict an individuals susceptibility, the car could change its driving behaviour, resulting in a more comfortable ride in an autonomous vehicle. Modern research on motion sickness has led to two theories: sensory conflict theory and ecological theory. Both attempt to give an explanation on the origin of motion sickness and both have a different look on the cause.

The most accepted theory is the sensory conflict theory and has been researched by Reason {2}{3}). This states that a neural mismatch between the signal sent by the sensory organs and the expected signal, which are stored in the 'neural store'. If these signals create a conflict vector, this results in motion sickness. Oman gives a more mathematical explanation based on an observer model{4}. Even though these models thoroughly describe the motion sickness within the nervous system, it does not explain what gives rise to the difference in susceptibility between individuals. The second theory of motion sickness is the ecological theory, devised by Stoffregen{5}. In his paper he argues that motion sickness is a result of postural instability. A person who is more unstable with respect to posture has a larger body sway (which is the movement of the body while standing still). Therefore an individual with bad postural control will have more trouble correcting him/herself to a new motive situation. Riccio & Stoffregen (1991) hypothesize that it all has to do with the amount of body motion a person experiences in the car{6}. In order to improve or make a model which could predict the susceptibility of motion sickness of a person, one should know whether the dynamics of motion sickness is solely dependent on motion exposure.

Repeatability of the experiment is useful for making the first steps in the prediction of motion sickness response. However, a lot of confounders can influence motion sickness response, making it difficult to illicit repeatable responses even from identically run experiments. Primarily the habituation of the participants to the motion process is of prime influence in this case. To explain, habituation is whereby subsequent exposure to motion sickness after sufficient recovery

time has been allowed for, yields a much smaller sickness response than before. Research has shown participants habituate after daily exposure{7}, therefore a long rest period in between experimental sessions should be given to minimize habituation. Experimental research has been done on the behaviour of people after they just experienced motion sickness, called hypersensitivity. In literature, models exist that try to model the hypersensitivity as a fast pathway gain in a control loop where a certain threshold is reached{8}. Whenever hypersensitivity occurs it should be taken into account when predicting the motion sickness response of an individual.

Repeatability and hypersensitivity of motion sickness are of great importance in order to model susceptibility and to improve the comfort of autonomous vehicles. Therefore this paper will show whether the behaviour of participants during the experiments that are done are repeatable and whether or not hypersensitivity occurs. Besides this, the postural stability of participants is taken into account related to their susceptibility {9}. The expectation is that the responses of the participants are repeatable compared to the group deviation through the weeks and that they show hypersensitive behaviour after they just experienced motion sickness. The different levels of susceptibility of individuals to motion sickness is expected to be caused by the postural stability of the body. This is due to the individuals ability to correct their posture in accordance with the vehicle's motions.

Method

A. Experimental Setup

In total sixteen randomly selected participants from the TU Delft student and PhD population, ranging from 19 to 30 years (μ =22.9 σ =2.56) (12 male and 4 female), were selected to join the experiments three times with an interval of one week between sessions to minimize habituation {7}. In order to simulate eyes-off road conditions, similar to users of automated vehicles that could be occupied with reading or operating digital devices, the participants were seated on the middle back seat of a Toyota Prius of which its windows were blocked. So the passengers had no view of the outside surroundings. The test drive represented a sinusoidal drive with a frequency of 0.2 Hz and an amplitude of 3.5 m. This pattern with a speed of 25 km/h resulted in lateral accelerations of 0.4 G {10},{11} which is also the maximum experienced in urban driving. According to O'Hanlon {12}, ~~the~~ 0.2 Hz is the frequency at which peak motion sickness incidence is seen. Along with the internal vision condition and large lateral accelerations a robust sickness response was sought. MISC is the 'Misery Score' which is generally accepted in motion sickness research{13} and is used to express the amount of motion sickness someone experiences at a given point. The MISC scores are on a scale from 1 to 10, where a MISC score of 1 is equal to no feeling of nausea or its symptoms and a MISC score of 7 corresponds to a moderate feeling of nausea. The first drives, denoted as Motion Track 1 or MT1, take up to 30 minutes or until the participant reaches a MISC of 7. After this drive a resting period of maximum 15 minutes is given, or until the participant reaches a MISC of 2. During the second test drive, denoted as Motion Track 2 or MT2, the hypersensitivity of the participant is tested.

B. Gathering Data

The motion sickness during the experiment was expressed via the MISC, for which every 40 seconds a response from the participant was recorded. The orientation, (angular) acceleration, position and velocity of all body segments of the participant were also recorded by a motion capture suit, the Xsens{14}. In advance of the drive an individual body sway test was done, in which a participant stood still for three minutes, this was used to quantify pre experiment postural stability. The sway recording took three minutes and the feet distance apart was the distance of the participants natural stance during the first test and from then on taken as the standard distance between the feet for all subsequent sway tests for that particular participant. The acceleration of the car was tracked via an IMU attached to a solid horizontal pane beneath the seat of the passenger.

C. Processing Data

Formula 1 uses the weighted accelerations of the car and time to express the motion sickness dose value {15}. Whenever this increases linearly the accelerations are constant over time. This way the accelerations and time are taken into account to evaluate the MISC development.

$$lin.MSDV = \left[\int_{t=0}^{t=T} a_w^2(t)dt \right] \tag{1}$$

The MISC recorded is used to express the amount of motion sickness someone experiences. The MISC rate formula 2 was used in order to compare results of individuals. The maximum and minimum MISC were subtracted and divided by the duration to get ~~up~~ to the maximum MISC.

$$MISC_{rate} = \frac{MISC_{max} - MISC_{min}}{Duration_{drive}} \tag{2}$$

The Detrended Fluctuation Analysis uses formula 3 in order to calculate the variance of each frame length (l) of an increasing sample path. This way, a local trend is weighted over a moving and increasing frame which results in a changing trend value. This value expresses the magnitude of motion over time.

$$F(l) = \sqrt{\frac{l/s}{N} \sum_{n=1}^{N/(l/s)} \frac{1}{l} \sum_{k=1}^{l} [y(k) - \hat{y}(k)]^2} \tag{3}$$

Using the formula $log(F(l)) \sim log(L^{\alpha})$, retrieves the scaling exponent α which is an index of long-range auto correlation in the data, that is, the extent to which the data is self-similar over time.

To get the head accelerations of the participants, the orientation and acceleration data in the global frame are tracked with the Xsens. Those are converted to the local frame, which is done via rotation matrices. Afterwards a third order Butterworth filter is applied with cutoff frequencies of 0.05 Hz and 0.99 Hz. This low cut-off frequency is used to remove orientation drift in the orientation data of the Xsens{10}. This finally gives head accelerations in x, y and z direction during the test drives.

In order to express the head acceleration in a ratio which can be compared among individuals and different runs the root mean square value is used in the y direction. This direction corresponds with the roll of the head and is shown in formula 4 (in the same way the RMS can be calculated for the head roll).

$$RMS(a_{head,y}) = \sqrt{\frac{1}{t - t_0} \int_{t_0}^{t} a_y^2 dt} \tag{4}$$

The following statistical tests are used in order to validate the stated results. The Ranksum test returns the p-value of a two-sided Wilcoxon Ranksum test. The null hypothesis of this test is that data of two sets are samples with equal medians. Next to this test the Levene's test is used which returns the p-value for the null hypothesis which states that the columns have the same variance. The Surrogate test detects nonlinearity in time series. The null hypothesis describes a linear process and if the value of the statistic is significantly different from the original series the null hypothesis is rejected and nonlinearity is assumed.

Results

MISC vs linear MSDV

The MISC of each participant was plotted along the linear MSDV(formula 1), it takes the acceleration magnitude and frequency into account while having a linear relationship with time. One can see in figure 1, which shows the development of a participants MISC during the first motion track. These graphs were made for all the participants and give insight into the results of repeatability, habituation and low or high susceptibility of the individuals. The other graphs for MISC and linear MSDV can be found in the appendix, figure 9 on page 8. As one can clearly see there is a change in how the MISC develops when comparing consecutive weeks. In order to quantify the differences within the individuals and the different runs the MISC rate using formula 2 was used, which states a ratio for the maximum reached MISC over the time to reach this score.

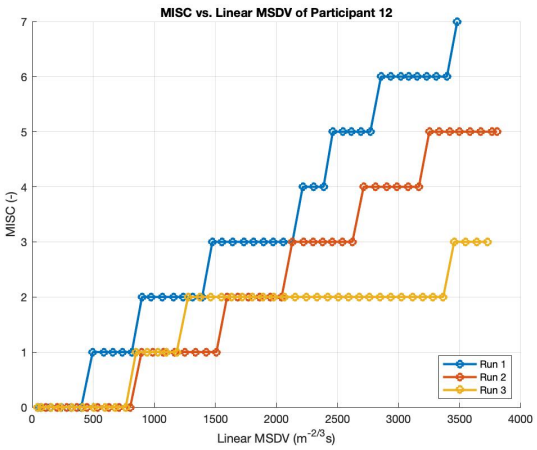

Figure 1: MISC vs. Lin.MSDV MT1

Car accelerations

The lateral acceleration of the car was similar over all the drives, this is in accordance with the predetermined method. As such, for the proceeding analysis, the deviation between drives is assumed to negligible. In the appendix, figure 16 shows the boxplot of the Root Mean Square value of the lateral acceleration of the car during MT1 of all weeks. It shows a clear decrease in the extreme values of the RMS over the weeks. This means the drives get more constant over the weeks. The table 1 shows the median RMS value of the car acceleration, the ranksum tests do not reject the null hypothesis within the weeks. This Implies that the median within the weeks is the same with corresponding p-values: week 1-2 0.23, week 2-3 0.77 & week 1-3 0.21.

	$\tilde{x}$	σ
Week 1	3.75	0.58
Week 2	3.25	0.38
Week 3	3.27	0.61
All weeks	3.30	0.55

Table 1: Median ($\tilde{x}$) and deviation (σ) of Ay of the car during MT1

Repeatability

Using the MISC rate, formula 2, the repeatability of an individual over the weeks can be compared and used to express the difference between the first drive (MT1) and hypersensitivity drive (MT2). Figure 2 and figure 3 show the MISC rates for participants against week numbers for MT1 and MT2 respectively. The flatter lines show repeatable MISC rates over the entire testing period. Larger variations in the MISC rates show non-repeatability. Clearly the participants with a MISC rate lower than one show repeatable results during MT1. A more quantified result can be given when one looks into the deviation of a MISC rate compared to its average rate between individuals and the group rates, over all runs. Whenever the deviation

of an individual is significantly smaller than the deviation within a group, repeatable results can be assumed.

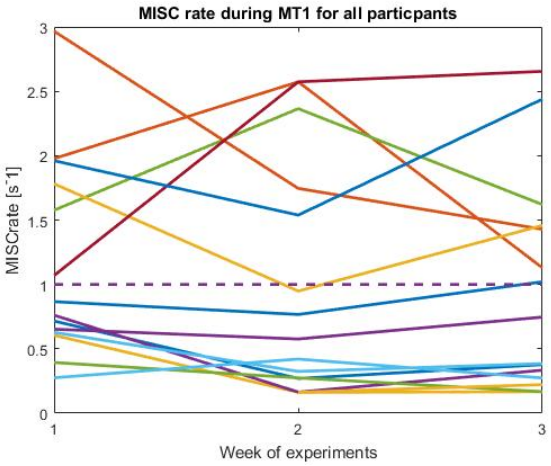

Figure 2: MISC rate in MT1

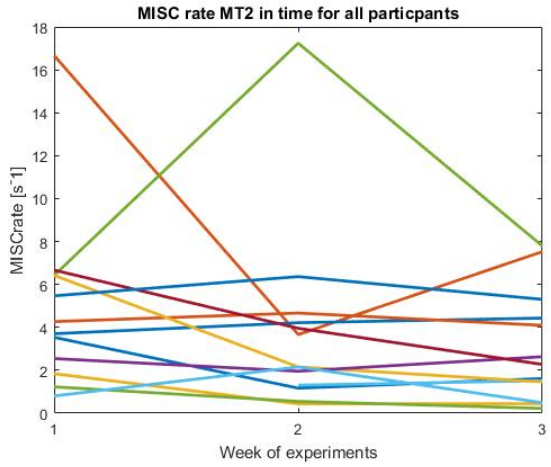

Figure 3: MISC rate in MT2

The mean MISC rates of all weeks in table 2 show the following relations: the effect between week 1 and 2 shows signs of habituation, with an average decreasing effect of 0.13 (p = 0.9137) and between week 1 and 3 an effect of 0.16 (p = 0.8869). This high p-value can partially be explained by looking at the group-average and not the average for the individuals. Another difference that can be seen is that deviations on the median come out lower. This can be explained by the fact that the median is less sensitive for outliers by definition, which results in an overall lower deviation. Combining these to the findings, there is also evidence for the importance of medians and looking at individuals when it is clear that deviation can differ by a factor of 5.75. Another interesting phenomenon that can be shown is the difference in decrease for the mean in misc-rate. Whereas the difference between week 1 and 2 is 0.13 on average, the difference for 2 and 3 is just 0.03 on average. This difference is visualized in figure 2 and can be quantified by looking at deviations for individuals between weeks and deviations for the group between weeks, looking at table 2.

Using the Ranksum test, the median of the average MISC rates of MT1 can be compared among the weeks. The null hypothesis is not rejected for all tests, which implies equal medians with a corresponding p-value of: week 1-2 0.33, week 2-3 0.84 & week 1-3 0.37.

	$\overline{x}$	σ	$\tilde{x}$
Week 1	1.12	0.77	0.81
Week 2	0.99	0.92	0.58
Week 3	0.96	0.82	0.75
All weeks	1.02	0.82	0.75

Table 2: Average MISC rate of all weeks MT1

All the MISC rate distributions of MT1 follow a log-normal distribution and are tested as can be seen in the appendix in figure 14 (page 11). Plotting those in one figure for the different weeks shows a fit of week 1 with a higher distribution along a higher MISC rate. However the distribution of week 2 and 3 show comparisons at a lower MISC rate. This indicates that habituation of the participants occurs while the weeks progress (which is insignificant as described above) and can be seen in the appendix, figure 13 on page 10, however these fits are also proof of the repeatable responses of the participants. R^2 is used to express the validity of the log fits of the MISC rates and indicate the percentage of variance that is predicted by the fitted variable.

$R_1^2 = 0.56 \quad R_2^2 = 0.48 \quad R_3^2 = 0.30 \quad R_{all}^2 = 0.29$

Figure 4 shows the deviations of the average MISC rate within a participant and the group for MT1. An individual with a low deviation would imply that the gathered data is repeatable. The Ranksum tests show a p-value of 0.33 for the MISC rate week 1 and 2 and a p-value of 0.84 for the MISC rate of week 2 and 3, which does not reject the null hypothesis that the variance within the weeks is the same. The results of the Levene's test on the MISC rates is a p-value of 0.79, which does not reject the null hypothesis. It therefore can be stated that the variance within the weeks is the same. Table 3 states the mean and median with a Ranksum p-value for the individual and group of 0.00000014 which does reject the null hypothesis of equal means.

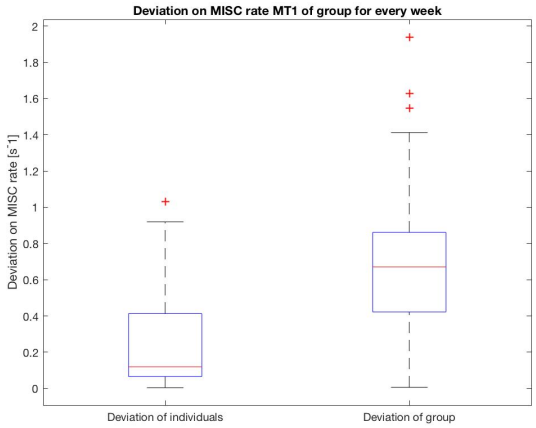

Figure 4: Deviation MISC-rate of MT1 of group & indv. every week (boxplot)

	$\overline{x}$	$\tilde{x}$
Individual σ	0.25	0.12
Group σ	0.70	0.69

Table 3: Avg. MISC-rate of MT1 in 3 runs

Hypersensitivity

The strong increase of the MISC rate within the two rides is shown in figure 5. It is presented using a boxplot of all the average MISC rates of all participants in MT1 and MT2. The boxplot shows a strong increase of the mean with a factor 3.7 for the MISC rate during this hypersensitivity track. The Ranksum test has a p-value of 0.00091 so this clearly rejects the hypothesis of equal medians of all weeks combined for MT1 and MT2. When looking at individual level of hypersensitivity, there were some unique cases in which the response of MT1 and MT2 of a participant were the same. Participants 3, 4, 12 and 13 showed these behaviors in which the rates between MT1 and MT2 were approximately the same.

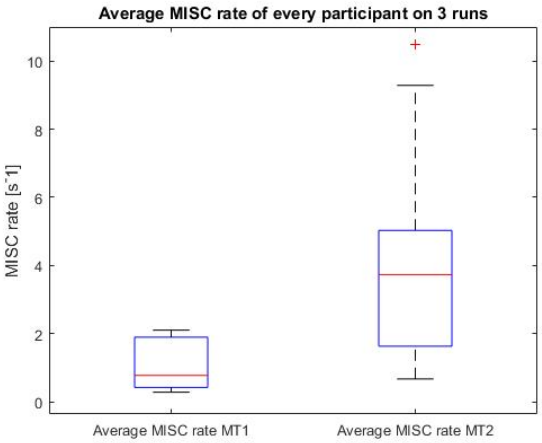

Figure 5: Avg. MISC-rate in 3 runs, (boxplot)

	$\overline{x}$	σ	$\tilde{x}$
MT1	1.1	0.75	0.8
MT2	4.1	3.1415	3.7

Table 4: Avg. MISC-rate in 3 runs

Variance

All given results were focussed on the comparisons and variances within the runs and the participants, but finding out what causes these variances turns out to be difficult due to human factors. In this research this is done by analyzing the personal body sway of an individual using the Detrended Fluctuation Analysis (DFA){16} and a density of motion analysis. These two methods are useful for obtaining quantifiable results on the postural stability of a participant while standing still. During the test drive and stability test, the importance of the head movements is paramount, due to the location and orientation of the vestibular organs. The head acceleration as well as the head roll during the drive has been accounted for using a Root Mean Square method, formula 4. Figure 6 shows the correlation between the α value of the Detrended Fluctuation Analysis and the MISC rate of all weeks. It shows that people with a higher α value for the DFA have a lower MISC rate. This α has a value of -0.4 (p=0.0142) and it expresses the complexity of the movement along their y-direction (forward and backward) over time and therefore the stability, the scaling exponent α is an index of long-range auto correlation in the data, that is, the extent to which the data is self-similar over time. To gain insights into the correlation per week, see appendix 10 on page 9.

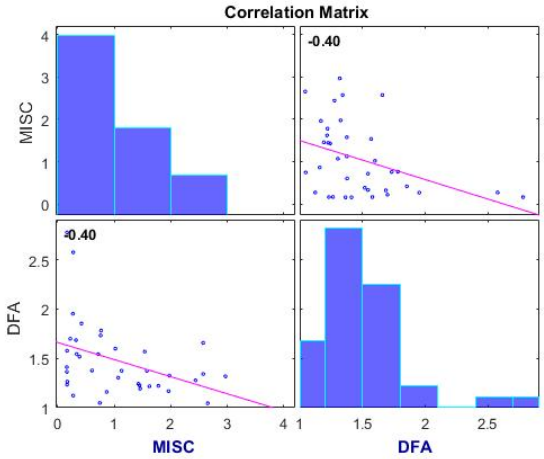

Figure 6: Corr(DFA,MISC-rate) (of all weeks, standing sway)

Figure 7 shows the Root Mean Square value of the head lateral accelerations in local frame without normalizing this with the cars acceleration during the drive correlated to the MISC rate of all weeks during MT1. All experienced RMS values of the head accelerations are within a range of 2 and 2.5 $[m/s^2]$. The Pearson correlation test gives a factor of 0.02 (p=0.92) with the MISC rates. The high p-value combined with the low correlation coefficient, imply that head accelerations highly likely do not explain the differences in susceptibility. The lateral direction is according to the roll of the head while driving. A low RMS head accel-

eration value suggests that the head moves less severe during the drive. To obtain more information about the correlation between each week is, see appendix 11 on page 9.

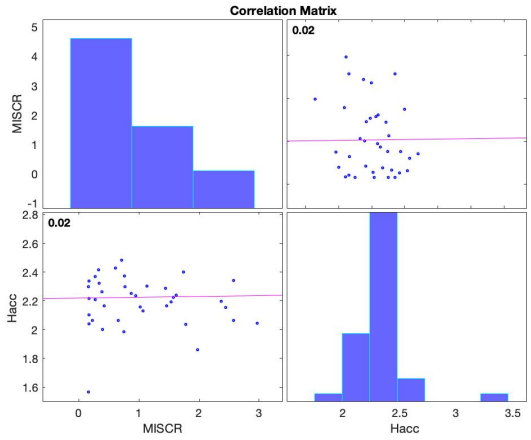

Figure 7: Corr(a_{head},MISC-rate) (of all weeks during MT1)

Subsequently to the head accelerations, the head roll is analyzed during MT1. The head roll of all participants are expressed using the root mean square value from formula 4 but then applied on the head roll. Comparison of these values to the MISC rates for all weeks shows a correlation coefficient of 0.05 (p=0.77)(shown in figure 8), which implies that the amount of head movement during a drive is highly likely to not account for the susceptibility of an individual to motion sickness.

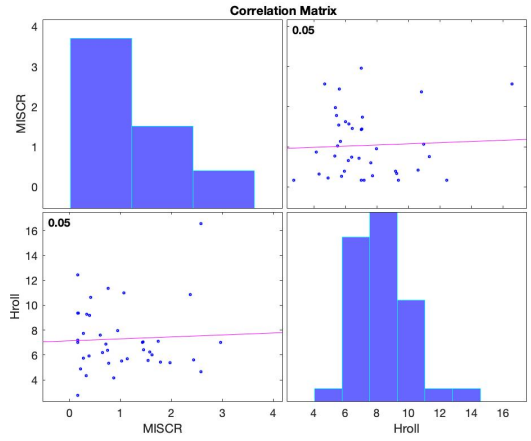

Figure 8: Corr($Roll_{head}$,MISC-rate) (of all weeks during MT1)

Combining the results of the detrended fluctuation analysis, which shows that less stable participants while standing are more susceptible to motion sickness, with the finding that there is no relation between the motions perceived by the head during the drive and the MISC rates, the theory of Stoffregen {5} is partially supported.

Discussion

In order to get statistically sound results for the stated research questions, a substantial amount of data had to be gathered. This research is based on fifteen proper 3-run data sets, however within these data sets not all data is available due to failure of the measurement equipment. There was a one week interval within the runs in order to minimize habituation. Nevertheless the data of the MISC rate (appendix 17) and log fits (appendix 13) show a habituation factor (however with a low statistical power) within the first week and week two and three. This does not correspond to the research conducted by McCauley et. al. (1976){7}, in this it was stated that 1 week rest was enough to discount habitation. However the nature of habituation is complex. It is dependent on the motion complexity, motion magnitude and duration, so it is not too surprising for some habituation to occur in this experiment. Difference in results may come from the fact that their research was done with five participants, whereas this experiment is conducted on fifteen participants, making it statistically more valid. However, these results have not been gathered from the exact same experiment and therefore the results cannot be compared one-to-one. When comparing the results with the theory by Oman(1990) {8}, there is a similar response in the participants as is the case in this experiment comparing the MISC rate of MT1 and MT2. However the deviation for individuals is smaller (for the median) than the group deviation by a large margin. This can be explained since the median is less sensitive for outliers and thereby resulting in a more statistically viable deviation. The relatively large deviation in individual MISC rate responses are mainly caused by the few outliers with high MISC rates. This can be explained when further investigation of the participants is done, on for example the individuals physical and mental state on that particular moment. There is a difference with Stoffregen's experiment for the share of head motion in determining body motion {17}, their results were based on how body parts behaved with respect to each other. In this experiment only the motion of the head with respect to itself is analyzed, considering that the vestibular organ is located there. As Stoffregen poses a theory on how postural control precedes all motion, this paper takes an interest in the effects with respect to motion sickness. Therefore the head motion was the motion that was worth considering. However to quantify someone's stability, one could also look at the sway of the ankles or compensations by the feet, or use a pressure board instead of the displacement of the head. Moreover the results from this paper are based on test drives which were on a relative short track of 240 meters. This resulted in a large amount of 3 point turns to turn around, when an infinity track would be used more stable results could be gathered.

Conclusion

Results gave an increase of the mean MISC rates with a factor of 3.7 (p = 0.00091) between MT1 and MT2, thereby confirming the theory about a hypersensitivity reaction of the participants.

The deviation within the MISC rate is a factor of 2.8 smaller within an individual than within the group and participants with a low MISC rate show a more stable development without many fluctuations, however when the MISC rate is larger there is a greater range of MISC rates. This gives clear results for repeatability and for the more susceptible participants there is less evidence to prove this hypothesis.

As for the variation in the group, detrended fluctuation analysis shows that people with a lower postural stability have a higher MISC rate and thus get sick more easily. The correlation plots show that the α value negatively correlates with the MISC rate with a value of -0.4 (p=0.0142). This substantiates the theory of Stoffregen {5}, considering the theory states the standing postural instability results in larger body sway.

However, the correlation of the RMS of the head acceleration and MISC rate, shows an correlation coefficient value of 0.02 (p=0.92). A similar low correlation coefficient value of 0.05 (p=0.77) is observed when doing the same with the RMS value of the head roll. So there is strong evidence that the motions effecting the vestibular organs are not at all related to the amount of motion sickness.

Concluding, this research shows a strong increase in the MISC rates of the second drive and supports the hypothesis about hypersensitivity. Besides this, the individuals show repeatable results within the weeks excepted for the outlying participants. These differences within susceptibility are due to the core stability within the anterior–posterior direction. Nevertheless the amount of motion of the head in roll and lateral acceleration during a drive does not relate to the susceptibility of an individual to motion sickness.

Further studies

Firstly, introducing a fourth week subsequent to this research would be helpful to gather more data for the repeatability research, since there is a progression in MISC-rate that cannot be fully explained with the current data. Therefore, to make the results more statistically valid, a larger sample size and amount of experiments would suffice. Secondly, there would be a better understanding in the process of repeatability or habituation if the data on MISC vs. Linear MSDV would be exponentially curve-fitted. By doing this, these parameters would result in quantifying the process of motion sickness even further. Thirdly, using another tracking device for validating the measurements on body motion would be suited for results even more valid, for which in this case the measuring equipment to be validated is the Xsens. As the sensors on the Xsens have local frames that are transformed from an global reference frame, its possible to validate the measurements made by these sensors.

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Appendix

In this section the following graphs and information can be found:

1. MISC vs. lin MSDV
2. Correlation DFA and MISC-rate
3. Correlation a_{head} and MISC-rate
4. Correlation $Roll_{Head}$ and MISC-rate
5. Log fits of the MISC rates of 3 different weeks
6. Histogram results with a log fit of all runs
7. LinMSDV of the car of all the runs
8. RMS lateral acceleration of car over the weeks
9. Boxplot of Misc rates of every week

Appendix 1: MISC vs. lin MSDV

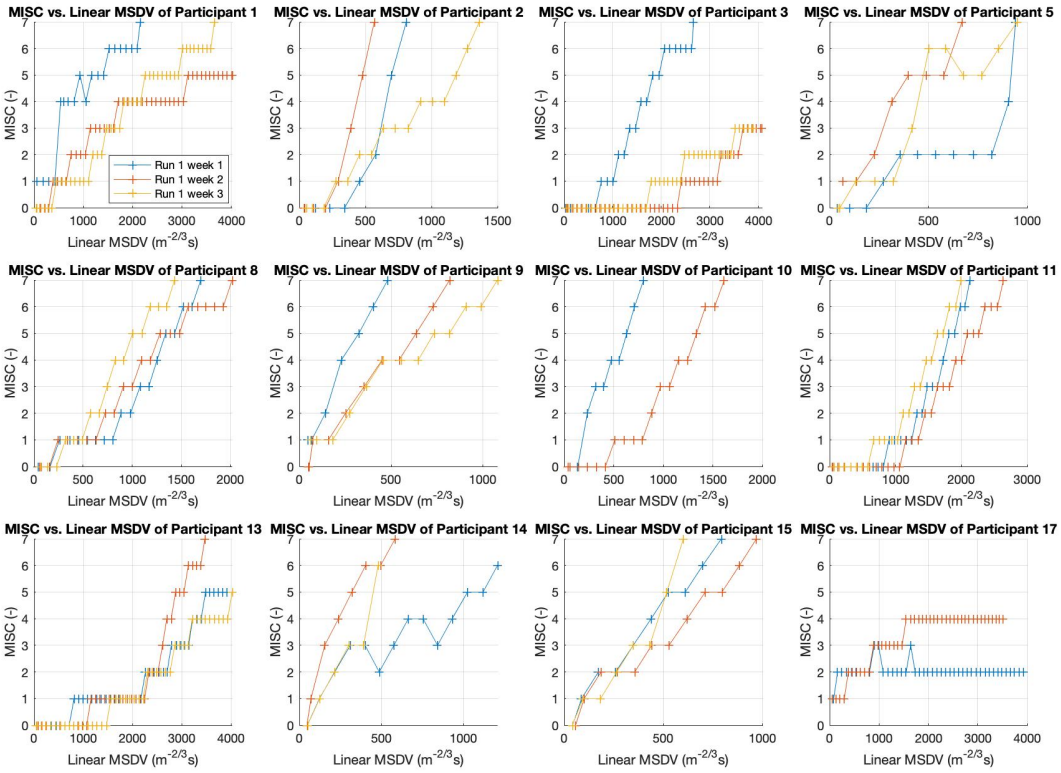

Figure 9: MISC vs. lin MSDV in MT1

Appendix 2: Correlation DFA and MISC-rate

In figure 10 on the x-axis the MISC rates of every week is scattered. This has been plotted against the α coefficients determined by DFA. The diagonal graphs in this figure show the correlation within each week. The other elements are part of the analysis, but do not have a direct physical meaning.

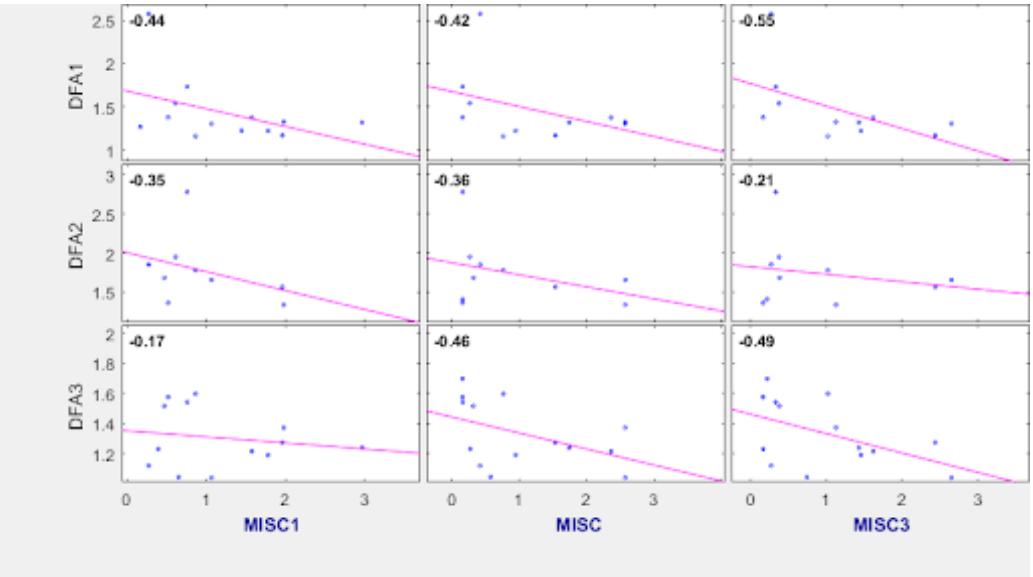

Figure 10: Corr(DFA,MISC-rate)(standing sway)

Appendix 3: Correlation $R.M.SHead_{Acc}$ and MISC-rate

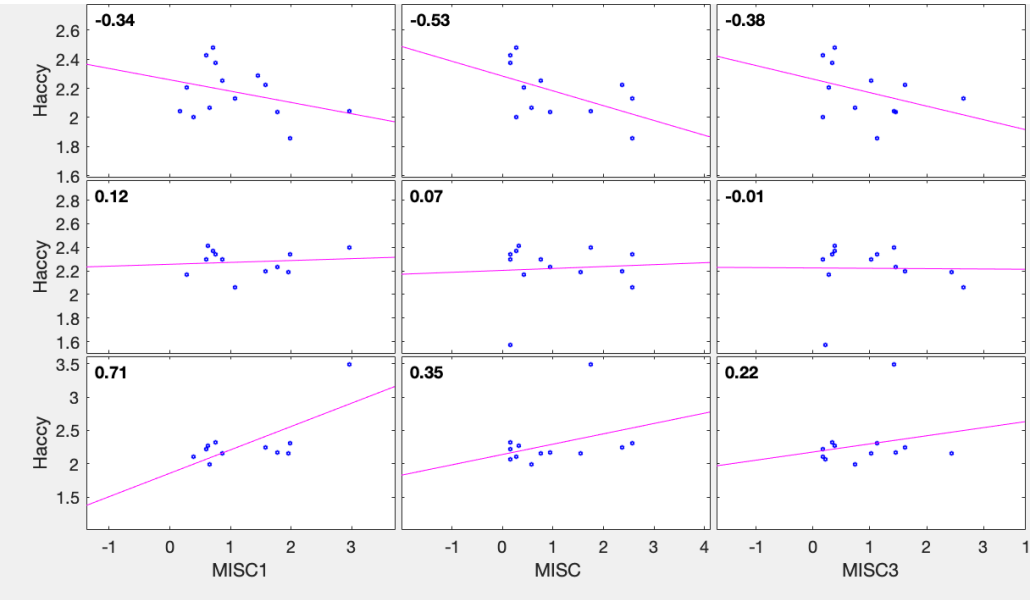

Figure 11: Corr(a_{head},MISC-rate)(while driving)

Appendix 4: Correlation $R.M.SHead_{roll}$ and MISC-rate

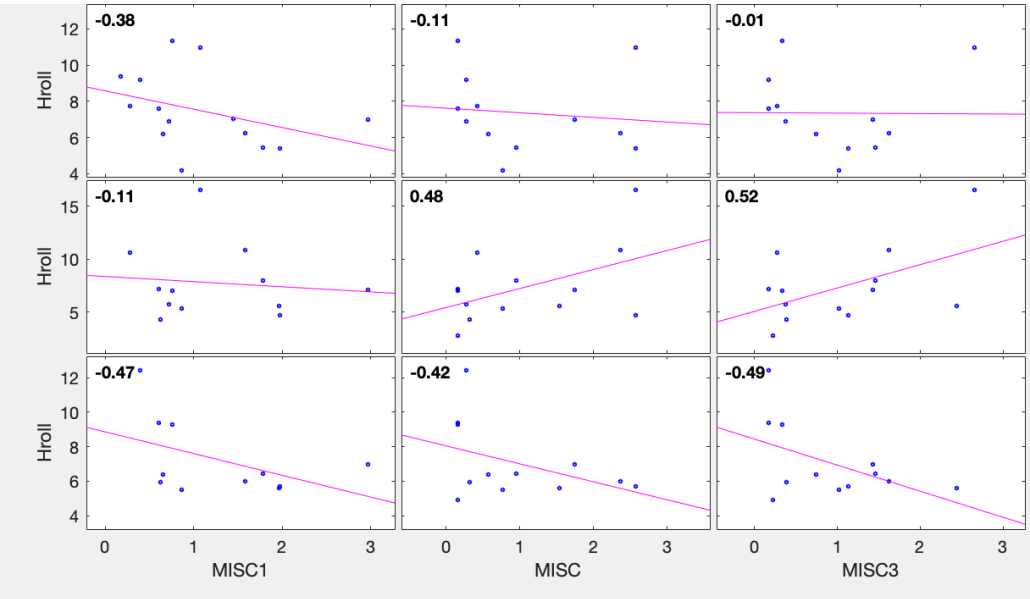

Figure 12: Corr($Roll_{head}$,MISC-rate)(while driving)

Appendix 5: Log normal fit of all MISC rate in every week

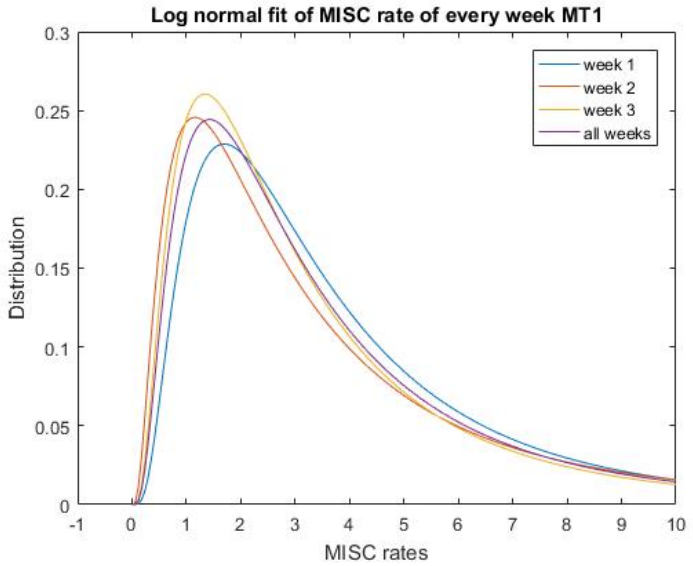

Figure 13: Log normal fit of all MISC rate in every week

Appendix 6: Histogram data of all MISC rates with the according log fit

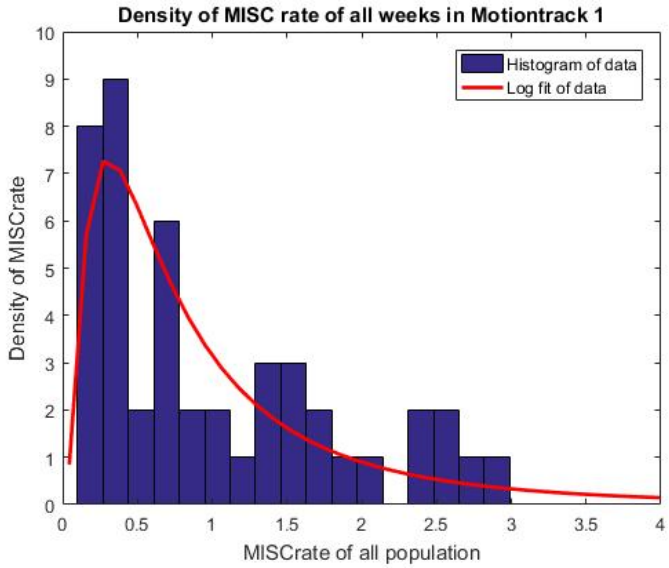

Figure 14: Histogram data of all MISC rates with the according log fit

Appendix 7: LinMSDV of all runs

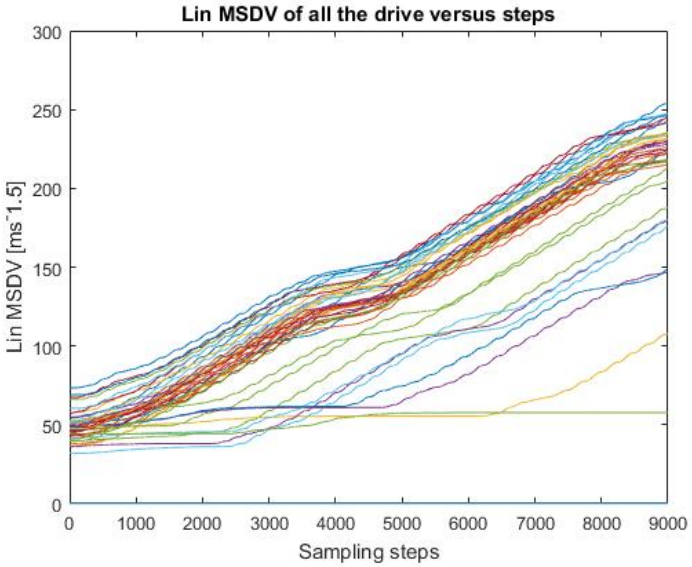

Figure 15: LinMSDV of all runs

Appendix 8: Lateral acceleration of the car over the weeks, (Boxplot)

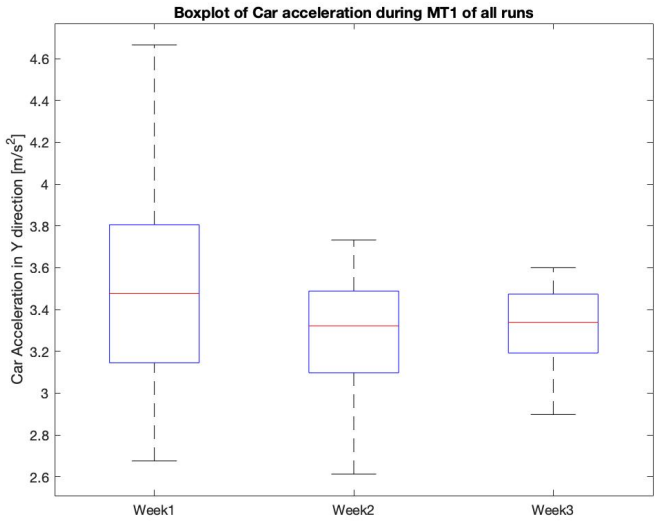

Figure 16: Lateral car acceleration of MT1 of all weeks, (Boxplot)

Appendix 9: MISC rate of individual of every week, (Boxplot)

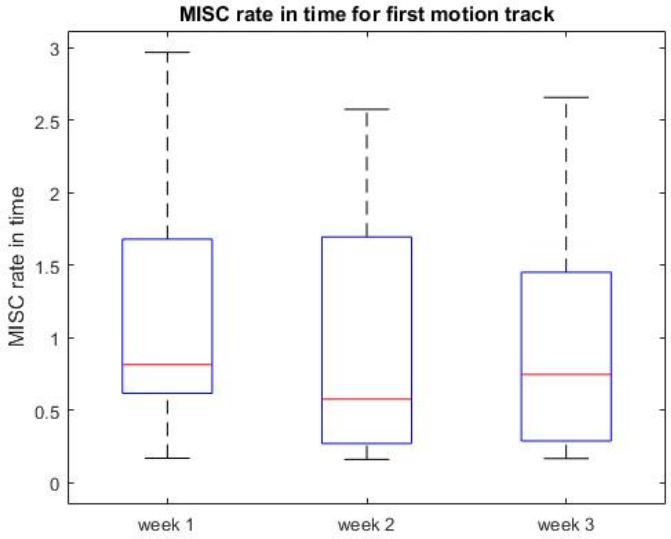

Figure 17: MISC rate of individual of every week, (Boxplot)