Preliminary Technical Test of Different Physiological Modalities to Detect Workload in Humans in Microgravity

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Abstract: In this work we aim to investigate whether eye tracking, electrocardiogram and respiration are good measures to detect workload (WL) of humans in microgravity. To this end, an auditory N-back study was performed during a parabolic flight in microgravity and during a control condition in the lab under Earth gravity by 3 operators of the experiment. The data were analysed regarding their predictive nature to estimate WL. The results show that none of the parameters are suitable for WL detection in humans due to the very short microgravity phases (~22s) and due to scopolamine intake. Nevertheless, some parameters are potentially suitable for longer stay in microgravity. In addition, the results of this study were compared with the results of a previously published electroencephalogram (EEG) analysis on the same data set. This comparison shows that EEG is a more promising predictor modality for WL. In future work, we will conduct another study to extend the number of operators. Different conditions than short term parabolic flights and measurement with longer duration are needed to investigate the stability of WL prediction.

1 INTRODUCTION

To be aware of the overall workload (WL) level of a person during a given task is helpful in different areas. It is an advantage to know the overall WL level of a person to prevent mental disorders as, for example, burnout due to permanent stress and overload (Greif & Bertino, 2022). The tendency towards mental disorders increased in the past (World Health Organization, 2024) and this must be avoided as much as possible. To protect people working in safety-critical environments, they must be better monitored in terms of WL. In space it is important to know the WL level of each astronaut, since a higher level of WL is related to a higher risk to make mistakes (Morris & Leung, 2006). For astronauts it is important not to make mistakes during complex tasks outside the ISS, as this can quickly end fatally. During space missions people experience microgravity, so gravitational conditions are different from those on Earth. As people are used to perform their tasks in Earth gravity, microgravity will likely have an impact on the overall WL since astronauts are not used to it in general. The Multiple Resource Model by Wickens (2008) shows that many different dimensions have an influence on the overall WL of a person. The model shows that spatial activities and visual processing have an influence on the WL, which can be transferred to objects in microgravity that behave significantly differently from those in Earth gravity. As a result, the astronauts need more resources to analyse how the objects behave, which implies a higher WL. Because of all these aspects, the effect of changing gravitational conditions on the WL is important. To introduce different gravitational conditions for short periods of time, especially microgravity, without going in space, it is possible to carry out parabolic flights. However, these flights are very expensive and the time available in microgravity is comparatively short. For this, an airplane (A310 Zero-G) based at Mérignac International Airport in Bordeaux, France follows a given flight protocol, which is shown in Figure 1. Each flight begins with a test parabola after launch, followed by 30 parabolas that can be used to conduct experiments. Each parabola lasts about 70s, starting with about 20-25s hyper-gravity (1.8G), followed by 21-22 seconds microgravity (0G), which is highlighted in grey in Figure 1, and ends up with again 20-25s hyper-gravity (1.8G). Before the next parabola begins, there is a

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break of 90s under Earth gravity (1G). After each set of 5 parabolas there is a longer break of 5 or 8 minutes after 15 parabolas. (Novespace, 2011)

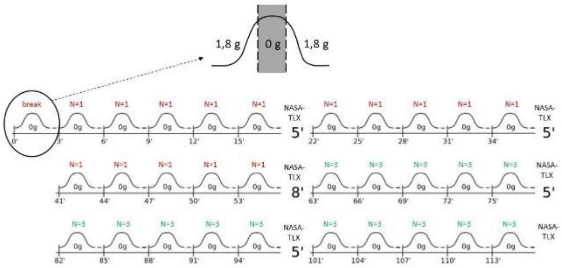

Figure 1: Experimental design (Bütefür, Trampler, & Kirchner, 2024)

The literature shows that WL can be determined based on different physiological signals.

In this work we will investigate, if the prediction of changes in WL in microgravity is possible using the following modalities:

- Eye Tracking (ET),
- Electrocardiogram (ECG) and
- Respiration (RESP)

ET is a very common modality for WL estimation in Earth gravity. ECG and RESP are very interesting to compare for Earth gravity and microgravity, since different gravity conditions have an impact to the cardiovascular system of a person (Schlegel, et al., 1998) as well.

The aim of this paper is to see, if measuring the three mentioned modalities is possible in microgravity during a parabolic flight and compare the results to the results of electroencephalogram (EEG) measurements recorded in the same study, which are already analysed (Bütefür, Trampler, & Kirchner, 2024). Therefore, the data from the parabolic flight will be analysed in terms of WL and compared to the analysed data from the control condition in the lab. A comparison to the results from the EEG analysis will also be done. It was already shown in Bütefür et al. (2024) that it is possible to analyse EEG data to determine WL in microgravity. Therefore, the change in frequency bands was analysed.

2 WORKLOAD DETECTION BASED ON DIFFERENT MODALITIES

This section provides information about the modalities ET, ECG and RESP with respect to the expected changes due to changing levels of WL.

In the following section the levels of WL are divided into "lower" and "higher" WL. This always means the distinction between the same task (auditory N-back) with a lower and higher WL condition.

2.1 Eye Tracking

ET measures the eye movements during an experiment with use of infrared light. For WL detection in humans, it is a common modality, if the experimental setup is designed carefully. If too many eye movements are caused by the experimental setup, the ET data can be distorted. Because it is not clear whether the eye movements are caused by the change of WL or the experimental setup. The same applies to changing lightning conditions. Some of the parameters that can be extracted from ET data to analyse WL are, for example, the fixation duration, pupil dilation or the blink frequency in a certain time window (Singh, Ponzoni Carvalho Chanel, & Roy, 2021; Volden, Alwis, de Viveka, & Fostervold, 2018).

Some groups reported an increase of the pupil dilation if the WL is higher in comparison to lower WL conditions (Grimmer, Simon, & Ehlers, 2021; Singh, Ponzoni Carvalho Chanel, & Roy, 2021; Volden, Alwis, de Viveka, & Fostervold, 2018).

Other changes of parameters in higher WL conditions are a higher blink frequency (more eye blinks in a certain amount of time) and an increase of the peak blink duration as well as the number of eye blinks (Volden, Alwis, de Viveka, & Fostervold, 2018).

2.2 Electrocardiogram

The ECG is a modality that is often measured in the context of physical demanding tasks, as these have a strong influence on the cardiovascular system. However, there are also some parameters that change when the subject performs cognitively demanding tasks.

Volden et al. (2018) reported a significant higher ratio of low frequency (LF) parts to high frequency (HF) parts of the heart rate (HR) for higher WL in comparison to lower WL conditions.

Singh et al. (2021) reported a significant increase in the HR and a significant decrease in the heart rate variability (HRV). Ding et al. (2020) reported an almost significant increase in the HR for high WL in comparison to low WL, whereas there was no significant change in HR between low and medium WL level.

2.3 Respiration

RESP is also a modality which is often used in the context of physical demanding tasks as it changes significantly, in this case, as does the ECG. But there is also one parameter of respiration reported, that changes due to changing cognitive WL. Ding et al. (2020) reported a significant lower respiration rate (RR) for lower WL in comparison to higher WL.

3 METHODS

In this section the dataset will be presented in general as well as the experimental setup and procedure. A detailed description can be found in the main study of Bütefür et al. (2024). The section also contains information about the data recording of ET, ECG and RESP, as well as pre-processing and the data analysis.

3.1 Dataset

The dataset consists of two studies. The first study took place during a parabolic flight campaign (flight environment) organized by DLR Space Agency and Novespace. The experimental setup during the flight is shown in Figure 2. The second study was used as a control condition and took place in the laboratories of the University of Duisburg-Essen (lab environment). The experimental setup in the lab is similar to the setup in flight (cf. Figure 2), except the operator is sitting on a chair and not on the ground and the response button was a key on the keyboard in front of the operator.

3.2 Participants

EEG, ECG, RESP and ET data for both studies were measured from three healthy, native German speaking team members who were operators of the experiment (1 male, average age = 43 ± 12,7). The study was a purely technical test, which is why no ethic statement was required under French law. For the parabolic flight all operators took scopolamine (a medication to prevent motion sickness) on a voluntary basis.

Operator AE41D had to be excluded for the analysis, as the measurement took place on two days due to technical problems with the aircraft during the first flight and was therefore not comparable to the analysis of the other operators who did the whole study in one session.

Figure 2: Experimental setup (adapted from (Bütefür, Trampler, & Kirchner, 2024))

3.3 Experimental setting

The operators had to perform an auditory N-back task during the microgravity phases in the plane (see Figure 1 depicting microgravity phases and experimental design). The operator must listen to numbers (0, 3, 4, 7, and 9 spoken in German) presented as stimuli via headphones. During the first 15 parabolas (15*22sec=5.5min) the operators had to perform an N=1 or N=2 task, which corresponds to low WL condition. During the second half of the flight (parabolas 16-30) operators had to perform an N=3 task to increase the difficulty of the task and corresponds to high WL condition. The relation of targets to standards was 1:6 for 135 stimuli in total under each condition. The stimulus interval was 600ms and the inter-stimulus interval 1800ms. Each run was followed by a ~90s break. Each set consisted of 5 runs followed by a longer break of 5 or 8 minutes, where the operator had to fill out the NASA-TLX questionnaire. The operators had to perform 3 sets for each condition. Each set consists of 5 runs (parabolas).

The flight procedure was replicated for the control conditions in the lab, but the breaks were shortened from 90 seconds to 20 seconds and from 5 or 8 minutes to 90 seconds.

3.3 Data recording and pre-processing

In the following paragraphs the data recording of the different modalities is described as well as the pre-processing.

ECG and RESP data were recorded synchronously to EEG data with the same system. Therefore, each operator was prepared with the ANT eego mini (https://www.ant-neuro.com/products/

eego_24), which measured ECG and RESP with a sampling frequency of 500 Hz. ECG was measured with 3 channel lead and RESP with a respiration belt. All operators were prepared with a 24-channel dry electrode headset as well. EEG data recording is described more detailed in Bütefür et al. (2024). During the experiment the operator was sitting in front of the Tobii Pro Fusion Eye Tracker (https://www.tobii.com/products/eye-trackers/screen-based/tobii-pro-fusion) with a sampling frequency of 250 Hz during the parabolic flight and 120 Hz in the lab and an accuracy of 0.3°. Data recording took place using the Tobii Pro SDK (Tobii AB, 2024). During the parabolic flight a synchronized inertial measurement unit (IMU) measured the acceleration data.

Pre-processing for ECG and RESP data was done with the python-library MNE. A bandpass filter between 0.1 and 45 Hz was applied. Microgravity phases during the parabolic flight were detected using an IMU. This was used to mark the microgravity phases within ECG, RESP, and ET data for evaluation.

3.4 ET analysis

For ET analysis the data were segmented into single runs (1 run = 1 parabola). The analysis was done in python based on the eye position data recorded from the eye tracker. The validity of the ET data was checked before the analysis could start. The validity was calculated based on the detection percentage of pupil images for each eye during microgravity phases.

The number of blinks, blink frequency and maximum blink duration was also calculated from the validity parameters, as no eye image could recognized when blinking. A blink was recognized if the no eye images could be detected for the left and the right eye for 100-500ms and anything above 500ms was considered as drowsiness (Aksu, Cakit, & Dagdeviren, 2024). The blink frequency was calculated using the time between the first and last blink and the number of blinks. The pupil diameter was also analysed. This parameter is calculated by the Tobii Pro SDK (Tobii AB, 2024) during measurement and can be extracted and analysed from the data for each eye individually. To analyse the parameters the median of each run was calculated for each parameter individually with respect to the different WL conditions. Also, the median over all runs for lower and higher WL condition was calculated for each operator in both environments.

3.5 ECG and RESP analysis

For ECG and RESP analysis the NeuroKit2 toolbox (Makowski, et al., 2021) was used.

To analyze the ECG data, the N-back task data were segmented into epochs of 15s with 10s overlap. Afterwards, HR was interpolated between R-Peaks and HRV was calculated using the standard deviation of RR intervals. LF/HF ratio was also calculated. All calculations were done using the NeuroKit2 toolbox (Makowski, et al., 2021).

The median of each parameter and run for lower WL condition was calculated as well as the median of each parameter and run for higher WL condition. Also, the median over all runs for lower and higher WL condition was calculated for each operator in both environments.

To analyze the RESP data, the N-back task data were segmented into epochs of 20s without any overlap. The inhalation onsets were calculated using the NeuroKit2 toolbox (Makowski, et al., 2021). The RR was calculated and the median for each set was built. An outlier removal was performed, whereby the 90^{th} percentile of data was used. Also, the median over all runs was built for the lower as well as the higher WL condition.

4 RESULTS

In the following section the results for all modalities and the different parameters are presented.

4.1 ET results

The ET data were evaluated with respect to the validity, number of blinks, blink frequency and the maximum blink duration.

In Table 1 the percentage of validity is shown for each operator and for lower and higher WL condition in both environments (flight and lab).

Table 1: Validity of left and right eye for each operator and condition in both environments

Subject		AC07D		BU87D	
Validity (%)		Left	Right	Left	Right
Lab	Low WL	81.88	82.44	97.06	96.62
	High WL	82.15	83.94	96.60	96.26
Flight	Low WL	74.73	71.35	84.46	79.82
	High WL	57.96	52.71	76.00	71.00

The results show an overall validity over 50% for each WL condition in both environments. The highest difference between left and right pupil validity is 5.25% for BU87D in flight environment. The smallest difference is 0.34% for BU87D in lab environment. The average validity in lab environment is 89.62% ± 7.53%. In flight environment the average validity is 71.00% ± 10.71%.

The average validity for both eyes for Operator AC07D is 73.39% ± 12.03% and for BU87D 87.23% ± 10.73%.

For lower WL condition the average validity is 83.55% ± 9.25% and for higher WL condition 77.08% ± 16.12%.

4.1.1 Eye Blinks

In this section the results of all parameters regarding eye blinks will pe presented. In Figure 4A the boxplots for the number of eye blinks for all runs and WL conditions in both environments are shown, while Figure 4B presents the blink frequency for all conditions and Figure 4C the maximum blink duration. The median is marked with a red line. The absolute number of eye blinks increased for higher WL condition for each operator in both environments except for BU87D in the lab environment.

On the contrary the blink frequency decreases for higher WL condition for each operator in both condition except for BU87D in the lab environment. These results are inverted to the number of eye blinks. Furthermore, for BU87D, the blink frequency in lab environment for higher WL condition could only be calculated for one run, as the number of blinks was less than 2 in all other runs. For this one run the frequency was higher for higher WL condition in comparison to lower WL condition. For lower WL condition the frequency could be calculated for 2 runs.

The pattern of the maximum peak blink duration is the same as for the number of eye blinks, which means that the maximum peak blink duration decreases for higher WL condition in comparison to lower WL condition for both operators in each condition except for Operator BU87D in lab environment, there it remains the same.

4.1.2 Pupil Diameter

The boxplots of the median of pupil diameter per run for the right eye are illustrated in Figure 4D representative for both eyes. The median pupil diameter decreases for higher WL condition in comparison to lower WL condition for both operators in the flight environment and increase from lower to higher WL condition for both operators in the lab environment. For the right eye the changes were similar.

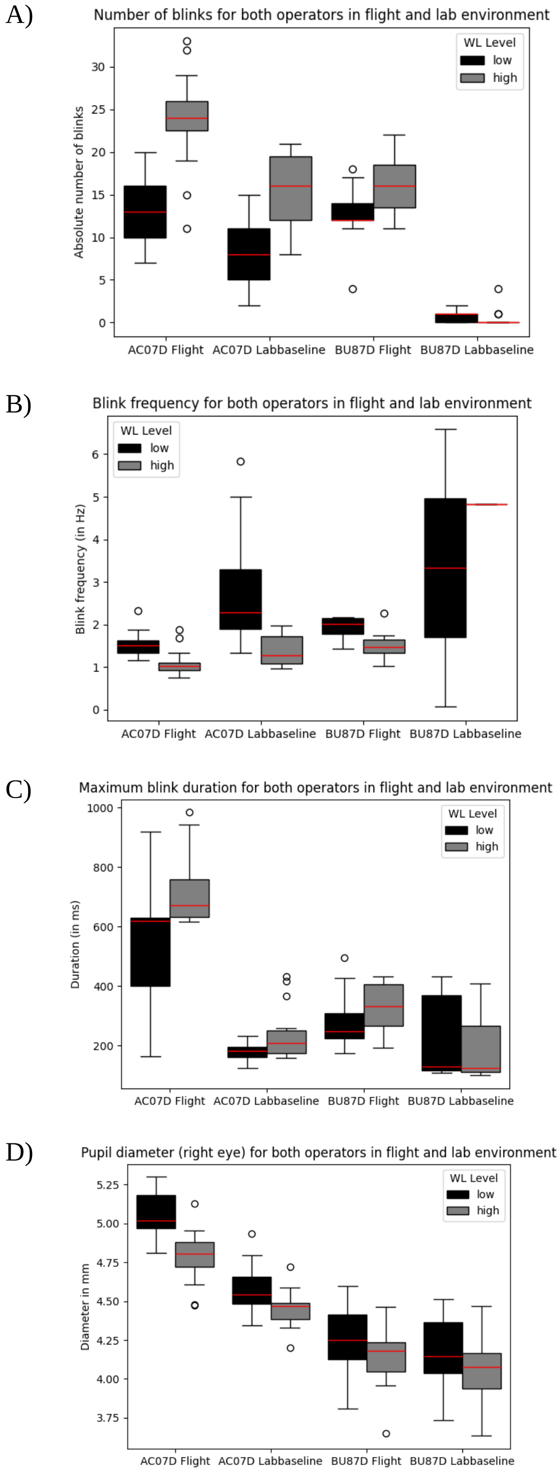

Figure 4: Eye blink parameters for both operators under each condition; A) Number of eye blinks; B) Blink frequency; C) Maximum blink duration

4.2 ECG results

In the following section the results of the ECG analysis will be presented.

Figure 5 shows the results for both operators in each environment. In Figure 5A the boxplots of the median HR for each run and operator under lower and higher WL condition is shown. The HR decreases for both operators in the flight environment and for AC07D in the lab environment for higher WL condition in comparison to lower WL condition. For Operator BU87D in the lab environment the median HR decreases for higher WL condition in comparison to lower WL condition (cf. Fig. 5A).

Figure 5B shows the boxplots of the median HRV of each run for lower and higher WL condition for each operator in both environments. The median HRV over all runs decreases for higher WL condition in comparison to lower WL condition for both operators in lab environment and for AC07D in flight environment. For BU87D in flight environment the median HRV over all sets increased for higher WL condition in comparison to lower WL condition.

The boxplots of the median of the LF/HF ratio for each run and operator under lower and higher WL condition are depicted in Figure 5C. It decreases for both operators in the flight environment and for BU87D in the lab environment for higher WL condition in comparison to lower WL condition. For Operator AC07D in the lab environment the median LF/HF ratio decreases for the higher WL condition in comparison to the lower WL condition.

4.3 RESP results

In the following section the results of the RESP analysis will be presented.

The boxplots of the median RR for each run and operator in both environments are illustrated in Figure 6. The median RR increases for both operators in both environments for higher in comparison to lower WL condition.

5 DISCUSSIONS

The main objective of this paper was to investigate, if measuring the modalities ET, ECG and RESP is technically possible in microgravity during a parabolic flight in a quality that it allows to predict WL levels. Therefore, the data from the parabolic flight were analysed in terms of WL and compared to the analysed data from the control condition in the lab. As a subgoal the results for ET, ECG and RESP will be compared with the results from the EEG analysis, which are already published in Bütefür et al. (2024).

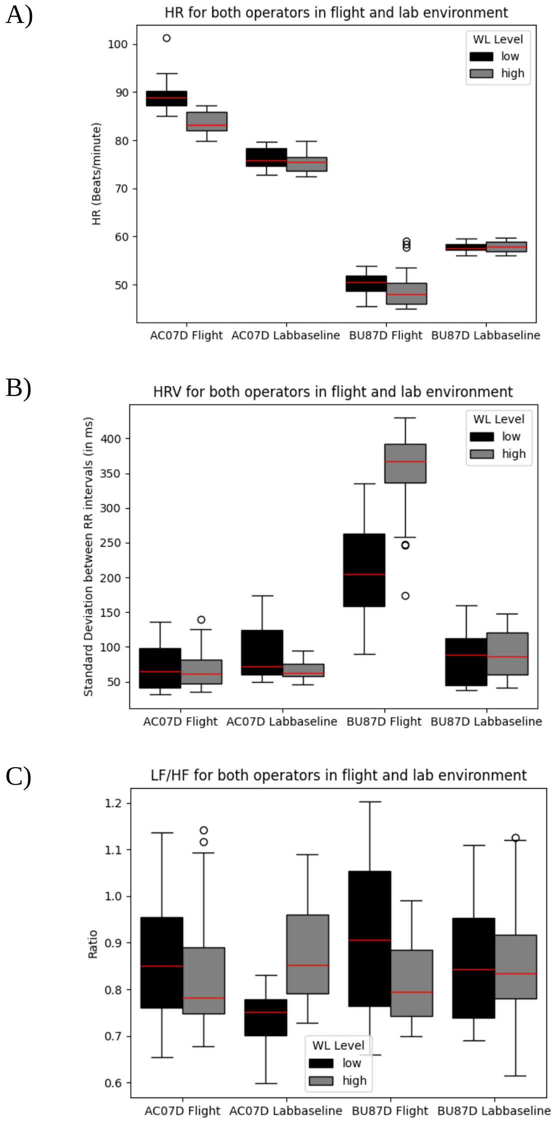

Figure 5: ECG parameter for both operators in each environment; A) HR; B) HRV; C) LF/HF ratio

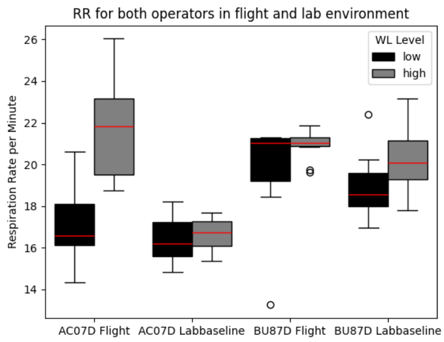

Figure 6: Median RR for each run and operator under both conditions

The results of the validity of the ET in Table 1 show that the validity of the data measured in lab environment was higher with an average validity of 89.62% ± 7.53% than in flight environment with 71.00% ± 10.71%. This is due to the fact, that during microgravity phases in flight environment the operator starts floating around. With the given experimental design, it was not possible to fixate the operator fully on the plane ground, so the operator floated out of the region of measurement from the ET. In lab environment, however, it was not the case since the operator was sitting on a chair in Earth gravity.

The validity was also not expected to have 100% because for each eye blink pupil images cannot be detected. If the validity is compared to the number of eye blinks (Fig. 4A), the validity is lower for conditions with a higher number of eye blinks and is also proportional related to the maximum blink duration (Fig. 4C), which was expected.

The analysis of the number of eye blinks (cf. Sec. 4.1.1) shows an increase of the number of eye blinks with an increase of WL condition in both environments except for BU87D in lab environment (cf. Fig. 4A). An increase of the number of eye blinks for increasing WL condition was also expected from literature (Volden, Alwis, de Viveka, & Fostervold, 2018) and is supported in this study by the higher validity percentage for lower WL condition (see Tab. 1). However, these results must be viewed with caution, as the duration of each run was only 22s and the standard number of blinks per minute are between 2 and 50 (Monster, Chan, & O'Connor, 1978). This means that if the operator blinks less in general, the number of blinks over a short period of time is not representative. As a conclusion, it seems like this parameter is technically measurable in microgravity, but within this experimental setup it is very limited due to the short period of time where it is measured.

The blink frequency was analysed as well (cf. Sec. 4.1.1) and results were contrary to the results of the number of eye blinks. From literature it was expected that the blink frequency is increasing with increasing WL condition (Volden, Alwis, de Viveka, & Fostervold, 2018), but Figure 4B shows a decrease in three out of four cases. For the fourth case, BU87D in lab environment, the median blink frequency increases, but in most of the runs there were less than two eye blinks, so it was not possible to calculate the frequency of eye blinks within these runs, which means that this result is not representative. As already discussed before, 22s for each run within this experiment is not sufficient for analysing changes in the WL levels of the operators based on ET parameters. Furthermore, the calculation of the blink frequency is another limiting factor. Due to long phases of closed eyes at the beginning of single runs, as well as inaccuracies of measures due to the onset of hyper-gravity at the end of each run, the blink frequency was only calculated in the time between the first and the last recognised blink. This leads to a low robustness of the calculation for a small sample size, which becomes clear due to the large variation of the calculated frequencies, e.g., for Operator BU87D in the lab environment (cf. Fig. 4B). Operator AC07D also shows many outliers in the flight environment, which indicate this. It seems like this parameter is not suitable for experimental setups with short-term measurements independent of the prevailing gravitational conditions.

The results of the maximum blink duration are shown in Figure 4C, which illustrates an increase of the overall median of the maximum blink duration for higher WL condition in comparison to lower WL condition in all environments except for BU87D in lab environment. For BU87D in lab environment the maximum blink duration decreases. The results are inhomogeneous which could be due to the small sample size of only two operators within this study. Volden et al. (2018) had 21 subjects and removed four outliers to obtain normal distribution. Also, the definition of the maximum length of a blink varies. In this work a blink was defined between 100ms and 500ms (cf. Sec. 3.4) regarding the work of Aksu et al. (2024), because a typical blink lasts between 100ms – 300ms and blinks about 500ms are considered as drowsiness (Johns, 2003). Volden et al. (2018) did not define time limits for eye blinks and had a mean maximum blink duration of 973.21ms ± 637.66ms, which would be drowsiness instead of eye blinks regarding the definition within our work. Therefore, this parameter needs to be more investigated in Earth gravity as well as in microgravity with longer periods of measurements and the given limitations.

The last parameter analysed for ET data was the pupil diameter for both eyes (Sec. 4.1.2). Figure 4D depicts that the median pupil diameter over all runs of the right eye decreases for higher WL condition in comparison to lower WL condition for both operators in both environments. For flight environment the decrease seems higher and could be explained by the use of scopolamine since ophthalmic adverse effects are expected with that (Merck & Co., Inc., 2024). The pupil diameter seems also not to be a suitable parameter in microgravity with scopolamine intake and also need further tests for Earth gravity.

The HR was analysed from ECG data with respect to the WL conditions (Fig. 5A). The HR decreased for both operators for higher WL condition in comparison to lower WL condition, which was not expected from literature (Ding, Cao, Duffy, Wang, & Thang, 2020; Singh, Ponzoni Carvalho Chanel, & Roy, 2021). Due to these results, it is not possible to decide if the HR is a suitable parameter for WL detection in microgravity since with the sample size of two operators it was not even possible to reproduce the results from Ding et al. (2020) in Earth gravity.

For the HRV the results are very similar to those for HR. Figure 5B shows that only for Operator AC07D in the lab environment the HRV slightly decreases for higher WL condition in comparison to lower WL condition as it was expected from literature (Singh, Ponzoni Carvalho Chanel, & Roy, 2021). For Operator BU87D in the flight environment the HRV increased for higher in comparison to lower WL condition, which was not expected. Figure 5B also illustrates that the median HRV over all runs for Operator BU87D in flight environment is unexpectedly high. Therefore, the signal was visually checked and the calculation was correct. The unexpected high HRV for BU87D in flight environment could be affected by use of scopolamine since one of the adverse reactions are also cardiac arrhythmias (Merck & Co., Inc., 2024). Due to this fact, HRV seems not to be suitable for WL detection in microgravity by use of scopolamine.

The results of the LF/HF ratio analysis, which are presented in Figure 5C, show also similar results to HR and HRV. Only for Operator AC07D in the lab environment the LF/HF ratio is increasing from lower to higher WL as expected in literature (Volden, Alwis, de Viveka, & Fostervold, 2018). As already mentioned before, because of scopolamine intake and adverse reactions the LF/HF ratio also seems not to be a suitable parameter for WL detection under scopolamine.

Figure 6 shows that the RR increases for both operators in both environments for higher in comparison to lower WL condition as expected in literature (Ding, Cao, Duffy, Wang, & Thang, 2020). But only for Operator AC07D in flight environment the increase seems relevant, as for the other conditions the overall median remains almost the same. Data from a longer period of time is required to analyse the RR because the frequency of RESP is low in comparison to the length of one run. It seems like that RR is not a suitable parameter for short term measurement in microgravity. Nevertheless, it should be analysed for longer measurement durations.

After analysing all mentioned parameters, it can be summarised that none of the parameters would be suitable for WL detection in humans in the very short microgravity phases (~22s) and using scopolamine for the described experimental setting. For the HR and RR more data would be needed to reproduce the results from literature also in Earth gravity.

As a subgoal we wanted to compare the results of this work to the results of the EEG analysis. In the work of Bütefür et al. (2024) the EEG data of the study were analysed in the frequency domain. To this end, the single frequency bands were compared regarding increasing or decreasing power spectral density for changing WL conditions. The conclusion of the analysis was that dry electrode headsets could be a promising alternative for the detection of WL in microgravity if the headset fits the subject.

In this work we could not show a suitable parameter for analysing WL for the mentioned experimental setup.

In summary, comparing the results of this work with former results, EEG frequency bands for the detection of WL in microgravity with scopolamine intake and short-term measurements is the most promising approach, as it brings the only reliable results.

For future work another experimental setting should be set up where longer measuring durations are possible so that the HR and RR, as well as the ET parameter could be analysed more detailed, and the state of the art could be reproduced to verify the parameters in microgravity. The measurement period during parabolic flights is pretty fixed so that another possibility to introduce microgravity needs to be found. Also, more operators should be included to minimize the effect of individuality in humans and a statistical analysis could be performed. Scopolamine intake should be avoided as well.

6 CONCLUSIONS

In this study we investigated whether the use of the modalities ET, ECG and RESP could be a viable way to detect WL of humans in microgravity. Our results suggests that under scopolamine and for short-term measurements only EEG data brings results comparable to the control condition in Earth gravity. Therefore, we would suggest using EEG measurements for WL detection as they bring the most stable results as shown in an earlier published work (Bütefür, Trampler, & Kirchner, 2024). As a next step a larger sample size of operators is needed. Also, the experimental setup needs to be adapted to get data from a longer period to investigate ET, ECG and RESP data more detailed.

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