Biofeedback in the Cockpit

Optimizing Form and Function, and the Effects of Biofeedback and Simulator Motion on Task Performance and Physiology.

Leon van Mierlo, Utrecht University, MSc Student
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Table of contents

1. Preface

This report is the final component of my MSc in Bioinformatics & Biocomplexity at Utrecht University. The research for this final thesis has been conducted at TNO Soesterberg, within the Human Performance department, as part of the Defense Research Program V2306 'NextGen Aircrew Performance'. Within this program, TNO is building knowledge on the in-flight physiological- and mental state of the pilot.

This thesis focuses on the topic of 'biofeedback' in a cockpit environment, and is divided into two distinct parts. The first part involves a questionnaire conducted among subject matter experts, exploring the form and function of biofeedback when being utilized in a cockpit environment. The second part focuses on a simulator experiment, where we investigated the added value of biofeedback and the effect of simulator motion on flight performance and arousal level. The results contribute to the knowledge of pilot physiological state and the added value of biofeedback in a cockpit environment.

I would like to express my gratitude to my supervisor, Wietse Ledegang, for his excellent guidance and continuous support throughout the process of this thesis. His expertise and insights have been invaluable in shaping the outcome of this work. I am also very thankful to Eric Groen and Ivo Stuldreher for their thoughtful feedback and the assistance they provided. A special thanks to Mark Houben, programme leader of V2306 'NextGen Aircrew Performance', for organizing the program such that I was able to undertake my internship, offering me this unique opportunity. I would also like to express my gratitude towards Desdemona B.V. and multiSIM, with special thanks to Joris Booms, for their invaluable support in conducting the simulator experiment. Additionally, I would like to extend my appreciation to the subject matter experts who contributed to the questionnaire aspect of this study, as well as to all the participants involved in the simulator experiment. Your cooperation and contributions were essential to the success of this research.

2. Abstract

In recent years, there has been increasing international attention on physiological phenomena experienced by pilots in-flight. Currently, various wearables and sensors are being developed to better monitor the pilot. Within the Defense Research Program V2306 'Next Gen Aircrew Performance', TNO is building knowledge on the in-flight physiological- and mental state of the pilot. In this context, the current exploratory study is conducted to investigate the effects of providing feedback on the operator's state, based on physiological measures, in the cockpit. This is referred to as 'biofeedback'.

In this study, the added value of biofeedback in a cockpit environment was explored in two parts. First, a questionnaire was conducted among nine subject matter experts to explore the different forms and functions of biofeedback. Experts found alarming biofeedback valuable, preferring tactile and auditory cues, while visual feedback was favored for informative purposes. A dual-pointer design was considered most effective as arousal indicator, which was further investigated in the second part of this study.

In the second part, an experiment was performed in the all-attitude Desdemona flight simulator with eighteen participants without significant flying experience. The participants were requested to fly a final approach with a simplified Pilatus PC-7 flight model and level-off as low as comfortably above the runway without landing the plane. In four conditions the presence of physical simulator motion (on/off) and the presence of biofeedback (on/off) were varied. Besides flight performance measures, the participants' heart rate and skin conductance were measured as measure for their arousal level. In the two conditions with biofeedback these measures were visually presented with the dual-pointer indication as a visual overlay in the primary field of view. The results showed that simulator motion significantly increased the arousal level, measured via skin conductance, and participants leveled-off at significantly higher altitudes when simulator motion was present. No significant effects of biofeedback on arousal or flight performance were found, which may be related to the type of flight task that was conducted, the voluntary use and visual presentation of biofeedback, the inexperience of the participants with flying, and some order effects. Further research is recommended to explore the use of biofeedback in a cockpit environment.

3. Lay Summary

In recent years, there has been increasing international attention on physiological phenomena experienced by pilots in-flight. Currently, various wearables and sensors are being developed to better monitor the pilot. Within the Defense Research Program V2306 'Next Gen Aircrew Performance', TNO is building knowledge on the in-flight physiological- and mental state of the pilot. In this context, the current exploratory study is conducted to investigate the effects of providing feedback on the operator's state, based on physiological measures, in the cockpit. This is referred to as 'biofeedback'.

In this study, we explored how biofeedback might help pilots manage stress and improve performance in a cockpit environment. The goal was to investigate how biofeedback, which involves giving someone real-time information about their body's responses, can be used effectively while flying. Biofeedback could be useful for keeping the pilots calm, focused, and at their best during flights, particularly in stressful situations.

The research was done in two parts. First, we interviewed experts, who have extensive knowledge of flying and aviation systems, to find out what kind of biofeedback would be most useful in a cockpit. These subject matter experts answered that they found alarming biofeedback very helpful, such that the pilots attention can be grabbed in a potential dangerous situation. They preferred using sounds or physical cues like vibration for these alerts, while visual signals were better for sharing non-urgent, ongoing, information. The experts liked a biofeedback system that uses two pointers to give an indication of the pilot's arousal level, which was used in the second part of the study.

In the second part of the study, an experiment using the Desdemona flight simulator was conducted. Eighteen participants, with barely any (simulator) flight experience, were asked to fly a simulated Pilatus PC-7 aircraft. Their task was to fly an approach towards a runway and to fly low over it without landing. The experiment had four different conditions, where simulator motion (moving or not) and biofeedback (on or off) were varied. We measured the participants' performance in flying the plane as low as they felt comfortable and their arousal levels, using heart rate and skin conductance. When the biofeedback was activated, a pointer was moving up or down, based on their heart rate and skin conductance responses.

The results showed us that when the simulator was physically moving, the participants' arousal levels went up significantly, as shown by increased skin conductance. The participants also flew higher over the runway, when their task was to fly as low as comfortable, when the simulator was moving. However, the presence of the biofeedback, in real-time showing their arousal levels, did not seem to have a significant effect on the arousal level or how well they performed their flight task.

There are a few reasons why biofeedback did not seem to make a significant effect in this study. One possibility is that the biofeedback was not used at critical moments during the flight, when it might have had more impact. Another reason could be that the task itself was not suited for biofeedback to be useful. The study also only used visual biofeedback, which might not have been the most effective method. Plus, the participants did not have any real flight experience, so they might not have known how to use the biofeedback information to their advantage.

We conclude that more research is needed to investigate how to best use biofeedback in the cockpit. It is recommended that future experiments should involve experienced pilots and a different task where the biofeedback directly relates to managing stress or improving performance.

4. Part I: Subjective Assessment of Biofeedback Function and Form in the Cockpit

4.1. Introduction

In recent years, there has been increasing international attention on physiological phenomena experienced by pilots in-flight. In some cases, these phenomena are referred to as Unexplained Physiological Episodes (UPEs) (Elliott & Schmitt, 2019), varying from headache, disorientation, general malaise, dizziness, oxygen deficiency to mental consequences such as fear, panic and insecurity (Kingma, Gijsbertse, Kjellander, Panditha, & Valk, 2023). Additionally, military aviation is characterized by phases of (extremely) high workload for the pilot, during which large amounts of information need to be processed and situational awareness must be developed to make the right decisions (Wickens, 2002). Military pilots often encounter significant stressors such as extreme thermal- and gravitational forces, where they need to make split-second decisions (Fritts, 2018). Consequently, a pilot's performance is integral to managing these stressors effectively, as it directly influences their ability to maintain composure and make accurate decisions under pressure. Hence, optimizing pilot's performance is not only about enhancing efficiency but it is critical for safety and mission effectiveness.

Currently, various wearables and sensors are being developed to better monitor the pilot. One example is the Flight Sense system, currently being developed by Elitac Wearables and TNO in the Netherlands, which enables real-time physiological monitoring and post-flight feedback. Another example is a sensor system developed by NASA which measures several physiological breathing parameters (Napoli, Harrivel, & Raz, 2020).

Within the Defense Research Program 'V2306 Next Gen Aircrew Performance', TNO is building knowledge on the in-flight physiological- and mental state of the pilot. In this context, the current exploratory study is conducted to investigate the effects of providing feedback on the operator's state, based on physiological measures, in the cockpit. This is referred to as 'biofeedback'.

To explore the added value of biofeedback, we differentiate between its 'function' and 'form'. Biofeedback could serve various functions, such as informing, alerting, and intervening. Informing biofeedback provides information about the physiological state of the pilot, such as displaying heart rate, whereas alerting biofeedback issues an alarm when certain thresholds are exceeded. For instance, when oxygen levels are dangerously low, it could alert a pilot to the risk of hypoxia. Intervening biofeedback could take over control, for example to maintain safety with a G-recovery system, or in adaptive Human-Machine Interfaces.

Biofeedback can be delivered to different recipients in various forms. The presentation of biofeedback is not limited to a visual display; it can also be presented as auditory cues (e.g., alarm sounds or voice warning), or use tactile cues (e.g., vibrations or pressure).

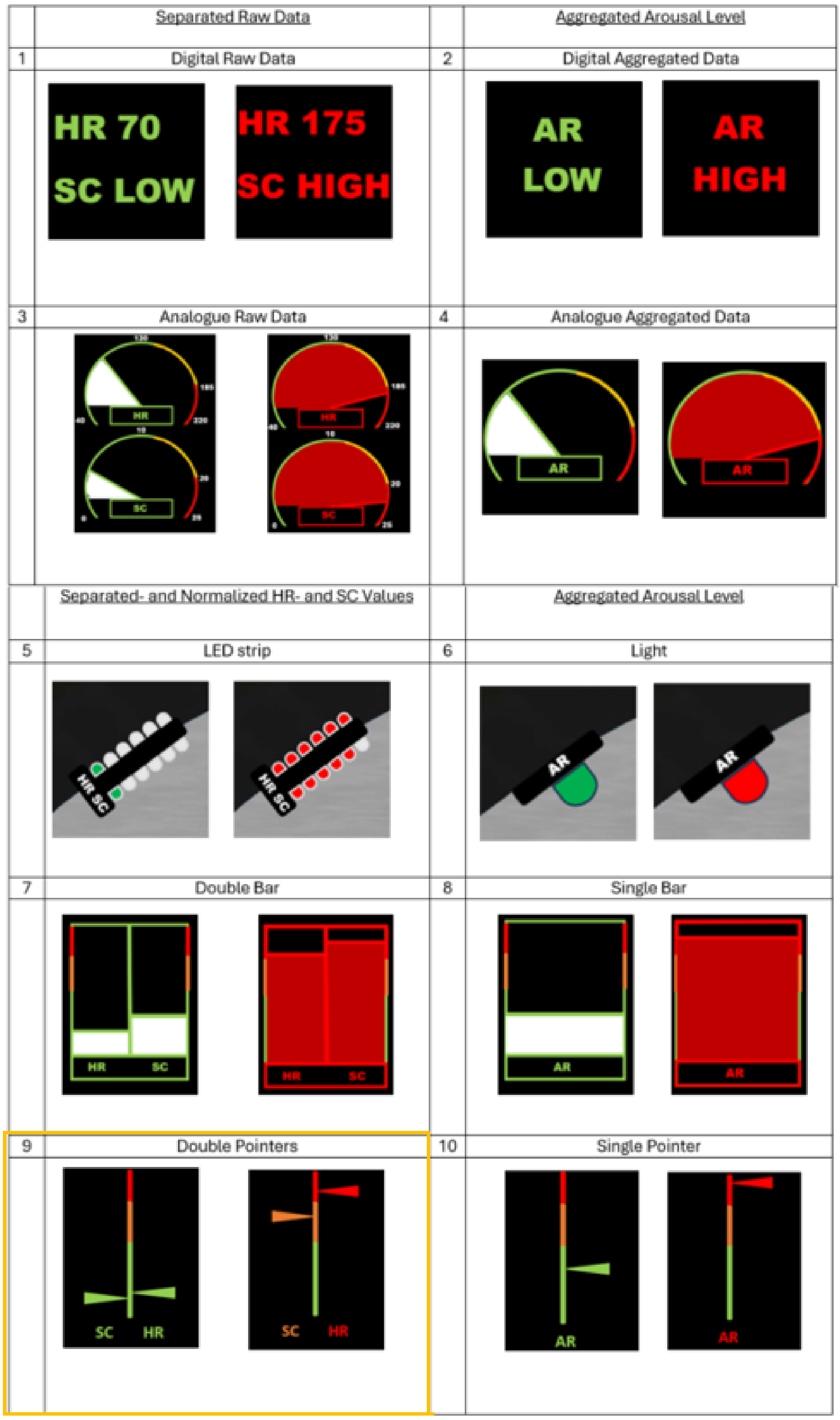

Figure 1. Biofeedback Designs used in the questionnaire among Subject Matter Experts. Design 9 was regarded as most suitable design.

4.2. Methods

To assess the ideal function and form for biofeedback in the cockpit, a questionnaire (see Appendix 1) was provided to nine subject matter experts (SMEs) with different expertise, such as pilots, human factors specialists, human-machine-interface designers and aerospace engineers.

The questionnaire comprised three sections. Section 1 focussed on the informing and alarming functions of biofeedback and its modalities (i.e., visually, auditory and tactile). For the function of alarming, the tactile modality—incorporating vibrating elements in the pilot flight equipment—presents additional possibilities beyond the visual- and auditory methods. However, for the questions concerning informing biofeedback, we focused on visual and auditory modalities only, as tactile information is regarded as not practical for this purpose. The questions in section 1 were either multiple choice questions or 10-points-scale questions (see Appendix 1).

Section 2 explored the biofeedback design (see Fig. 1) and location. For this section, the designs focused on visualizing heart rate (HR) and skin conductance (SC), which measures the skin's electrical conductance, to measure arousal levels (the state of physiological- and psychological activation). First, ten different biofeedback designs were shown and SMEs were asked to indicate their top three designs. Subsequent, three locations to implement biofeedback were discussed: the instrument panel, a kneepad or a head-mounted display (HMD; semi-transparent single-color overlay in the primary field of view). In this way, the SMEs choose the designs and locations that are best suited for implementing visual informing biofeedback in a cockpit environment.

Section 3 of the questionnaire addressed general aspects of biofeedback in the cockpit, and provided SMEs with an opportunity to offer tips and suggestions for future implementation of biofeedback in the cockpit.

4.3. Results

The results of the Section I questionnaire show that all nine SMEs found the biofeedback's alarming function to be valuable (nine respondents selecting 'yes', 0 selecting 'no'), while eight of them also considered the informing biofeedback to be beneficial. For alarming, the tactile- and auditory modalities were favored (seven respondents selecting 'audio' or 'tactile' as modality for 'alarming biofeedback'), while visual biofeedback was preferred for informative purposes (nine respondents selecting 'informing' as modality for 'informing biofeedback').

Regarding visual biofeedback, there was no strong preference between digital (five respondents selecting 'yes' for biofeedback to be presented as 'digital') and analogue data (six respondents selecting 'yes' for biofeedback to be presented as 'analogue'). Similarly, no clear consensus emerged regarding the use of separate (normalized) HR-and SC values (six respondents selecting ‘yes’ for biofeedback to be presented as ‘separate’) versus an aggregated arousal level (seven respondents selecting ‘yes’ for biofeedback to be presented as ‘aggregated’). Among the designs evaluated, the dual pointer visualization (Design 9 in Fig. 1), , was regarded as the most suitable (seven respondents selecting this design as a ‘suitable visualization’ from which three as first choice design, one as second choice design, and three as third choice design).

Regarding the location of biofeedback information, the instrument panel was identified as the optimal location (six respondents selecting ‘Instrument Panel’ as ‘best location’). Notably, the combination of the dual pointer visualization (Design 9 in Fig. 1) on the instrument panel was the most preferred pairing of design and location (five respondents selecting this design and ‘preferred location’).

All results of the Part I questionnaire are detailed in Appendix 2.

4.4. Discussion

A strong consensus emerged from Section 1 of the questionnaire, indicating that SMEs found the biofeedback system’s alarming and informative functions valuable, with a clear preference for tactile- and auditory modalities for alarming biofeedback and a visual modality for informing biofeedback.

This result can be explained by the context for which these biofeedback modalities are used. Tactile- and auditory modalities are immediate, capture attention quickly, and can hardly be ignored, making them ideal for alarming functions where an immediate response is critical. In contrast, visual feedback, which can be more detailed, easy to interpret at a glance and can be ignored, suits a more informative purpose where no immediate action is required. The mixed preference for digital versus analog and separate versus aggregated data suggests that SMEs have no strong preference for a specific type of visualization. The preference for the dual-pointer design with a separate pointer for HR and SC (Design 9 in Fig. 1), suggests that SMEs prefer a simple, yet elegant design, with minimal distractions.

Some data is missing in the questionnaire, as not all SMEs answered every question. This could be because they felt they lacked the appropriate experience to provide a suitable response. In total, question 1.3; 2.2; 2.5; and 2.6 are all skipped once. This is a total of four questions out of 153 questions, thus has no significant impact on the results of the questionnaire.

A notable observation in the results is that some SMEs contradict themselves within the questionnaire. For instance, an SME expressed that audio is an ineffective means of capturing attention and they have minimal sensory capacity remaining, yet still consider it to be the best modality. Another example involves an SME who recommended presenting biofeedback only as an aggregated arousal level but then selected a visualization design that separates heart rate and skin conductance values as the best choice.

The dual pointer visualization (Design 9 in Fig. 1), which was selected by SMEs, will be utilized in the simulator experiment as described in Part II. Although the instrument panel was identified as the optimal location for this design, we have opted to implement this design on an HMD instead (i.e., as a visual overlay in the primary field of view). This decision was made to ensure that the biofeedback remains visible to participants at all times during the flight task. Given that our participants have no prior flying experience, placing the biofeedback on the instrument panel could increase their workload, as they would need to divide their attention more between the task and the instrument panel, risking they do not fully utilize the biofeedback.

5. Part II: Flight Simulator Study on the Effects of Physical Motion and Providing Biofeedback on Flight Performance and Arousal

5.1. Introduction

There is a growing interest in measuring the cognitive- and physiological states of aircrew, with increasing attention being paid to the potential applications of in-flight feedback of this information. This approach, known as biofeedback, involves providing real-time physiological data to aircrew. Although various physiological measures have been widely studied in the literature, the effects of implementing biofeedback within the cockpit environment are still not fully understood and call for further exploration.

(Middendorf, McMillan, Calhoun, & Jones, 2000) described the concept of biofeedback for aviation over twenty years ago, however, according to (Fritts, 2018), its integration into the cockpit has been minimally researched. This biofeedback could fulfill multiple roles, such as providing informational physiological updates (e.g., monitoring oxygen saturation levels or hydration status), issuing alerts (e.g., warning of dangerous hypoxia levels), or even enabling interventions (e.g., activating an automatic Ground Collision Avoidance System based on the operator’s physiological state). Theoretically, providing biofeedback during flight could enhance pilots’ awareness of their physiological- or mental state, potentially leading to improved decision-making and performance.

Various physiological responses could be valuable indicators of a pilot’s physiological state when utilizing biofeedback, such as heart rate (Fritts, 2018; Wascher, 2021; Azarbarzin, Ostrowski, Hanly, & Younes, 2014) as measured with electrocardiogram (ECG), oxygen saturation as measured via Functional Near-Infrared Spectroscopy (fNIRS) sensors (Kurkin, Badarin, Grubov, Maksimenko, & Hramov, 2021), blinking frequency and pupil dilation (Ayres, Yeonjoo Lee, Paas, & van Merriënboer, 2021; Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2014; Ehlers, Strauch, Georgi, & Huckauf, 2016) as measured via eye-tracking devices, brain activity (Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2014) as assessed through electroencephalography (EEG), muscle activity and skin temperature (Fritts, 2018) as measured using electromyography and thermocouples, respectively, skin conductance (Christopoulos, Uy, & Yap, 2016) as recorded with galvanic skin response sensors. The slower fluctuations in skin conductance, referred to as the tonic component, are associated with overall arousal levels and thermoregulation, the rapid changes in skin conductance, known as the phasic component, indicate the activity of the sympathetic nervous system (Amin & Taghih, 2019).

In addition to the different physiological measurements, there are interesting higher-level physiological constructs, such as workload, fatigue, situational awareness and arousal, which is a state of heightened alertness. Related to measuring arousal and other physiological constructs, it recommended to combine different responses in order to achieve a more comprehensive understanding of a pilot's overall state and performance (Hankins & Wilson, 1998; Brouwer, Stuldreher, Huertas Penen, Lingelbach, & Vukelić, 2021).

The literature demonstrates that both heart rate and skin conductance are well-established indicators of arousal and mental stress (Taelman, Vandeput, Spaepen, & Van Huffel, 2008; Jacobs, et al., 1994; Wang, et al., 2018). Arousal refers to a state of being physiologically and psychologically alert, which can be triggered by both positive and negative stimuli. It has been proposed that arousal at medium levels reduces anxiety and enhances selective attention (Mahoney & Chapman, 2004). However, due to a cascade of stress hormones, a "fight-or-flight" response can be triggered when a person experiences high levels of arousal (Mahoney & Chapman, 2004) (Chu, Marwaha, Sanvictores, Awosika, & Ayers, 2024). Note that in situations where there is an uncertainty about how to respond or -handle to the challenges effectively stress is encountered (Minnesota, 2015). Hence, experiencing high levels of arousal and experiencing stress have similarities.

Part of arousal is related to mental stress, which can be induced, for example, through the Sing-a-Song Stress Test (SSST) as shown by (Brouwer & Hogervorst, 2014). During the SSST, participants are shown neutral messages on a screen, interspersed with 1-minute intervals. The final message instructs the participants to a sing a song aloud after the interval has elapsed. Brouwer and Hogervost showed that during this one minute prior to singing a song, skin conductance and heart rate are substantially higher compared to intervals prior to neutral messages which is indicative for an increased arousal level. The arousal response can be either positive negative, which is described by valence. Valence indicates if the emotional response is negative or positive. Arousal is therefor often described together with valence (Citron, Gray, Critchley, Weekes, & Ferstl, 2014).

Arousal is also affected by the realism of a simulated situation. A more realistic scenario can lead to a higher perception of risk which can increase the level of arousal, as shown in the study of (Beenhakker, Houben, & Groen, in preparation). In that study, the effects of physical simulator motion on the perceived level of arousal, physiology (heart rate) and flight performance (altitude above ground level, AGL) were investigated. Its results show that the presence of physical motion in two relatively simple flying tasks ("Straight and level with turbulence" and "Lower level") induced significant higher heart rates as compared to conditions without physical simulator motion. Inspired by the findings of (Beenhakker, Houben, & Groen, in preparation), it is decided to combine the ingredients of these two conditions to investigate the added value of biofeedback related to flight performance and physiological responses associated with the level of arousal.

In the current simulator study we addresses the following research questions: “What are the effects of physical simulator motion on the level of arousal and flight performance during a low-pass flight task?” and “What are the effects of providing visual biofeedback, presented as an information overlay in the primary field-of-view, on the level of arousal and flight performance during a low-pass flight task?”.

For the research questions, we have the following hypotheses. First, we hypothesize that the presence of physical simulator motion increases the level of arousal and results in flying at higher AGL during a low-pass flight task. Secondly, we hypothesize that the presence of visual biofeedback reduces the level of arousal and results in flying at lower AGL.

5.2. Methods

5.2.1. Participants

A total of N=18 participants with an age of 28.67 ± 8.27 (mean ± SD) years old participated in this study, consisting of 11 men and 7 women. All participants had negligible (simulator) flight experience (0.11 ± 0.46 flight hours and 0.22 ± 0.71 simulator flight hours), and were not highly sensitive to motion sickness.

Participants were eligible to participate if they met the following criteria: they were between 18 and 65 years old, had no significant flight experience, and did not have any cardiovascular- or pulmonary conditions. Additional exclusion criteria included the use of heart rate-lowering medications such as beta blockers, epilepsy, or anxiety disorders related to Virtual Reality (VR). Participants were also required to abstain from alcohol- and drug use within twelve hours before the experiment, avoid excessive caffeine intake on the day of the experiment, and meet certain physical criteria (e.g., height under 1.96m, weight under 125kg, not pregnant, and no high- or low blood pressure). Furthermore, participants were excluded if they had a neurological disorder, stomach, liver, neck or back issues, kidney stones, diabetes, or complains related to the head or neck, or if they experienced dizziness.

All participants volunteered for the study, were informed that they could withdraw at any time without providing a reason, and provided written informed consent. The experiment was conducted with approval of the institutional ethics committee in accordance with the (revised) Helsinki Declaration.

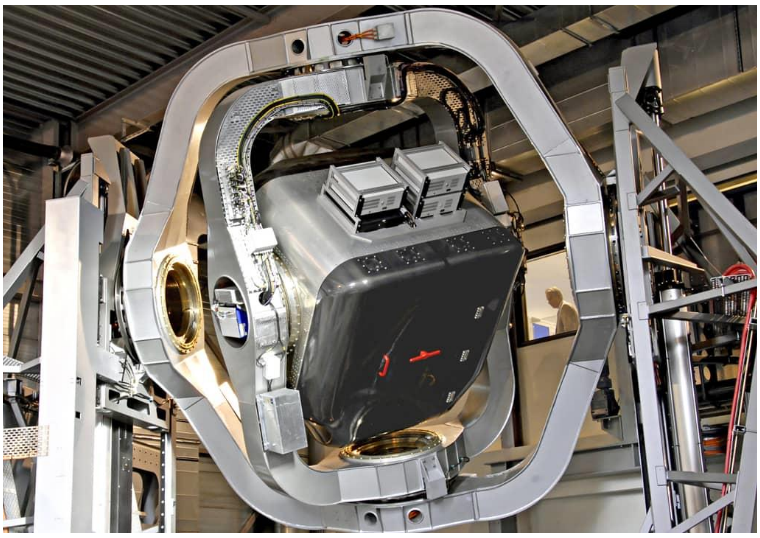

Figure 2. DESDEMONA Centrifuge-Based All-Attitude Simulator. Photo by (AMST, sd)

Figure 3. Participant in the DESDEMONA simulator, wearing the VARJO AERO, David Clark H10-13.4 and physiology sensors.

5.2.2. Apparatus and Materials

The experiment was conducted using the Desdemona simulator (Fig. 2), a highly advanced simulator capable of reproducing a wide range of (flight) conditions. The cockpit was configured as a Pilatus PC-7 cockpit mock-up, including a seat, PC-7 center stick, pedals, and a throttle.

Participants wore a VARJO AERO VR headset, which provided high-fidelity visuals at a refresh rate of 90 Hz, and a David Clark H10-13.4 headset for sound and communication (Fig. 3). The VR environment depicted the Aviano Air Force Base in Italy, using the D-WORLD visual system (Fig. 4).

A simplified PC-7 flight model was used in the D-SIM software environment, which was configured for final approach scenarios, with fixed throttle settings. Light turbulence was modelled by introducing disturbances to the pilot's stick inputs (both longitudinal and lateral). The lateral disturbances primarily induce a roll rate, which is both visible and perceptible along the roll axis, while the longitudinal disturbance is primarily noticeable in the heave axis of the simulator.

Physiological data were collected using a Polar H10 heart rate monitor around the chest and the Shimmer GSR3+ combined with gel electrodes for skin conductance on the left hand (Fig. 3).

Figure 4. Participant's view within the simulation. The light grey square represents the HMD, with the biofeedback interface positioned on the left side. In this scenario, the biofeedback is deactivated and fixed at 20% of the display height. The green circle, which serves as an eye tracker (not visible to participants), is centered over the runway.

Data collection, both during the SSST and simulator runs, was synchronized via Lab Streaming Layer (LSL) and recorded using LabRecorder. A short guide on how to connect the GSR3+ Shimmer to LSL is attached in Appendix 9. A dedicated Python script was created to real-time measure and normalize the physiological measures, which were presented in the biofeedback visualization (Fig. 4). The HR- and SC values were normalized to enable consistent comparison and visualization in the biofeedback interface. The normalization process involved a 30-second baseline measurement prior to each experimental run, during which HR and SC were continuously recorded. Between 5 and 25 seconds, the mean HR- and SC values were calculated and used as the participant's baseline levels. These baseline values were then mapped to 20% of the dual-pointer scales of the biofeedback interface (Fig. 4). This ensured that participant's typical resting physiological state was visually represented at a consistent level across all trials. The maximum, or 100% of the scale was set for a skin conductance value of 20 µS (James, Spottiswoode, & May, 2003; BIOPAC, 2015), and a heart rate of 200 beats per minute. The values between 20% (baseline) and 100% (maximum) were scaled linearly.

5.2.3. Procedure

The experiment began with a welcome and introduction. In this introduction, participants viewed a brief presentation outlining the procedures of the experiment and the flight task, after which participants signed an informed consent form and completed an initial questionnaire (see Appendix 3) regarding personal information and (simulator) flight experience. The Polar H10 heart rate monitor and Shimmer GSR3+ device for measuring skin conductance, were then installed around the participant’s chest and on the left hand, respectively. The participants also got a kneepad with the paper questionnaires on their left knee.

Participants were then seated in the Desdemona simulator, where they first performed the SSST, followed by a short questionnaire about the experienced arousal level during the SSST (see Appendix 4). The SSST was conducted within the Desdemona cabin to ensure the environment remained consistent with the subsequent simulator experiment.

Next, participants conducted a familiarization run, where they practiced the experimental run to familiarize themselves to the flight controls, the motion of the Desdemona simulator, and the flight task itself. In this task, they were required to control a simulated PC-7 aircraft. They were instructed to descend and fly a low-pass over the runway. After the familiarization session, participants completed a questionnaire (see Appendix 5) to confirm their readiness.

Following the familiarization, participants were introduced to the experimental conditions in which half of the conditions featured simulator motion and half of the conditions featured biofeedback visualization, cumulating to four conditions in total. In other words, in two of the four conditions, the Desdemona’s physical motion was active, to induce a higher arousal level, as shown by (Beenhakker, Houben, & Groen, in preparation). In two conditions, participants received real-time visual biofeedback on their HR and SC, while in other two, the biofeedback interface was visible but did not actively reflect their physiological responses. These conditions were counterbalanced using Latin Square to prevent order effects.

Each run began with a 30-second baseline measurement during which participants viewed a grey screen, while remaining at rest. After the baseline measurement, the participants received verbally their task: “Fly as low as comfortably possible above the runway, but it is very important that you absolutely do not touch the runway. Once you have reached a comfortable altitude, verbally indicate this and try to maintain it for about five seconds by flying straight. Then, gently raise your nose slightly. Keep your left hand steady and divide your attention between flying and watching the biofeedback”. The participants were also informed about the characteristics of the current condition and were asked if they were ready to perform their task. If their response was ‘yes’, the run was started.

Symptom		Score
No problems		0
Slight discomfort but no specific symptoms		1
Dizziness, warm, headache, stomach awareness, sweating, etc.	vague	2
	some	3
	medium	4
	severe	5
Nausea	some	6
	medium	7
	severe	8
	retching	9

Figure 5. The MISC rating scale (Reuten, Nooij, Bos, & Smeets, 2021) to monitor effects of motion sickness. A MISC score of 6 or higher was used as stop criterion to prevent negative effect on performance or comfort due to motion sickness.

After the participants verbally indicated they received the lowest altitude and maintained it for about five seconds, the simulation was stopped. After each run, the participants were asked to give their current MISC-score (Reuten, Nooij, Bos, & Smeets, 2021), which is a scale used to express the level of experienced motion sickness of a scale from one to ten (see Fig. 5). A MISC score of 6 or higher was used as a stop criterion to prevent negative effect on performance or comfort due to motion sickness. After verbally indicating their current MISC score, they were asked to carefully lift up the VR headset and fill in the fourth questionnaire (see Appendix 6).

Upon completing all runs, participants filled out a final questionnaire (see Appendix 7) comparing the different conditions and providing feedback on the inclusion of biofeedback in the cockpit environment. Before leaving, the experimenter ensured that the participants were in a suitable condition to return home safely.

5.2.4. Measurements

In this experiment, the following objective measures were recorded: aircraft altitude above ground level (m) at a sampling frequency of 100 Hz, x- and y-coordinates of the aircraft at a sampling frequency of 100 Hz, the flight model state, heart rate (bpm) at a sampling frequency of 1 Hz, skin conductance (μS) at a sampling frequency of 20 Hz, and control inputs at a sampling frequency of 100 Hz.

In addition, the following subjective measures were collected with Visual Analog Scales (VAS): perceived arousal (‘bored/relaxed/calm’ to ‘excited/energetic/stressed’, (Bruin, et al., 2024)), perceived valence (‘unpleasant’ to ‘pleasant’, (Bruin, et al., 2024)), motivation (‘unmotivated’ to ‘motivated’), realism (‘unrealistic’ to ‘realistic’), effort exerted ('none at all' to 'a lot'), motion- and biofeedback influence on task performance and arousal ('none at all' to 'a lot'), run manageability ('unmanageable' to 'manageable'), biofeedback interpretability ('easy' to 'difficult'), biofeedback effectiveness to get attention ('ineffective to 'effective'), distractiveness of biofeedback ('not distractive' to 'distractive'), biofeedback caused more awareness on emotional state ('disagree' to 'agree'), and influence of biofeedback on arousal level ('lower' to 'higher').

The initial questionnaire, prior to the simulator experiment, contained open questions about age, sex, and (simulator) flight experience. The second questionnaire, after the SSST, contains questions regarding perceived arousal using a VAS scale. The next questionnaire, after the familiarization run, contains five yes/no questions. All these questions have to be answered with 'yes' to confirm that the participant is prepared for the flight task. The fourth questionnaire, after performing a flight task, contains questions regarding motivation, performance, and arousal levels using a VAS scale and a multiple choice question about how often the biofeedback was checked during the task. The final questionnaire contains questions about the biofeedback, arousal, and performance using a VAS scale, a ranking question, and an open question. All questionnaires can be found in Appendix 3-7.

Subjective measure are calculated by measuring the position of the mark on the VAS scale. Then the averages per condition are calculated.

The final 5 seconds of the run, during which participants were instructed to fly at their lowest comfortable altitude, are designated as the Final Phase (FP). The difference between the HR- and SC values during the FP and their respective baseline measurements are used in the analyses.

Changes in HR and SC during the SSST were calculated by comparing the mean values from the minute preceding the singing task with baseline measurement of HR and SC, as done by (Brouwer & Hogervorst, 2014).

The data and questionnaire results are pseudonymized by assigning a personal identification number.

5.2.5. Statistical analysis

To examine the effects of biofeedback and simulator motion on the dependant variables of arousal level and flight performance, a Two-Way Analysis of Variance (ANOVA) was chosen as the most appropriate statistical analysis.

Independent t-tests were conducted to compare Heart Rate (HR) and Skin Conductance (SC) between the Sing-a-Song-Stress-Test (SSST) and the simulator conditions with- and without motion.

A mixed-effects model was used to assess order effects in the flight task and changes in physiology throughout runs.

In the results, p-values <.05 are considered significant.

5.3. Results

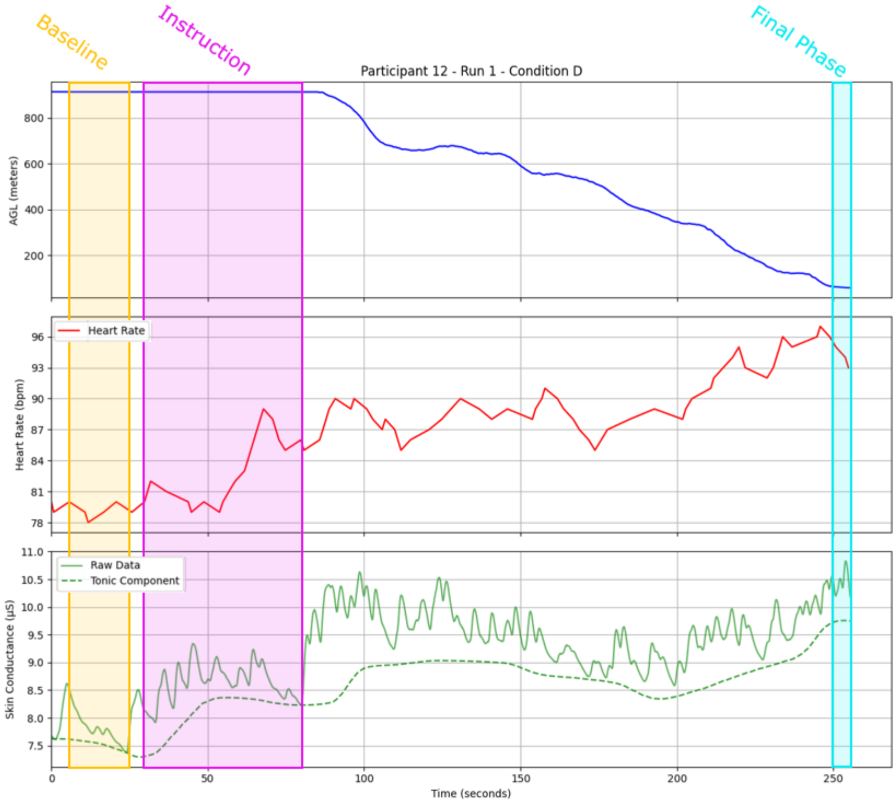

Figure 6. Example time-history of a single recording in terms of Altitude above Ground Level (AGL, top panel), Heart rate (middle panel) and Skin Conductance (bottom panel) in which the baseline measurement, instruction phase and final phase are highlighted.. The response values for HR and SC are calculated by taking the difference between the Final Phase of the experiment and the corresponding value measured during the baseline measurement.

Figure 6 presents an example time-history of a single experimental run in terms of AGL, HR and SC. As illustrated, both HR and SC levels increase as participants descended to lower altitudes. The timelines for AGL, HR and SC can be found in Appendix 8 for all participants.

The results of the objective data of all participants shows physical simulator motion significantly affected flight performance and arousal levels of participants, with participants flying at higher altitudes and with a higher skin conductance response when motion was present. Table 1, 2 and 3 show the results in more detail.

For Participant 2, the data for Run 4 Condition D is missing due to the cessation of simulator motion. Therefore this run is excluded from the data.

In Participant 15's third run, Condition B, the participant nearly lost control and therefore reported a minimum altitude that is likely higher than what would have been achieved under normal circumstances. Due to not following the task, this run is excluded from the data.

	Cond. A	**Cond. B**	**Cond. C**	**Cond. D**	**Effect Motion**		**Effect Biof.**		**Interaction effect Biof. Mot.**	
Objective Measures	**M- BF+**	**M- BF+**	**M+ BF-**	**M+ BF+**	**F-Value**	**p-Value**	**F-Value**	**p-Value**	**F-Value**	**p-Value**
AGL	16,02 ± 12,64	16,86 ± 17,15	25,24 ± 24,51	29,86 ± 32,34	**4,103**	0,047*	0,093	0,761	0,266	0,608
HR	9,13 ± 7,96	10,39 ± 12,06	10,63 ± 6,42	10,25 ± 9,8	0,093	0,761	0,037	0,848	0,129	0,72
SC	-0,07 ± 1,88	0,39 ± 2,5	1,02 ± 2,04	1,57 ± 2,69	**4,322**	0,042*	0,409	0,525	0,00	0,996

Table 1. Objective data during the simulator experiment, illustrated as mean ± SD. The objective measures are measured by the Desdemona, Polar H10 and Shimmer GSR3+. The AGL is in meters and is the lowest height flown of the participants in this condition. The heart rate value is in bpm and is the average of the last 5 seconds of the experiment (the final phase) minus the baseline value, measured during the first 30 seconds of the experiment. The skin conductance is in micro Siemens and is the final phase minus the baseline value.

No interaction effects were found between biofeedback and motion for the AGL (F=0.266, p=0.608), for the HR (F=0.129, p=0.720) or for the SC (F=0.00, p=0.996) (Table 1).

5.3.1. Simulator Motion and Physiological Measures

The results from Table 1 show the skin conductance response was higher in the motion-conditions compared to no-motion-conditions during the low-pass flight task (F=4.322, p=0.042). Participants in condition with simulator motion exhibited higher levels of skin conductance response compared to condition without simulator motion (Fig. 7).

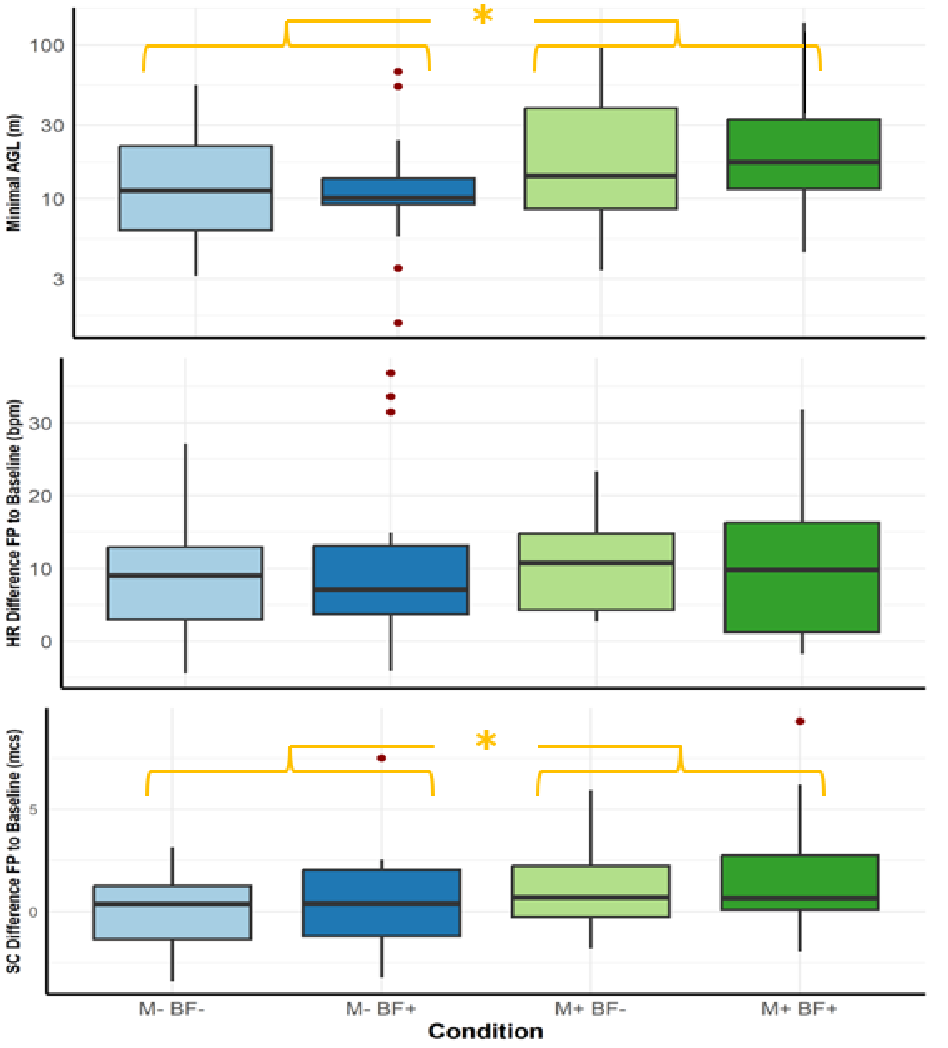

*Figure 7. Boxplots for AGL, HR and SC per condition. Significant differences are found between motion and no-motion for AGL and SC and are indicated with *. Note that the y-axis of AGL is log-scaled.*

In contrast to the effect on SC, simulator motion did not have a significant effect on heart rate (F=0.093, p=0.761) (Fig. 7). This result show that while motion impacts skin conductance, as an indicator of arousal, it does not significantly affect heart rate under these specific task conditions.

5.3.2. Simulator Motion and AGL

The results from Table 1 show that physical motion had a significant effect on the AGL during the low-pass flight task (F=4.103, p=0.047), with participants flying at significantly higher lowest altitude when motion was present (Fig. 7).

5.3.3. Biofeedback and Physiological Measures

No significant effects of biofeedback on arousal were observed for either skin conductance or heart rate (Table 1).

Biofeedback did not significantly influence skin conductance levels (F=0.409, p=0.525).

Similarly to skin conductance, biofeedback had no significant impact on heart rate (F=0.037, p=0.848).

5.3.4. Biofeedback and AGL

Biofeedback did not have a significant effect on AGL (F=0.093,p=0.761).

5.3.5. Subjective measures

Regarding the questionnaire results, six participants answered more questions on the questionnaire: "Post Run Condition" than instructed, despite clear guidance to the contrary. Specifically, they responded to questions related to biofeedback or simulator motion, even when these features were deactivated.

The results of the subjective data shows that conditions with motion have been perceived as more realistic compared to conditions without motion (75.72 vs 52.94) (Table 2). Conditions with motion also exerted more effort to perform the task compared to conditions without motion (58.51 vs 48.58) (Table 2). Participants also indicated that motion influenced their ability to perform the task (59.) (Table 2). Furthermore, participants indicated a higher experienced arousal level in conditions with motion compared to conditions without motion (62.06 vs 44.00) (Table 2).

Participants indicated that biofeedback had very little effect on their ability to perform the task (29.06) (Table 2).

Participants indicated in the post experiment questionnaire that the biofeedback did not influence their arousal level much (51.72) (Table 3).

Motivation was similar between conditions without biofeedback and those with biofeedback (80.73 vs 81.95) (Table 1). Participants indicated that it was relatively easy to interpret the biofeedback (scores of 22.06 and 20.78 for HR and SC components, respectively) (Table 3). The effectiveness of biofeedback in capturing attention was rated a bit effective at 66.39, and was considered not very distractive with a score of 34.56 (Table 3).

	Cond. A	**Cond. B**	**Cond. C**	**Cond. D**
Subjective Measures	**M- BF+**	**M- BF+**	**M+ BF-**	**M+ BF+**
Motivation to Perform Run (Unmotivated - Motivated)	80,67 ± 13,79	80,18 ± 11,29	80,06 ± 14,51	83,71 ± 10,17
Run Manageability (Unmanageable - Manageable)	77,72 ± 19,13	78,29 ± 14,38	72,06 ± 18,8	72,06 ± 19,89
Realism (Unrealistic - Realistic)	48,22 ± 16,35	57,65 ± 16,58	75,5 ± 12,41	75,94 ± 11,77
Effort Exerted (Little Effort - Much Effort)	46,28 ± 23,28	50,88 ± 22,34	56,78 ± 25,32	60,24 ± 23,32
Effect Motion on Task (None at all - A lot)			61,78 ± 24,19	57,47 ± 21,97
Effect Biofeedback on Task (None at all - A lot)		31,53 ± 23,81		26,59 ± 20,93
Subjective Arousal Level (Calm/Relaxed/Bored - Stressed/Energetic/Excited)	40,06 ± 17,91	47,94 ± 20,47	59,24 ± 21,87	64,88 ± 15,44
Subjective Valence Level (Unpleasant - Pleasant)	68,11 ± 14,01	70,82 ± 10,82	70,88 ± 14,19	73,71 ± 17,54
Effect Motion on Arousal (None at all - A lot)			70,56 ± 15,28	65,41 ± 20,7
Effect Biofeedback on Arousal (None at all - A lot)		30,47 ± 23,33		28,18 ± 21,93

Table 2. Subjective data during the simulator experiment, illustrated as mean ± SD. The subjective measures are in millimetres, measured from the VAS scale the participants filled in after each run. Between brackets are the words given that belong to 0 mm and 100mm on the scale.

General Biofeedback Questions	
Interpreting Biofeedback HR (Easy - Difficult)	22,06 ± 24,38
Interpreting Biofeedback SC (Easy - Difficult)	20,78 ± 25,7
Effectiveness Biofeedback to get Attention (Ineffective - Effective)	66,39 ± 21,94
Distractiveness Biofeedback (Not Distractive - Distractive)	34,56 ± 22,59
Biofeedback Caused More Awareness on Emotional State (Disagree - Agree)	60,61 ± 21,64
Biofeedback Influence on Arousal Level (Lower - Higher)	51,72 ± 14,2

Table 3. Subjective data post experiment, illustrated as mean ± SD. The subjective measures are in millimetres, measured from the VAS scale the participants filled in after each run. Between brackets are the words given that belong to 0 mm and 100mm on the scale.

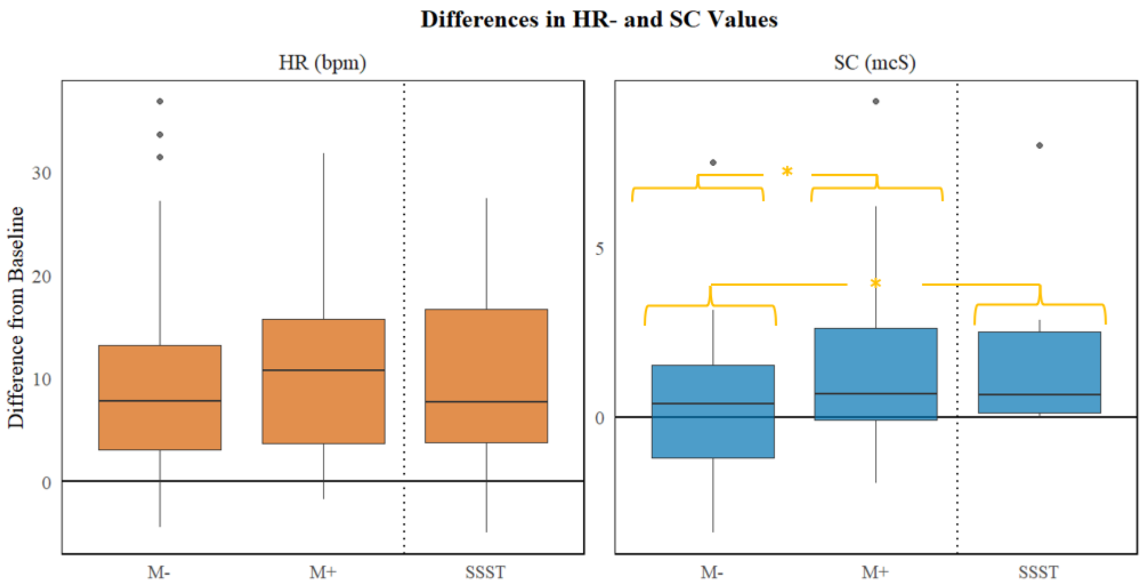

*Figure 8. Comparison between HR- and SC values in conditions with- and without motion and the SSST. Significant changes are indicated with *. Significant changes are found between conditions with- and without motion and between the SSST and conditions without motion.*

5.3.6. SSST

The results showed no significant differences in HR when comparing the SSST to conditions with motion (t=-0.230, p=0.820), or without motion (t=0.042, p=0.967), see Fig. 8. Similarly, no significant differences in SC were found between the SSST and conditions with motion (t=0.253, p=0.801). However, a significant increase in SC was found between the SSST and the no-motion condition (t=2.17, p=0.036) (Fig. 8), indicating that skin conductance during the SSST was significantly higher compared to the condition without motion.

5.3.7. Order effect

Although the participants indicated they were familiarized enough to start the experiment, the results show some learning effects throughout the runs, see Figure 9. Since the conditions were counterbalanced, each run in this figure contains all conditions. Note that participants with incomplete data sets (i.e. participants 2 and 15) are shown in the plot but excluded from the statistical analysis.

For AGL, the mixed-effects model revealed significant differences between Run 1 and Run 3 (estimate=13.180, p=0.0029), and between Run 1 and Run 4 (estimate=13.258, p=0.0027). No significant differences were found between Run 1 and Run 2 (estimate=6.855, p=0.2251), Run 2 and Run 3 (estimate=6.326, p=0.2900), Run 2 and Run 4 (estimate=6.404, p=0.2797), or between Run 3 and Run 4 (estimate=0.078, p=1.0000).

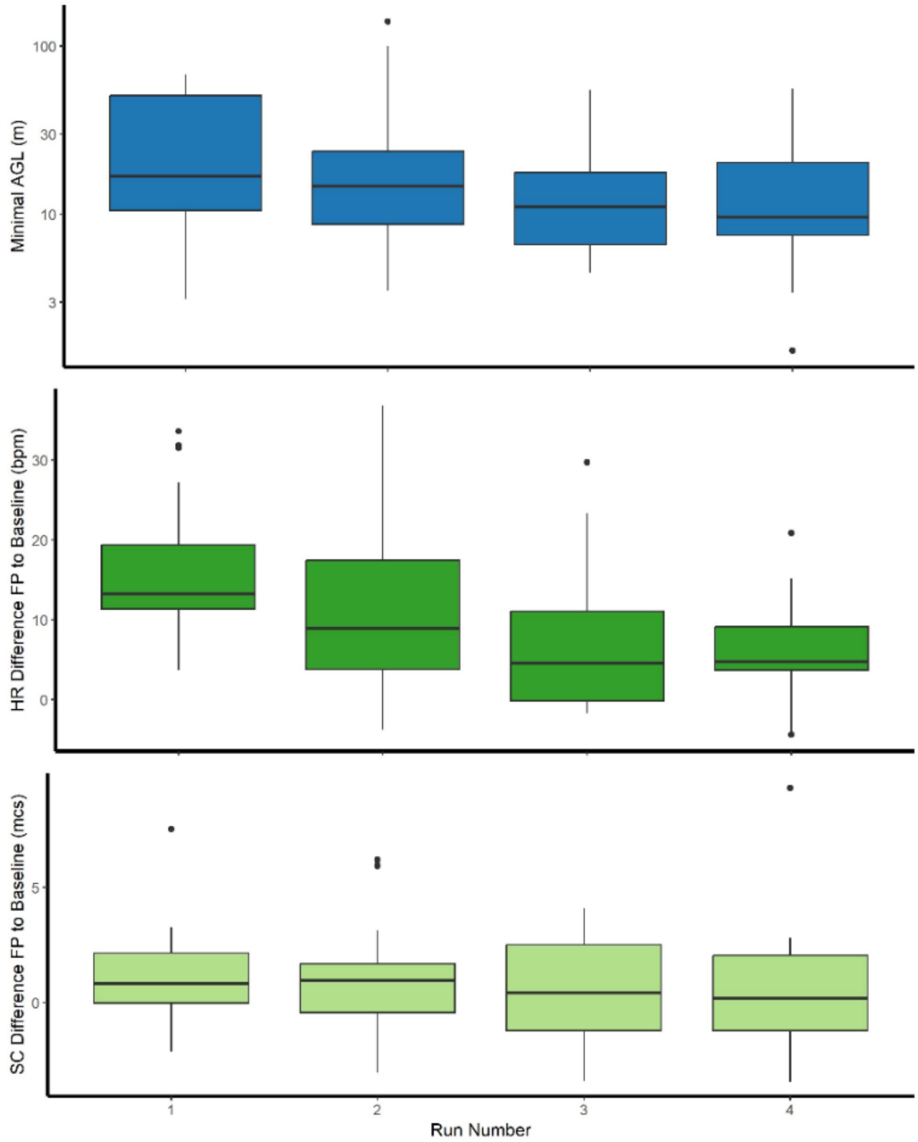

Figure 9. AGL, HR and SC per Run. Participants with incomplete data sets (i.e. participants 2 and 15) are shown in the plot but excluded from the statistical analysis. Statistical differences are in AGL between Run 1 and Run 3, and between Run 1 and Run 4. For HR, statistical differences are between Run 1 and Run 2, Run 1 and Run 3, and between Run 1 and Run 4.

For HR, significant differences were revealed by the mixed-effects model between Run 1 and Run 2 (estimate=5.86, p=0.0062), Run 1 and Run 3 (estimate=8.34, p=0.0001), Run 1 and Run 4 (estimate=9.77, p=<0.0001). Between Run 2 and Run 3 were no statistical differences found (estimate=2.48, p=0.4640), similar for Run 2 and Run 4 (estimate=3.91. p=0.1099), and Run 3 and Run 4 (estimate=1.43, p=0.8329).

For SC, the mixed-effects model revealed no significant differences between Run 1 and Run 2 (estimate=0.114, p=0.9983), Run 1 and Run 3 (estimate=0.761, p=0.6719), Run 1 and Run 4 (estimate=0.574, p=0.8285), Run 2 and Run 3 (estimate=0.648, p=0.7708), Run 2 and Run 4 (estimate=0.460, p=0.9024), and between Run 3 and Run 4 (estimate=-0.187, p=0.9923).

5.3.8. Correlation between objective and subjective results

The results show a moderate correlation (r=0.447) between the physiological measurements of skin conductance in conditions involving motion and the participants' self-reported arousal in response to simulator motion (Fig. 10).

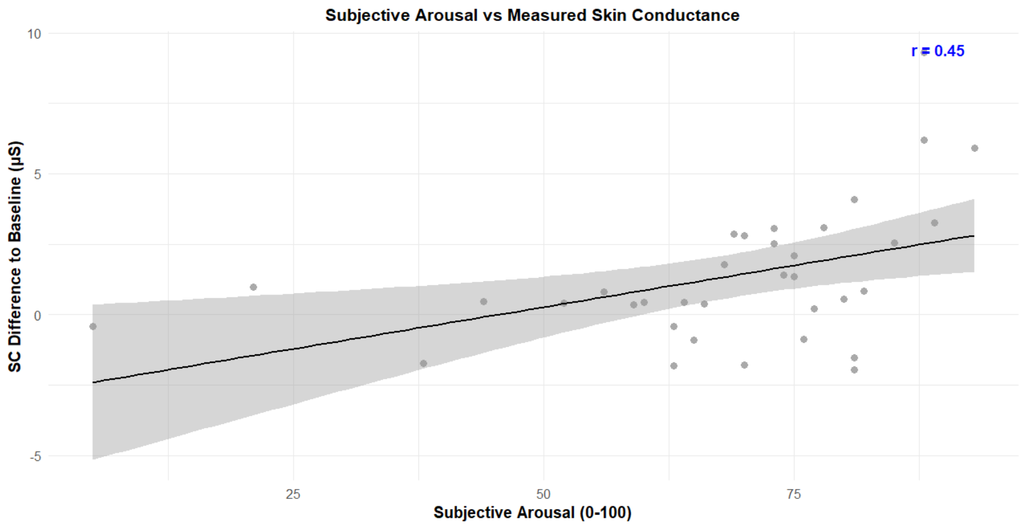

Figure 10. Correlation of r=0.447 between subjective experienced arousal and skin conductance. This suggests that there is a reasonable correlation between objective physiological responses and subjective experiences of arousal in the simulated environment.

5.4. Discussion

The results show that physical simulator motion significantly affected AGL and skin conductance, with participants flying at higher altitudes and with a higher skin conductance response when motion was present. Biofeedback had no significant effect on AGL, heart rate or skin conductance.

The fact that participants fly at a higher AGL in motion-conditions suggest that participant were more cautious in these conditions to avoid contact with the runway. This behaviour could be due to the additional physical feedback provided by the motion, which likely increased the participants' perceived risk of flying lower. This result aligns with (Beenhakker, Houben, & Groen, in preparation), where they also found that the addition of simulator motion resulted in a higher risk perception. Thus, the presence of simulator motion influenced not only the arousal levels but also the flight performance of the participants.

Participants indicated that motion influenced their ability to perform the task (see Table 2). This result is in line with the objective data since there was a statistical difference in AGL in conditions with motion compared to conditions without motion. Participants have also indicated that motion influenced their ability to perform the flight task (see Table 2). This result is in line with the objective data since there was a statistical difference in AGL in conditions with motion compared to conditions without motion. Participants indicated that biofeedback had very little effect on their ability to perform the task (see Table 2). This result is also what we found in the data since biofeedback no effect had on the AGL. Participants indicated in the post experiment questionnaire that the biofeedback did not influence their arousal level much (see Table 3). This result is in line with the data since biofeedback did not have a significant effect on arousal levels.

The lack of significant effect of biofeedback is unlikely due to differences in motivation (Table 1). The biofeedback was also not distractive according to the participants (Table 3).

The absence of a statistically significant difference between conditions with biofeedback and those without, does not necessarily imply that biofeedback lacks utility in cockpit environments. Several limitations of this study could explain these findings. First, during the experiment it was noticed that several participants tended to focus less on the biofeedback display when their altitude decreased, compared to when they were flying at a higher altitude. This suggests that the chosen modality (i.e., visual overlay of a dual-pointer biofeedback interface) may not have fully captured the participants' attention during the critical moments of the task. Secondly, biofeedback may not be useful in the flight task that has been used with non-pilots. Third, the chosen biofeedback function and/or form might not have been optimal. While we based our design on input from subject matter experts, the experiment involved participants who were not subject matter experts. Fifth, the participants did not engage in a task directly linked to the biofeedback, other than observing it. Incorporating an active task, such as attempting to maintain heart rate within a specific range, might have better demonstrated the potential of biofeedback to reduce mental stress and enhance performance since this makes participants actively use the biofeedback, instead of just looking at it. Finally, participants with no prior (simulator) flight experience were used in this study. It may be possible that, due to their unfamiliarity with the flight simulator task and lack of knowledge on how to perform, the biofeedback may not have been fully effective or perceived as intended. Biofeedback may have a different effect on people with significant (simulator) flight experience.

The SSST has been previously shown to increase arousal levels (Brouwer & Hogervorst, 2014). Based on the observed increase in SC during the SSST, the level of arousal appears to be similar between the SSST and the condition with motion. The statistical differences between the no-motion and motion conditions, as well as between the no-motion condition and the SSST, suggests that the conditions with motion did indeed induce an increase in arousal.

The results showed that there was a significant reduction in AGL due to a learning effect (Fig. 9). Specifically, there was a notable decrease from Run 1 to Run 3 and from Run 1 to Run 4, indicating improvement in performance. As the participants completed a familiarization run prior to the experiment, these findings suggest that at least three familiarization runs would have been necessary to prevent significant learning effects during the runs.

The results also show a significant reduction in arousal response, showed by HR, throughout the runs (Fig. 9). This indicates that participants arousal level was the highest during the first run, no matter which condition they started with. Interestingly, we found a significant effect of motion through skin conductance and a run order effect through heart rate.

The moderate correlation between physiological measurements of skin conductance in conditions involving motion and participants' self-reported arousal in response to simulator motion (Fig. 10) suggests a reasonable correlation between objective physiological responses and subjective experiences of arousal in the simulated environment. This result also confirms that skin conductance is a good measure for arousal.

Our experiment was based on the study by (Beenhakker, Houben, & Groen, in preparation), where arousal was measured through heart rate. In contrast, we observed an increase in arousal through skin conductance rather than heart rate. This discrepancy may be attributed to the fact that (Beenhakker, Houben, & Groen, in preparation) utilized turbulence motion in the “Straight and Level with Turbulence” scenario that had a ten times greater magnitude than in the present study. When preparing the study with an experienced pilot it was decided to reduce the turbulence motion because of the low-pass task that was implemented.

Participants frequently moved their left hand, where the skin conductance electrodes were attached, while putting on and taking off the VR headset. The VR headset needed to be lifted slightly upward on their heads to allow them to complete the questionnaire. This hand movement led to increased SC readings that were unrelated to arousal, introducing some uncertainty into the data. In certain cases, the recovery period after hand movements may have exceeded the duration of the baseline measurement, leading to imprecise baseline values. An example of this can be found in Appendix 8 Participant 4. In this example, it is visible that the skin conductance keeps declining, hence, returning to a baseline level, before increasing when a lower altitude, and hence a higher arousal level, are reached.u8

Although we did not observe a significant effect of biofeedback on arousal response or flight performance, the relevance of this topic warrants further exploration. We recommend that future experiments include experienced pilots and utilize a different task where biofeedback is directly used for stress management or performance enhancing.

5.5. Conclusion

This exploratory study demonstrates that biofeedback in the cockpit environment can be delivered through various modalities (e.g., visual, auditory, tactile) and serve different purposes (e.g., informing, alerting, intervening), depending on the specific context. Consequently, the appropriate form and function of biofeedback needs be tailored to the specific task.

The results show that simulator motion significantly increases the level of arousal and altitude above ground level during a low-pass flight task. Unfortunately, no significant effects of biofeedback on either arousal or flight performance were found.

Several factors may account for the lack of significant findings of biofeedback. One potential explanation is that the biofeedback was not used during critical moments of the flight task. Another potential explanation is the choice of flight task, which may not have been optimally suited for biofeedback implementation. The biofeedback was used only for visual information, without being directly linked to a specific task objective. Additionally, the participants had no prior (simulator) flight experience, which could have affected their ability to fully leverage the biofeedback.

For future experimental research on biofeedback in the cockpit, it is recommended to use participants with (military) flight experience and to select tasks that are explicitly linked to the biofeedback being utilized, for example involving stress management or performance enhancement.

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6. Appendices

6.1. Appendix 1: Questionnaire Biofeedback in the Cockpit

Questionnaire Biofeedback in the Cockpit

- In aviation, numerous parameters are measured related to the aircraft's state, yet monitoring the pilot's physiological responses is gaining interest. Consequently, I am investigating the potential for biofeedback within the cockpit for my internship, with regards to V2306 'NextGen Aircrew Performance'. Biofeedback involves delivering real-time feedback on physiological functions, such as heart rate, brain activity, and muscle tension, to enhance performance and safety.
- Within V2306, we would like to build knowledge about the application and added value of biofeedback in the cockpit. For this purpose, this questionnaire serves as a starting point.
- Biofeedback can be implemented through various modalities such as visual, audio, and tactile. This questionnaire will explore these three options for "informing" and "alarming" the pilot. Although "stimulating" and "intervening" are also functions for biofeedback, these will not be discussed in this questionnaire.
- With informing, the biofeedback only gives information about the physiological state such as heart rate or skin conductance. With alarming, the biofeedback indicates when a certain (unsafe) threshold is being exceeded, for example when a pilot is becoming hypoxic.
- Filling out this questionnaire will take approximately 15 minutes.
- All data will be anonymized.

<u>Instructions:</u>

- This questionnaire comprises three sections: Part I focuses on the function of biofeedback, Part II explores its design and location, Part III addresses general aspects.
- When you are asked to fill in a multiple-choice question, place an "X" next to your answer(s). For example:

Visual	X
Audio	
Tactile	

- When you are asked to circle around a number, do it as follows:

2

Thank you in advance for filling out this questionnaire,
Leon van Mierlo

Part I Functions of Biofeedback

Part I of the questionnaire is meant to get your opinion about different modalities (visual, audio, and tactile) for two different functions of biofeedback (informing and alarming).

For the questions concerning informing, we focus on visual and auditory modalities only, as tactile information is regarded as not practical for this purpose.

A *visual* example is a display showing the pilot's heart rate (HR) or skin conductance (SC) which indicates a level of arousal.
An *auditory* example is a voice that gives information about the heart rate of the pilot or the oxygen level.

For the function of alarming, it is believed that the tactile modality—incorporating vibrating elements in the flight suit—presents additional possibilities beyond the visual- and auditory methods. For instance, when a critical threshold is exceeded, and the pilot is at risk of becoming hypoxic, alarms could be triggered in visual-, auditory-, or tactile forms.

Please fill in the following seven questions.

1.1 For two functions of biofeedback, which do you expect to be valuable?

	Yes	No
Informing		
Alarming		

If your answer is "no" to both, you are not required to complete the remainder of the survey.

1.2 Indicate for each modality when you want to receive biofeedback.

	Continuous	On demand	To alarm
Visual			
Audio			
Tactile			

1.3 Taking into account other visual-, auditory-, and tactile signals in a cockpit, how much remaining "sensory-capacity" do you believe a pilot has for each modality?

Visual	1	2	3	4	5	6	7	8	9	10
Audio	1	2	3	4	5	6	7	8	9	10
Tactile	1	2	3	4	5	6	7	8	9	10
	None								A lot	

1.4 How effective do you expect each modality to be in capturing your attention?

Visual	1	2	3	4	5	6	7	8	9	10
Audio	1	2	3	4	5	6	7	8	9	10
Tactile	1	2	3	4	5	6	7	8	9	10

Not effective Very effective

1.5.1 Do you expect the *informing* biofeedback to distract? And if so, is the distraction acceptable for the situation?

	Yes, and not acceptable	Yes, but acceptable	No
Visual			
Audio			

1.5.2 Do you expect the *alarming* biofeedback to distract? And if so, is the distraction acceptable for the situation?

	Yes, and not acceptable	Yes, but acceptable	No
Visual			
Audio			
Tactile			

1.6 Reflecting on the previous questions, which of the three modalities do you expect to be most effective for integrating biofeedback in the cockpit for the two different functions of biofeedback?

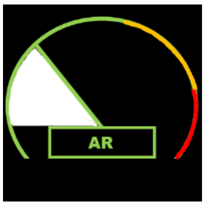
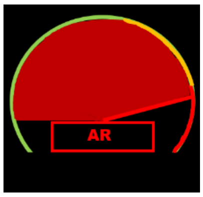
	Informing	Alarming
Visual		
Audio		
Tactile		

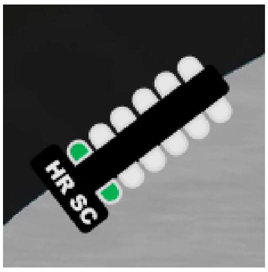
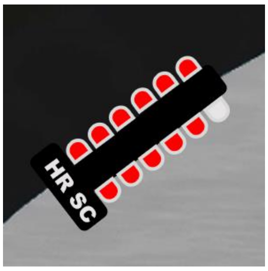
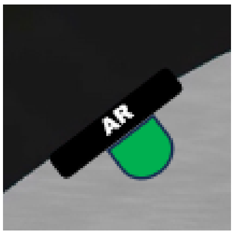
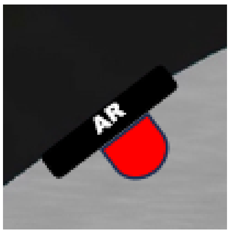
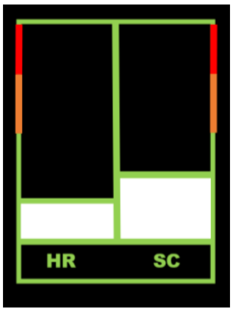
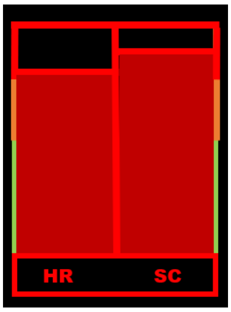
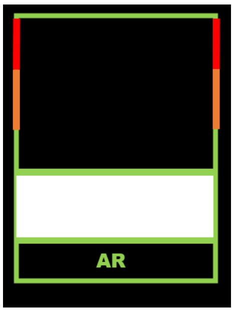
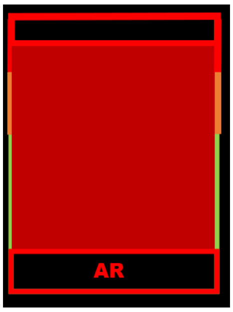
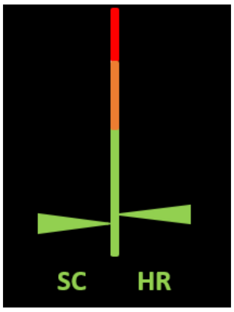
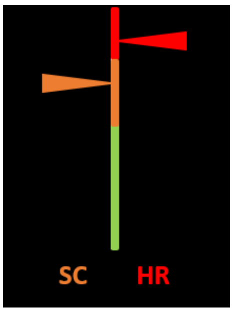
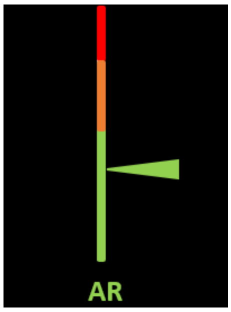
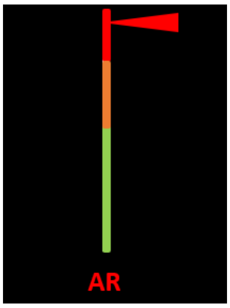
<u>Part II Design and Location</u>

For the practical part of my internship project, I plan to implement visual biofeedback using heart rate (HR) and skin conductance (SC), which measures the skin's electrical conductance, to measure arousal levels (the state of physiological- and psychological activation). I would like to ask you to examine the different design options presented below, which range from simple raw data to visualizations of aggregated arousal (AR) levels. For each design, the low aroused state is shown on the left and the high aroused state is on the right.

Questions will follow after the visuals.

<u>Biofeedback Design</u>

	Separated Raw Data		Aggregated Arousal Level
1	Digital Raw Data	2	Digital Aggregated Data
	 		 
3	Analogue Raw Data	4	Analogue Aggregated Data
	 		 

	Separated- and Normalized HR- and SC Values		Aggregated Arousal Level
5	LED strip	6	Light
	 		 
7	Double Bar	8	Single Bar
	 		 
9	Double Pointers	10	Single Pointer
	 		 

2.1.1 Based on the examples provided above, how would you prefer the biofeedback to be presented?

	Yes	No
Digital data		
Analogue data		

2.1.2 Based on the examples provided above, how would you prefer the biofeedback to be presented?

	Yes	No
Separate (normalized) values for HR and SC		
Aggregated arousal level		

2.2 Would you like the raw HR- and SC values to be included in designs that do not contain this?

Yes	
No	

2.3 Could you please give the number/name of the designs that you think are suitable visualizations?

………

………

………

2.4 Give your top 3 visualizations (For example: 7, 1, 3)

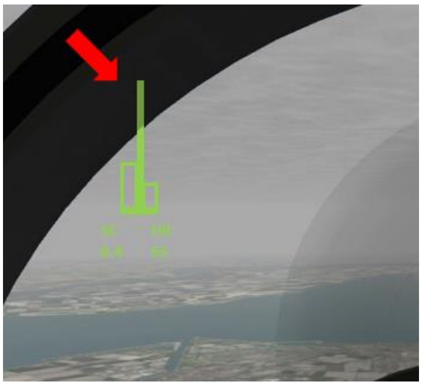
………

………

………

<u>Biofeedback Location</u>

For the implementation of visual biofeedback, I am evaluating three potential locations: instrument panel, kneepad or head-mounted display (HMD). The images below illustrate various visualizations displayed at these locations, presented in both zoomed-in- and zoomed-out views. Please note that the visualizations depicted are randomly selected and the focus of the table is solely for the location. It is important to remember that visualizations on the HMD, which appear as semi-transparent single-color overlay in the primary field of view, need to be simplified compared to those on the instrument panel and kneepad.

<table>
<tr>
<td><u>Instrument Panel</u>
+ Fixed location in cockpit.
- Integration with cockpit.</td>
<td><u>Kneepad</u>
+ No cockpit integration needed.
- Shift of attention from cockpit to knee.</td>
<td><u>HMD</u>
+ Always in view.
- Integration into HMD system.
- Clutter of information.</td>
</tr>
<tr>
<td></td>
<td>
</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</table>

2.5 What do you think is the best location to implement visual biofeedback in the cockpit? (multiple answers possible)

Instrument Panel	
Kneepad	
HMD	

2.6 Repeat your top 3 of designs from question 2.4, and indicate your preferred location for each of these designs.

	Design Name / Design Number	Instrument Panel	Kneepad	HMD
1				
2				
3				

Part III General

3.1 Do you have any tips for better visualizations?

……

……

3.2 Do you have any tips for better locations?

……

……

3.3 In this questionnaire we focussed on heart rate and skin conductance as a measure of arousal. Which other physiological measurements do you think are relevant for biofeedback applications in the cockpit?

……

……

3.4 Do you have any other remarks?

……

……

……

……

6.2. Appendix 2: Questionnaire Biofeedback in the Cockpit Results

If there is extra info at a non-open question after a black dot, this is a remark a SME wrote down.

Questionnaire Biofeedback in the Cockpit

- In aviation, numerous parameters are measured related to the aircraft's state, yet monitoring the pilot's physiological responses is gaining interest. Consequently, I am investigating the potential for biofeedback within the cockpit for my internship, with regards to V2306 'NextGen Aircrew Performance'. Biofeedback involves delivering real-time feedback on physiological functions, such as heart rate, brain activity, and muscle tension, to enhance performance and safety.
- Within V2306, we would like to build knowledge about the application and added value of biofeedback in the cockpit. For this purpose, this questionnaire serves as a starting point.
- Biofeedback can be implemented through various modalities such as visual, audio, and tactile. This questionnaire will explore these three options for "informing" and "alarming" the pilot. Although "stimulating" and "intervening" are also functions for biofeedback, these will not be discussed in this questionnaire.
- With informing, the biofeedback only gives information about the physiological state such as heart rate or skin conductance. With alarming, the biofeedback indicates when a certain (unsafe) threshold is being exceeded, for example when a pilot is becoming hypoxic.
- Filling out this questionnaire will take approximately 15 minutes.
- All data will be anonymized.

Instructions:

- This questionnaire comprises three sections: Part I focuses on the function of biofeedback, Part II explores its design and location, Part III addresses general aspects.
- When you are asked to fill in a multiple-choice question, place an "X" next to your answer(s). For example:

Visual	X
Audio	
Tactile	

- When you are asked to circle around a number, do it as follows:

2

Thank you in advance for filling out this questionnaire,
Leon van Mierlo

Part I Functions of Biofeedback

Part I of the questionnaire is meant to get your opinion about different modalities (visual, audio, and tactile) for two different functions of biofeedback (informing and alarming).

For the questions concerning informing, we focus on visual and auditory modalities only, as tactile information is regarded as not practical for this purpose.

A *visual* example is a display showing the pilot's heart rate (HR) or skin conductance (SC) which indicates a level of arousal.
An *auditory* example is a voice that gives information about the heart rate of the pilot or the oxygen level.

For the function of alarming, it is believed that the tactile modality—incorporating vibrating elements in the flight suit—presents additional possibilities beyond the visual- and auditory methods. For instance, when a critical threshold is exceeded, and the pilot is at risk of becoming hypoxic, alarms could be triggered in visual-, auditory-, or tactile forms.

Please fill in the following seven questions.

1.1 For two functions of biofeedback, which do you expect to be valuable?

	Yes	No
Informing	8	1
Alarming	9	

If your answer is "no" to both, you are not required to complete the remainder of the survey.

1.2 Indicate for each modality when you want to receive biofeedback.

	Continuous	On demand	To alarm
Visual	4	8	5
Audio		5	7
Tactile	1	2	8

1.3 Taking into account other visual-, auditory-, and tactile signals in a cockpit, how much remaining "sensory-capacity" do you believe a pilot has for each modality?

Visual	1	2	3 -> 1	4 -> 1	5	6 -> 1	7 -> 1	8 -> 2	9 -> 1	10
Audio	1	2	3 -> 2	4 -> 2	5 -> 1	6 -> 1	7 -> 1	8	9	10
Tactile	1	2	3	4	5 -> 2	6	7 -> 1	8 -> 2	9 -> 1	10 -> 1
	None								A lot	

- Can signal be turned off? -> else can become annoying
- No flight experience so guess

1.4 How effective do you expect each modality to be in capturing your attention?

Visual	1	2	3 -> 1	4	5	6 -> 1	7 -> 3	8 -> 3	9	10
Audio	1	2	3 -> 1	4	5	6	7 -> 2	8 -> 3	9 -> 2	10
Tactile	1	2	3	4	5	6 -> 2	7 -> 1	8 -> 4	9	10 -> 1

Not effective Very effective

1.5.1 Do you expect the *informing* biofeedback to distract? And if so, is the distraction acceptable for the situation?

	Yes, and not acceptable	Yes, but acceptable	No
Visual	2	6	1
Audio	5	4	

- Depends on situation
- Only if design is adequate
- Only “on demand”
- Depends on what is fed back and the situation

1.5.2 Do you expect the *alarming* biofeedback to distract? And if so, is the distraction acceptable for the situation?

	Yes, and not acceptable	Yes, but acceptable	No
Visual		8	1
Audio		8	1
Tactile		8	1

- Only if design is adequate

1.6 Reflecting on the previous questions, which of the three modalities do you expect to be most effective for integrating biofeedback in the cockpit for the two different functions of biofeedback?

	Informing	Alarming
Visual	9	3
Audio	2	7
Tactile	2	7

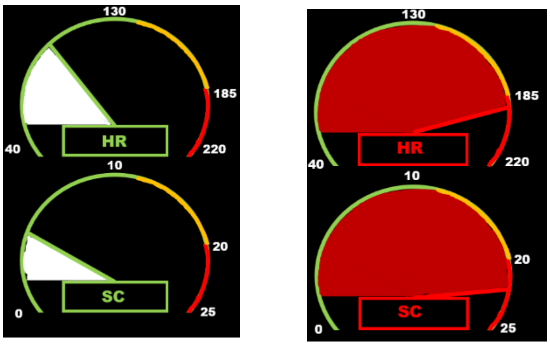
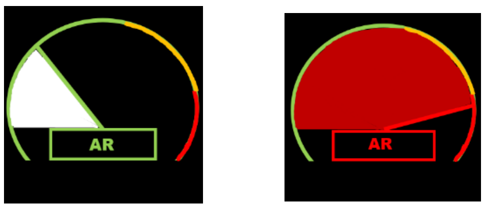
- Visual can be ignored, audio not.
- Depends on what info you want to give

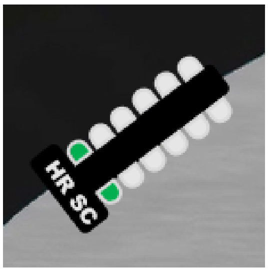
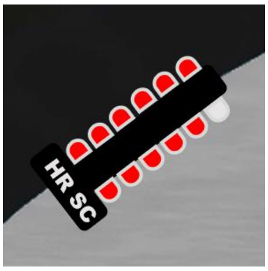
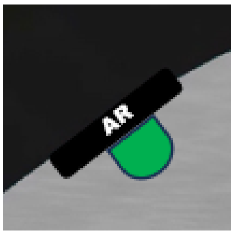
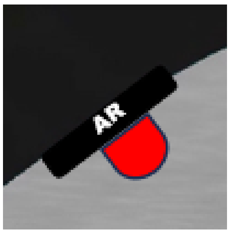
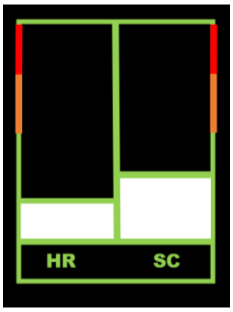
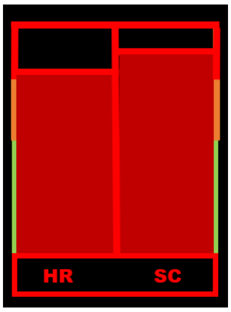
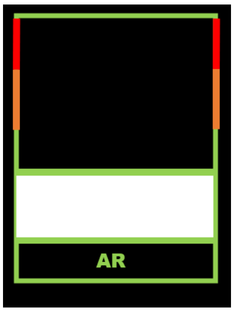
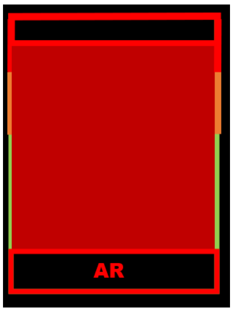
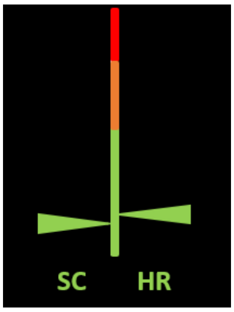
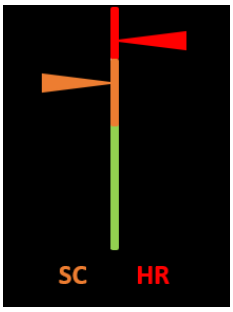
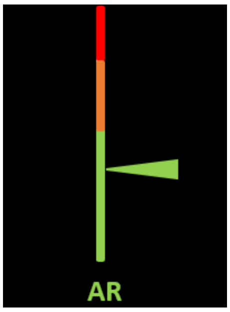
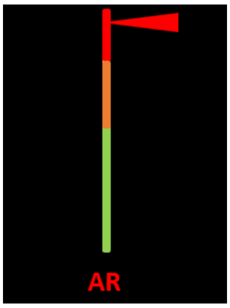
<u>Part II Design and Location</u>

For the practical part of my internship project, I plan to implement visual biofeedback using heart rate (HR) and skin conductance (SC), which measures the skin's electrical conductance, to measure arousal levels (the state of physiological- and psychological activation). I would like to ask you to examine the different design options presented below, which range from simple raw data to visualizations of aggregated arousal (AR) levels. For each design, the low aroused state is shown on the left and the high aroused state is on the right.

Questions will follow after the visuals.

<u>Biofeedback Design</u>

	<u>Separated Raw Data</u>		<u>Aggregated Arousal Level</u>
1	Digital Raw Data	2	Digital Aggregated Data
			
3	Analogue Raw Data	4	Analogue Aggregated Data
			

	<u>Separated- and Normalized HR- and SC Values</u>		<u>Aggregated Arousal Level</u>
5	LED strip	6	Light
	 		 
7	Double Bar	8	Single Bar
	 		 
9	Double Pointers	10	Single Pointer
	 		 

2.1.1 Based on the examples provided above, how would you prefer the biofeedback to be presented?

	Yes	No
Digital data	5	4
Analogue data	6	2

2.1.2 Based on the examples provided above, how would you prefer the biofeedback to be presented?

	Yes	No
Separate (normalized) values for HR and SC	6	2
Aggregated arousal level	7	2

2.2 Would you like the raw HR- and SC values to be included in designs that do not contain this?

Yes	5
No	4

- Yes for HR (x2)
- No for SC

2.3 Could you please give the number/name of the designs that you think are suitable visualizations?

Design	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Votes	5	3	4	4	2	1	4	2	7	4

2.4 Give your top 3 visualizations (For example: 7, 1, 3)

First choice:

Design	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Votes	2	1	2						3	1

Second choice:

Design	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Votes		1	1	2	1		1	1	1	1

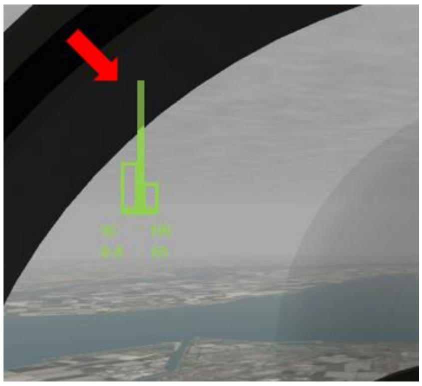
- Sorry, only top 2

Third choice:

Design	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Votes							2	2	3	1

Biofeedback Location

For the implementation of visual biofeedback, I am evaluating three potential locations: instrument panel, kneepad or head-mounted display (HMD). The images below illustrate various visualizations displayed at these locations, presented in both zoomed-in- and zoomed-out views. Please note that the visualizations depicted are randomly selected and the focus of the table is solely for the location. It is important to remember that visualizations on the HMD, which appear as semi-transparent single-color overlay in the primary field of view, need to be simplified compared to those on the instrument panel and kneepad.

Instrument Panel + Fixed location in cockpit. - Integration with cockpit.	Kneepad + No cockpit integration needed. - Shift of attention from cockpit to knee.	HMD + Always in view. - Integration into HMD system. - Clutter of information.
		
		

2.5 What do you think is the best location to implement visual biofeedback in the cockpit? (multiple answers possible)

Instrument Panel	6
Kneepad	4
HMD	2

2.6 Repeat your top 3 of designs from question 2.4, and indicate your preferred location for each of these designs.

Design Number	Instrument Panel	Kneepad	HMD
1	1	1	
2	1		1
3	3		
4		1	
5	1	1	
6			
7	3	2	
8	2	1	
9	5	2	2
10	1	1	

Part III General

3.1 Do you have any tips for better visualizations?

- Use of warning light (on HMD?) + Audio -> info on panel
- Double bar as LED strip (*I have this visualization as design 5)*
- I don't think the design should look like something that indicates motorpresetation. This could be confusing
- Use symbol + value
- Nr 10 with a circle on top of the line, instead of a pointer
- Nr 2 (or 1) with increase of font size with increase in level

3.2 Do you have any tips for better locations?

- Not really, but I was thinking that biofeedback tells something about the pilot himself, so maybe the instrument panel is less suitable because the instruments tell things about the aircraft. So is there a location that "belongs" to the pilot

3.3 In this questionnaire we focussed on heart rate and skin conductance as a measure of arousal. Which other physiological measurements do you think are relevant for biofeedback applications in the cockpit?

- Eye tracking -> focus, concentration, distraction
- (De-)hydration
- Hypoxia
- Pupil size, sweat, temperature
- Breathing frequency e i.r.t. hypoxic state
- Sleepiness ?? with blinks
- SpO2-levels (x2)
- CO2-levels
- Breathing rate (x2)
- Stress (x2)
- Gaze (and mind) wandering -> fatigued

3.4 Do you have any other remarks?

- Design 9 en 10 are used for flaps
- Consistent use of colors, no white but green/orange/red.
- Context info: flight hours, platform, most recent platform, most hours
- Success with your internship! :)

6.3. Appendix 3: Questionnaire Pre Experiment

Please fill in the following information about yourself:

1. What is your age? ……………..
2. What is your sex? Male / Female / Other
3. What is your total flight experience? …………….. (estimated flight hours)
4. What is your total simulator flight experience? …………….. (estimated flight hours)

Thank you for filling out this questionnaire

TNO

6.4. Appendix 4: Questionnaire after SSST

Arousal (in Dutch: mate van opwinding) is a state that reflects how physically and mentally stimulated or alert a person is. It can vary from being completely relaxed and asleep to being highly excited and active, influencing both sensory perception and physical readiness.

Valence (in Dutch: positieve of negatieve ervaring) indicates whether an emotion or experience is perceived as positive or negative. It determines how pleasurable or unpleasant a situation, object, or event is, and helps classify emotions as either good or bad.

1. Just before singing, I experienced a level of <u>arousal</u> that made me feel…

Calm Relaxed Bored	Stressed Energetic Excited

2. Just before singing, I experienced a level of _ that made me feel…

Unpleasant	Pleasant

6.5. Appendix 5: Questionnaire Post Familiarization

	Yes	No
1. I understand the task that is being asked of me.		
2. I can control the aircraft in a way that allows me to perform the task.		
3. I can see the external view in a way that allows me to perform the task.		

Biofeedback involves providing real-time feedback on physiological responses. Examples we all know are the visualization of the heart rate or quality of sleep of the person by using data of a smart watch.

4. I can adequately read the biofeedback information.		
5. I feel comfortable performing the task.		

TNO

6.6. Appendix 6: Questionnaire Post Run Condition

Participant Number	Run Number	Condition

Motivation

1. To perform this run, I was…

Unmotivated Motivated

2. Completing this run was…

Unmanageable Manageable

3. I experienced this run as…

Unrealistic Realistic

Performance

4. To complete this run, I had to exert…

Little effort Much effort

5. If physical motion of the simulator was present during this run, the influence it had on my flight performance / task was…

None at all A lot

6. If the biofeedback on heart rate and skin conductance was present during this run, the influence it had on my flight performance / task was…

None at all A lot

Experience

Arousal (in Dutch: mate van opwinding) is a state that reflects how physically and mentally stimulated or alert a person is. It can vary from being completely relaxed and asleep to being highly excited and active, influencing both sensory perception and physical readiness.

Valence (in Dutch: positieve of negatieve ervaring) indicates whether an emotion or experience is perceived as positive or negative. It determines how pleasurable or unpleasant a situation, object, or event is, and helps classify emotions as either good or bad.

7. During this run, I experienced a level of <u>arousal</u> that made me feel…

Calm Stressed
Relaxed Energetic
Bored Excited

8. During this run, I experienced a level of <u>valence</u> that made me feel…

Unpleasant Pleasant

Influence on Arousal Level

9. If **physical motion** of the simulator was present during this run, the influence it had on my <u>arousal</u> level was…

None at all A lot

10. If the **biofeedback** on heart rate and skin conductance was present during this run, the influence it had on my arousal level was…

None at all A lot

General

11. During this run, how often did you check the biofeedback information on heart rate and skin conductance?

Not at all / Once / Twice / 3-5x / 6-10x / All the time

6.7. Appendix 7: Questionnaire Post Experiment

1. Interpreting the biofeedback on heart rate was…

Easy | Difficult

2. Interpreting the biofeedback on skin conductance was…

Easy | Difficult

3. To get my attention, the way the biofeedback on heart rate and skin conductance was visualized was ….

Ineffective | Effective

4. The presence of the biofeedback visualization was…

Not distractive | Distractive

5. The presence of biofeedback made me feel more aware of my emotional state, including my levels of stress, excitement, and relaxation.

Disagree | Agree

6. The presence of biofeedback made my level of arousal…

Lower | Higher

7. What effect did the biofeedback have on you?

………

………

………

8. Please indicate the altitude above terrain at which you felt comfortable for each condition?

- Condition A: No physical motion, no biofeedback
- Condition B: No physical motion, with biofeedback
- Condition C: With physical motion, no biofeedback
- Condition D: With physical motion, with biofeedback

A. ____

B. ____

C. ____

D. ____

Touching the ground Low

9. If you experienced varying levels of arousal, please rank them from lowest to highest. For conditions where you experienced the same level of arousal, assign them the same rank.

- Condition A: No physical motion, no biofeedback
- Condition B: No physical motion, with biofeedback
- Condition C: With physical motion, no biofeedback
- Condition D: With physical motion, with biofeedback

(Lowest) 1.

2.

3.

(Highest) 4.

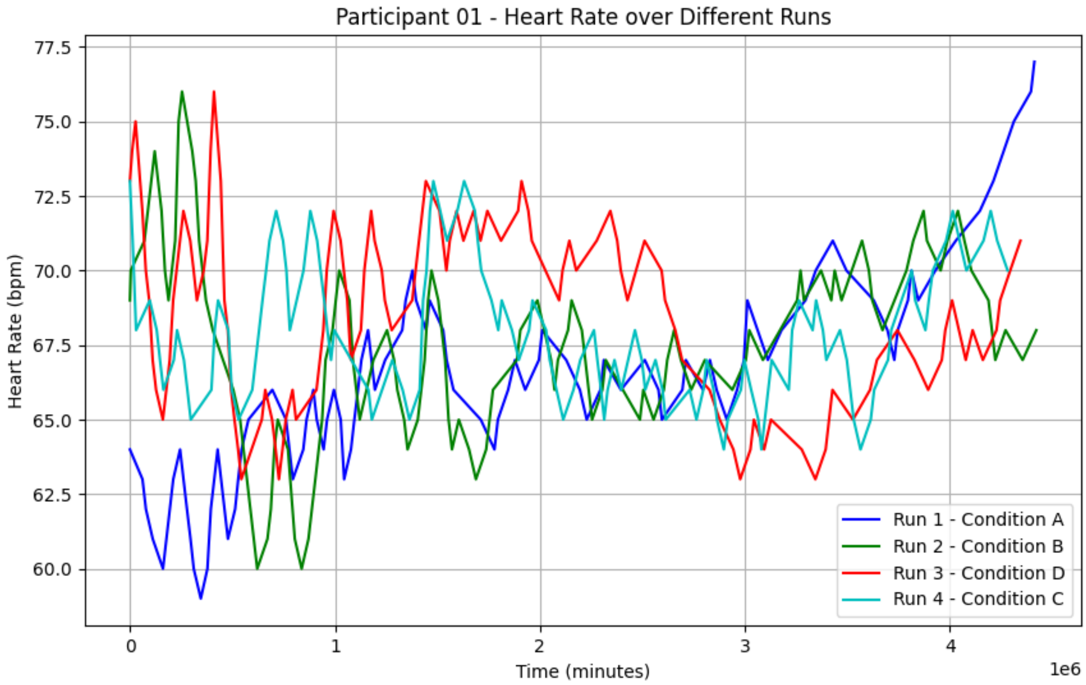
10. Other remarks:

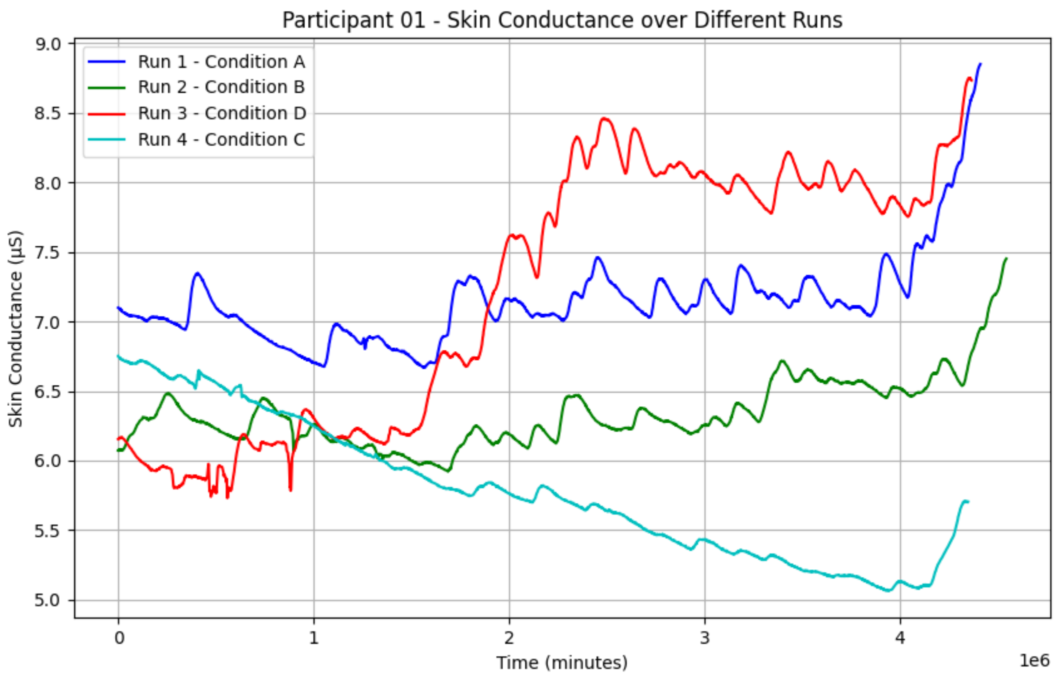
………

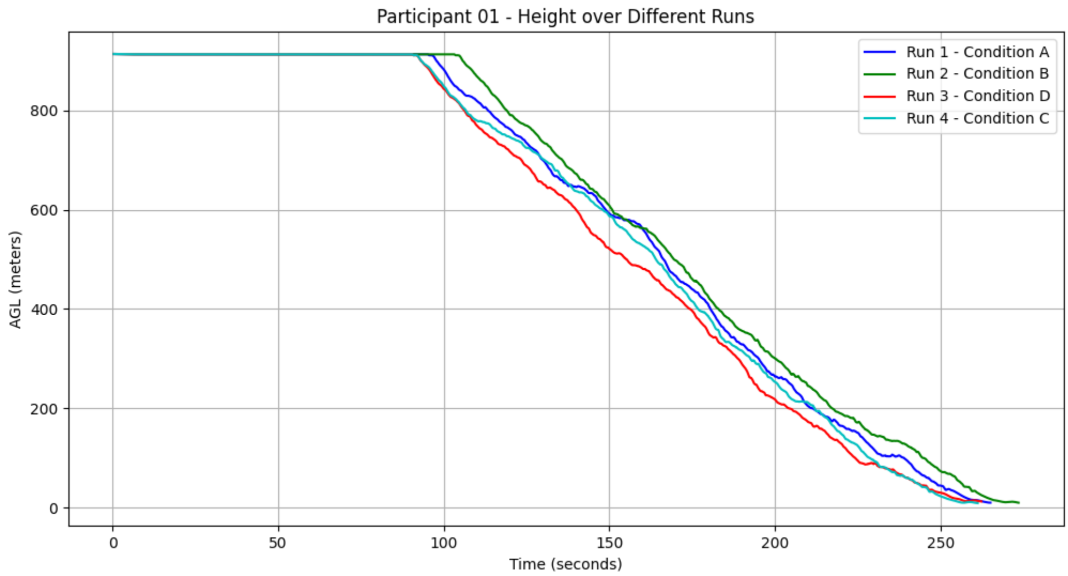
………

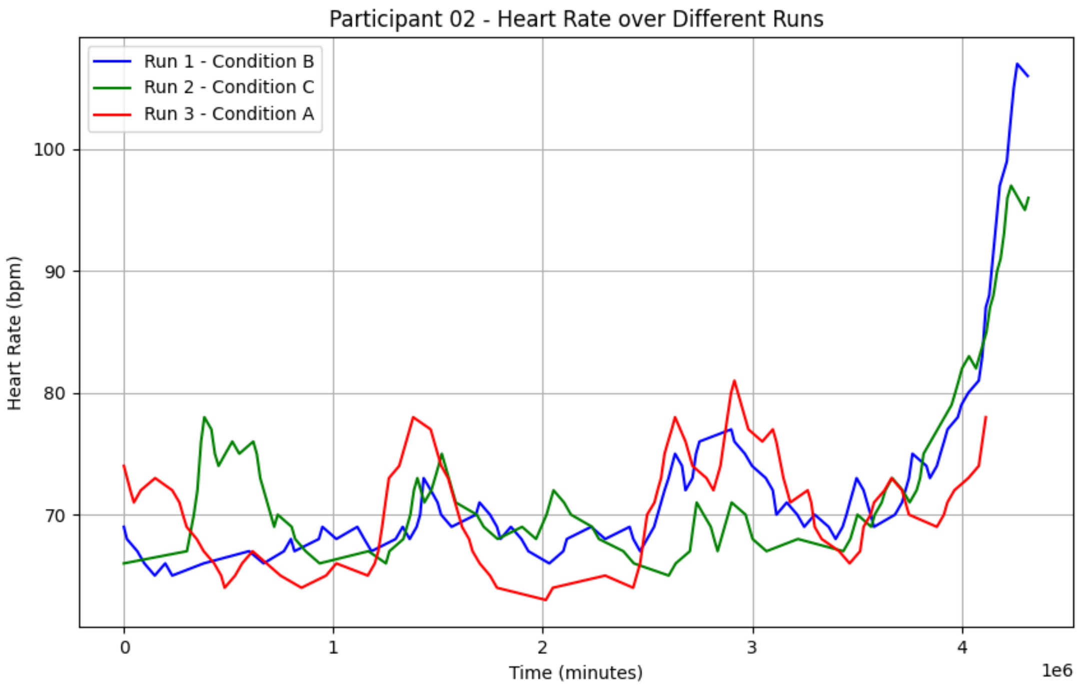
………

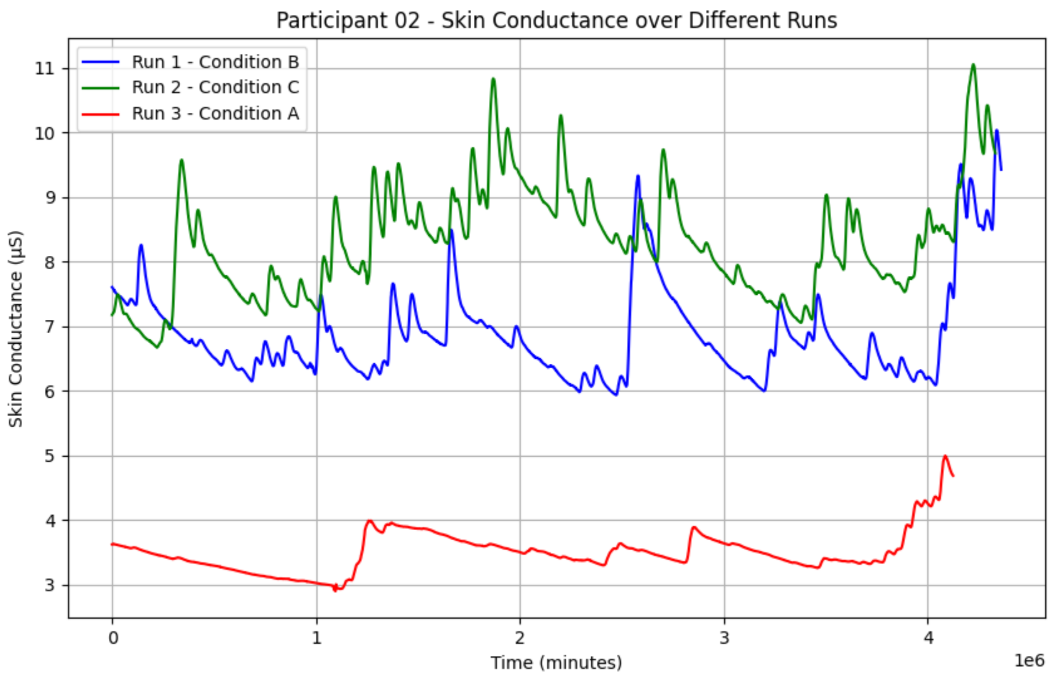
6.8. Appendix 8: Objective Data

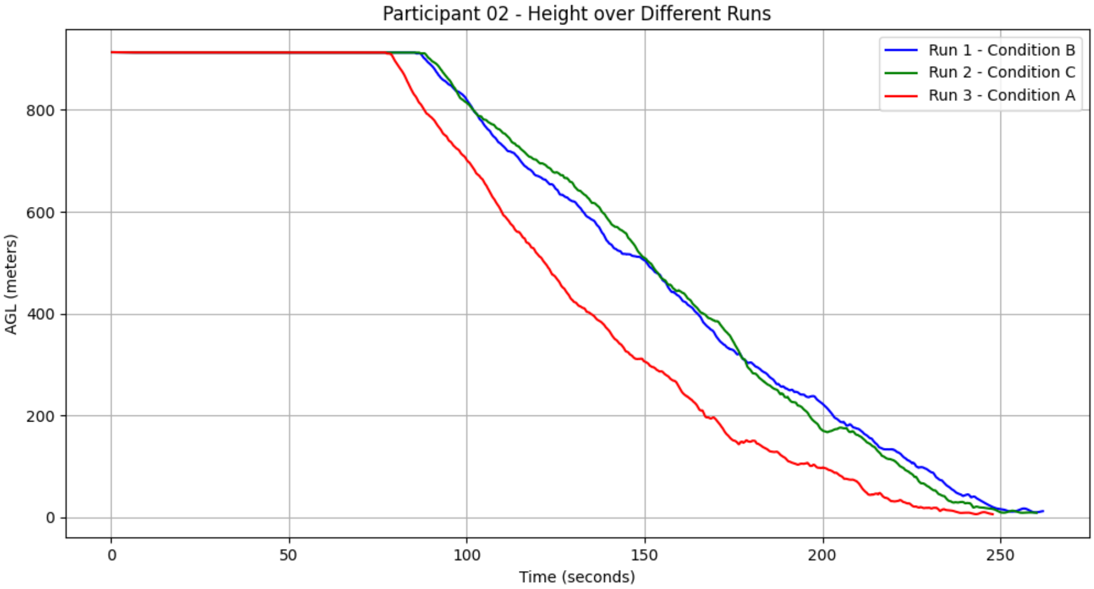


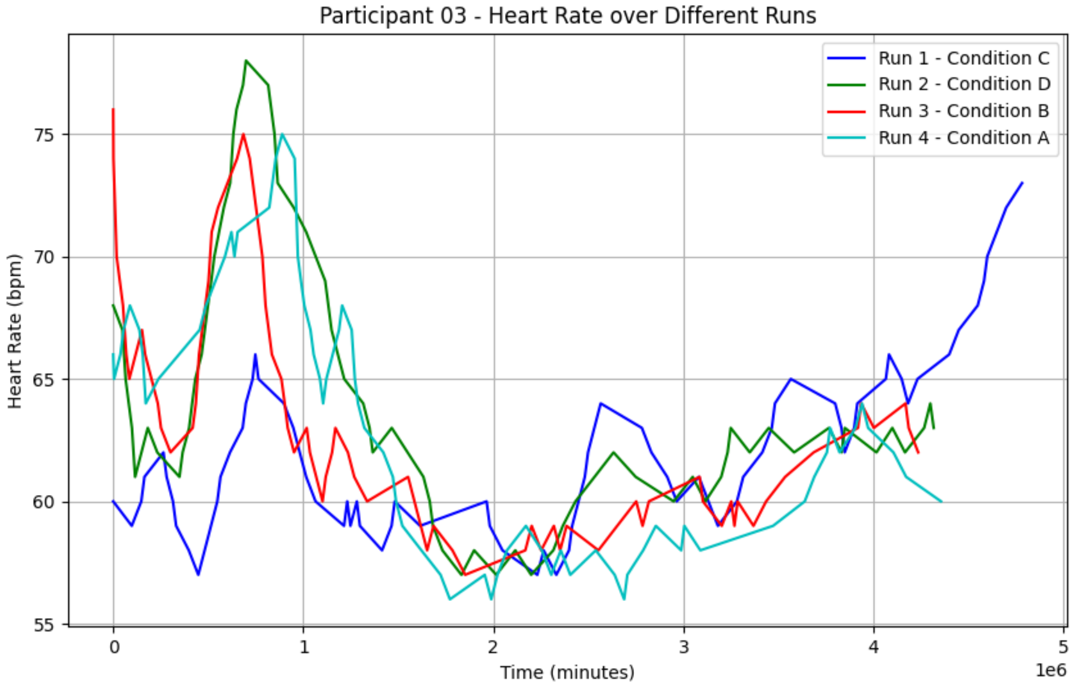


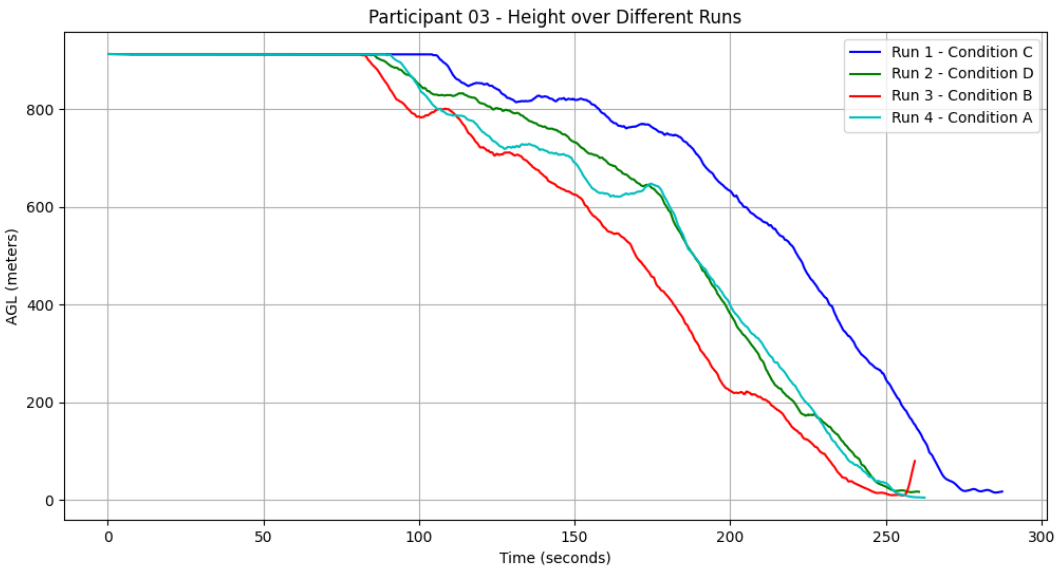

Participant 01 - Height over Different Runs
AGL (meters)
Time (seconds)
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
0
200
400
600
800
0
50
100
150
200
250

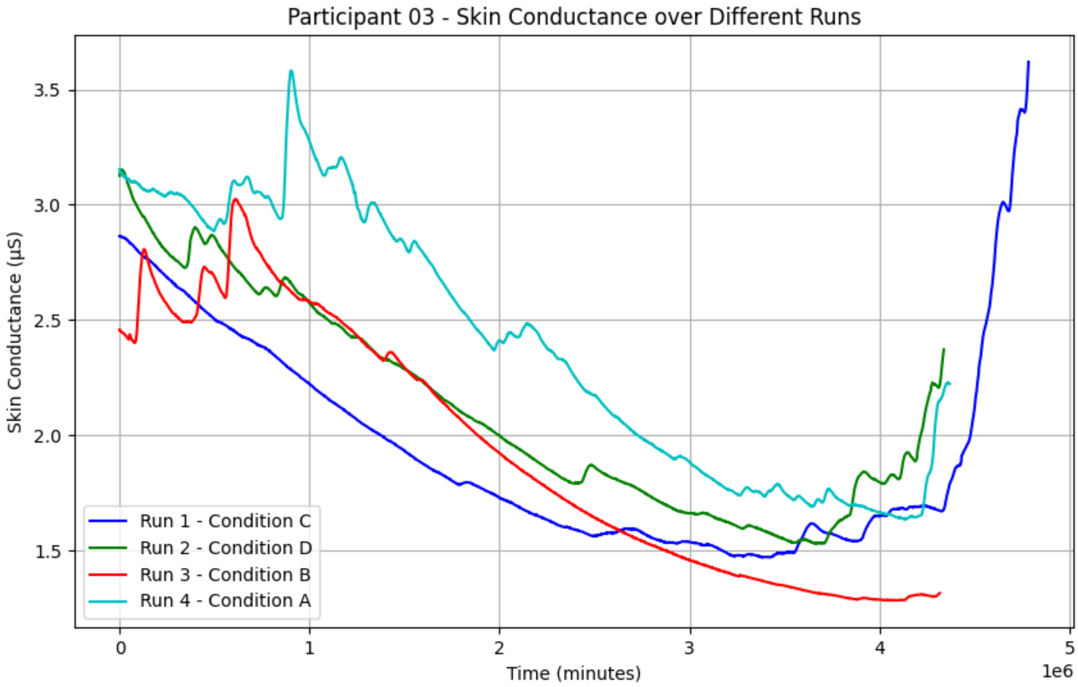

Participant 02 - Heart Rate over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Heart Rate (bpm)
100
90
80
70
0
1
2
3
4
Time (minutes)
1e6

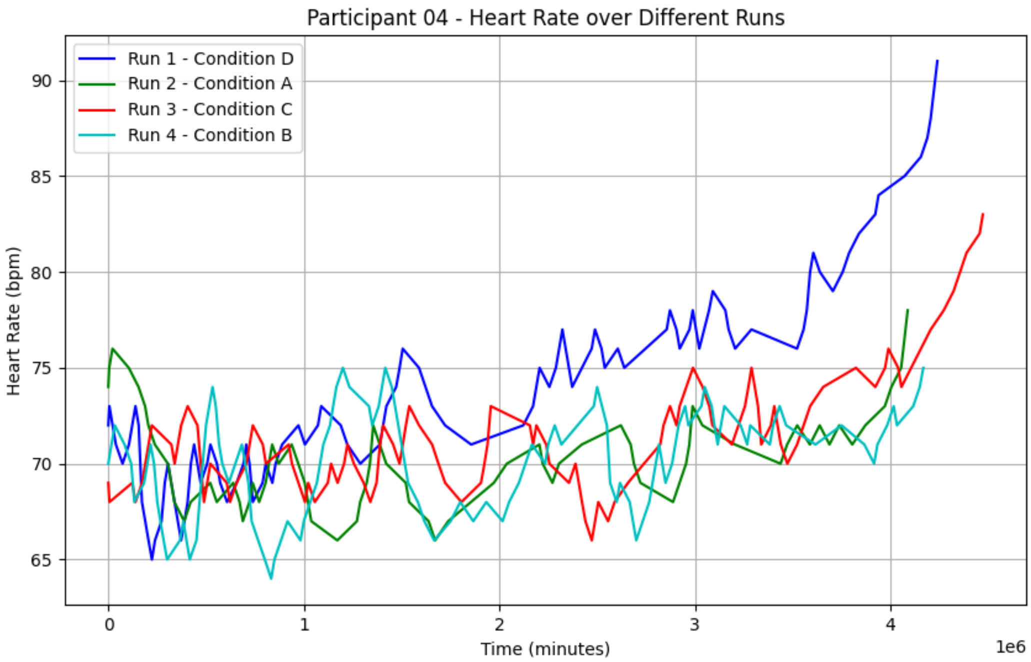

Participant 02 - Skin Conductance over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Skin Conductance (µS)
11
10
9
8
7
6
5
4
3
0
1
2
3
4
Time (minutes)
1e6


Participant 02 - Height over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
AGL (meters)
0
200
400
600
800
0
50
100
150
200
250
Time (seconds)

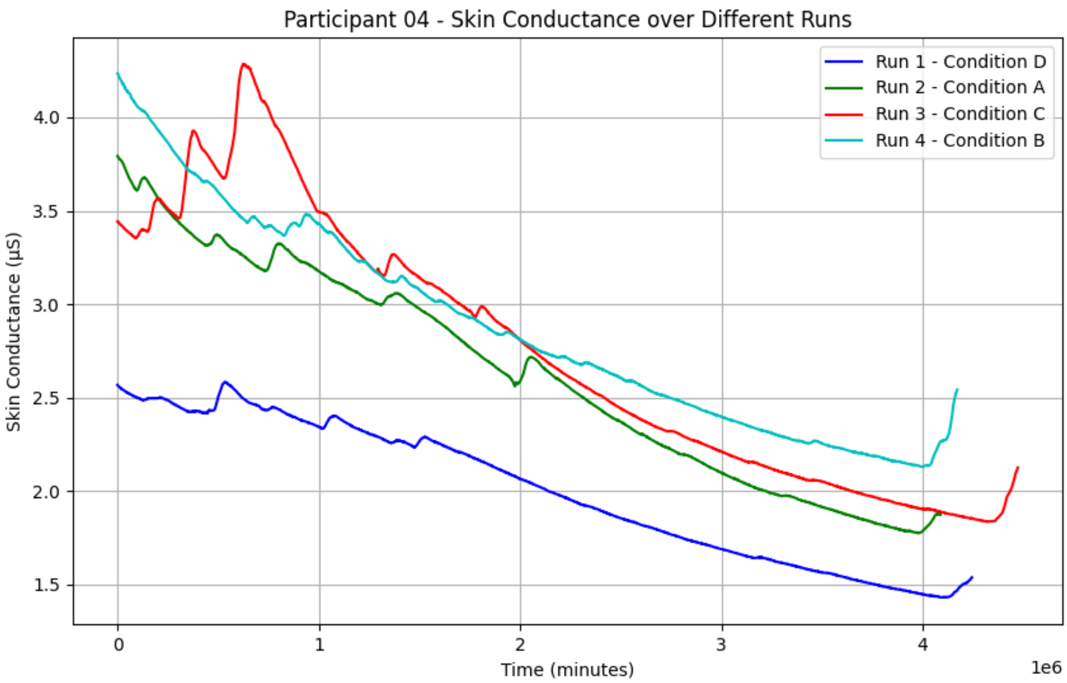

Participant 03 - Heart Rate over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Heart Rate (bpm)
75
70
65
60
55
0
1
2
3
4
5
Time (minutes)
1e6


Participant 03 - Height over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
AGL (meters)
800
600
400
200
0
0
50
100
150
200
250
300
Time (seconds)

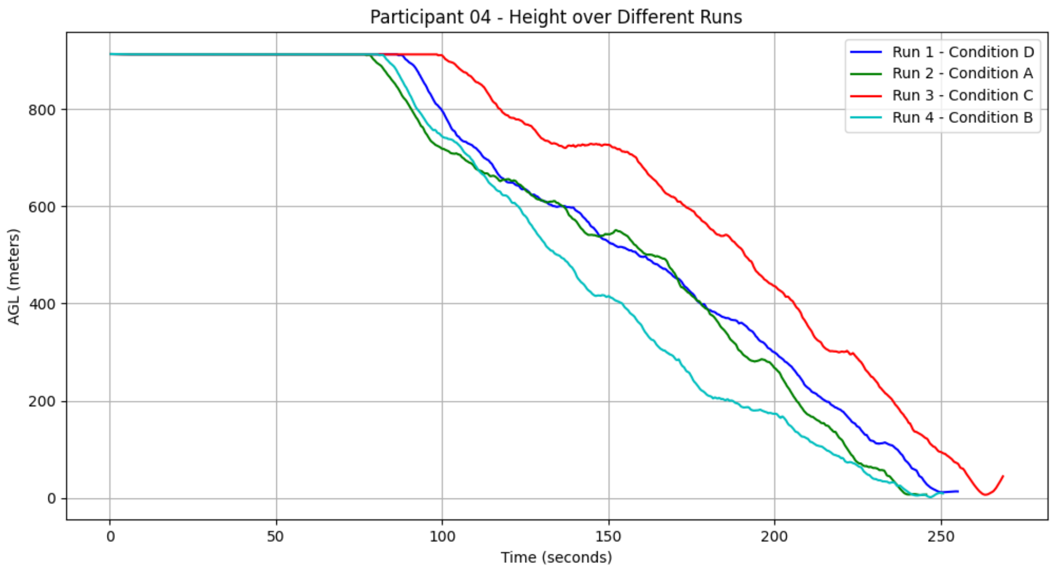

Participant 03 - Skin Conductance over Different Runs
Skin Conductance (μS)
3.5
3.0
2.5
2.0
1.5
Time (minutes)
0
1
2
3
4
5
1e6
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A

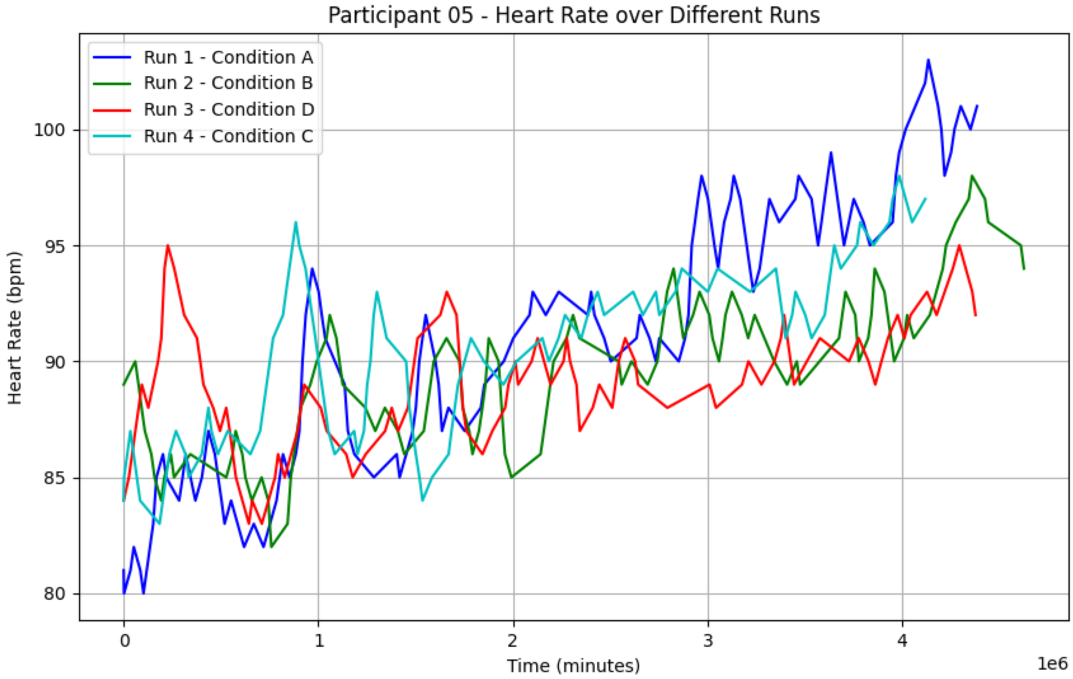


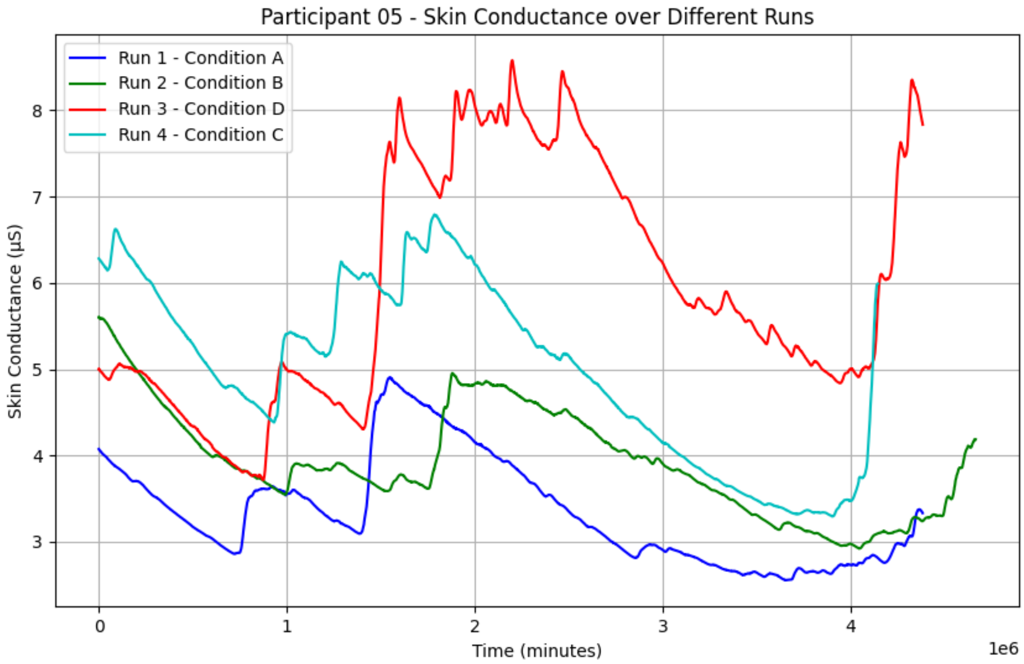
Participant 04 - Heart Rate over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Heart Rate (bpm)
90
85
80
75
70
65
0
1
2
3
4
Time (minutes)
1e6

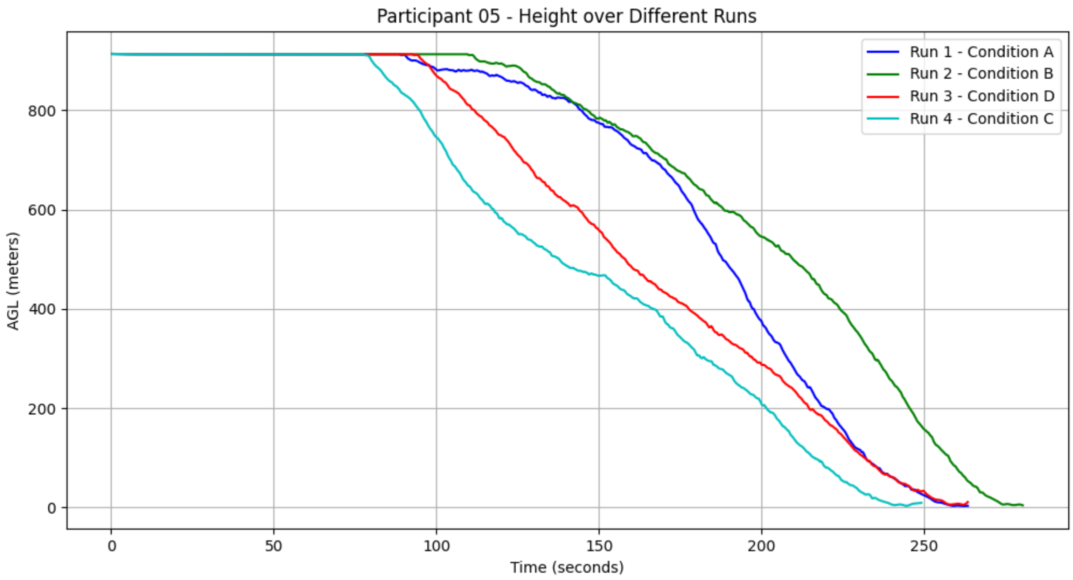


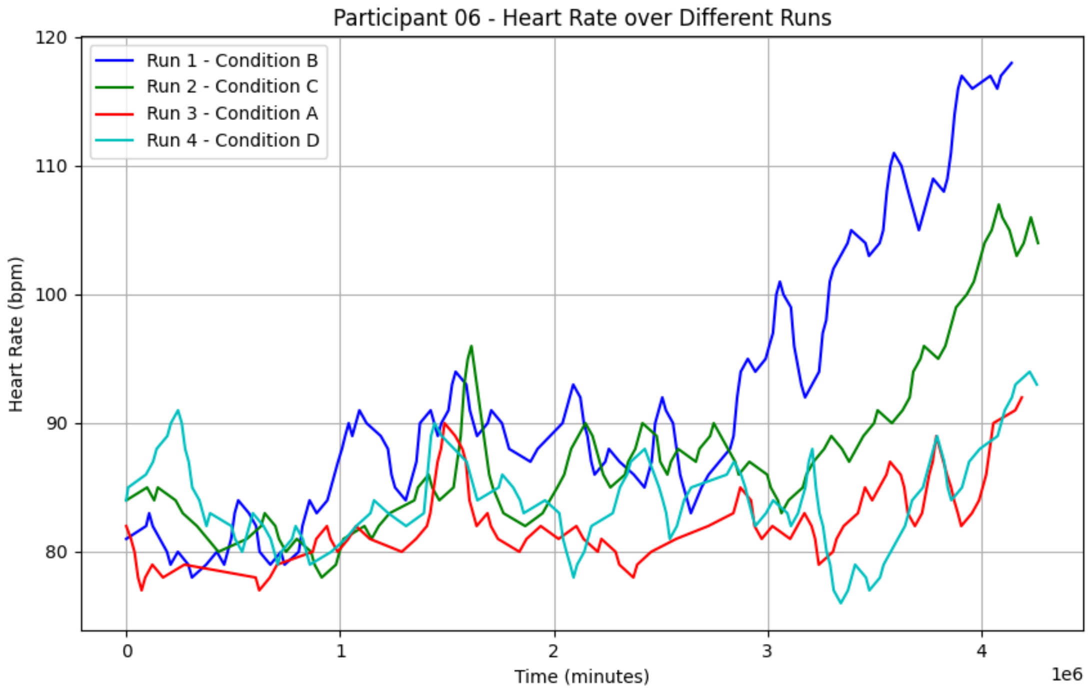
Participant 04 - Skin Conductance over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Skin Conductance (μS)
4.0
3.5
3.0
2.5
2.0
1.5
0
1
2
3
4
Time (minutes)
1e6

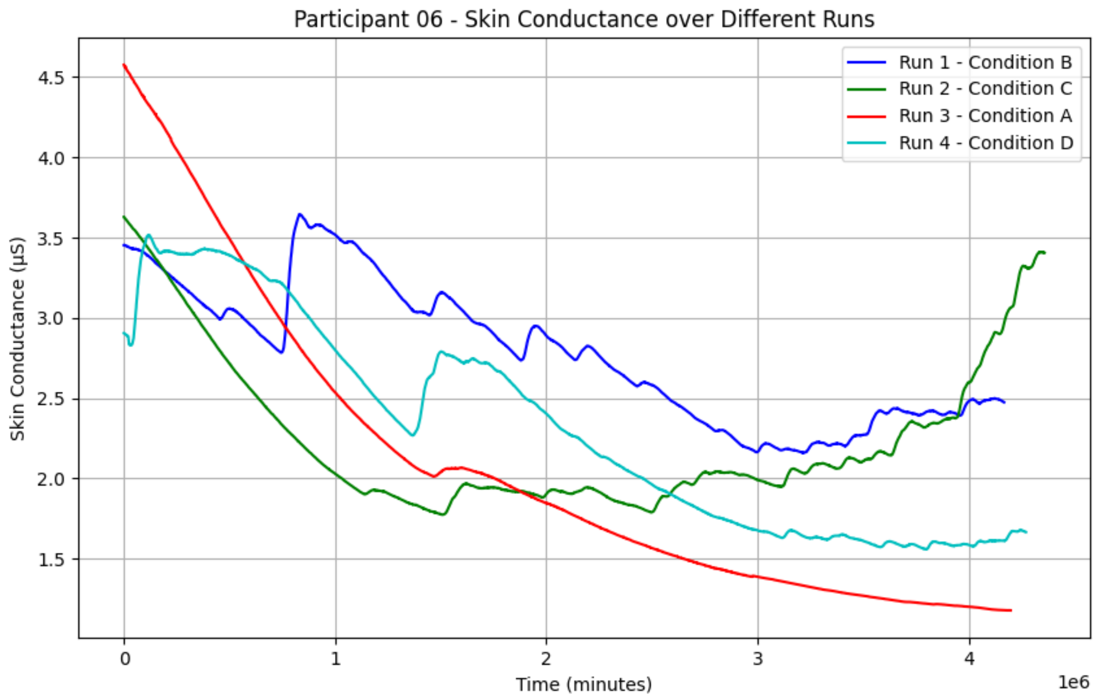

Participant 04 - Height over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
AGL (meters)
Time (seconds)
0
200
400
600
800
0
50
100
150
200
250

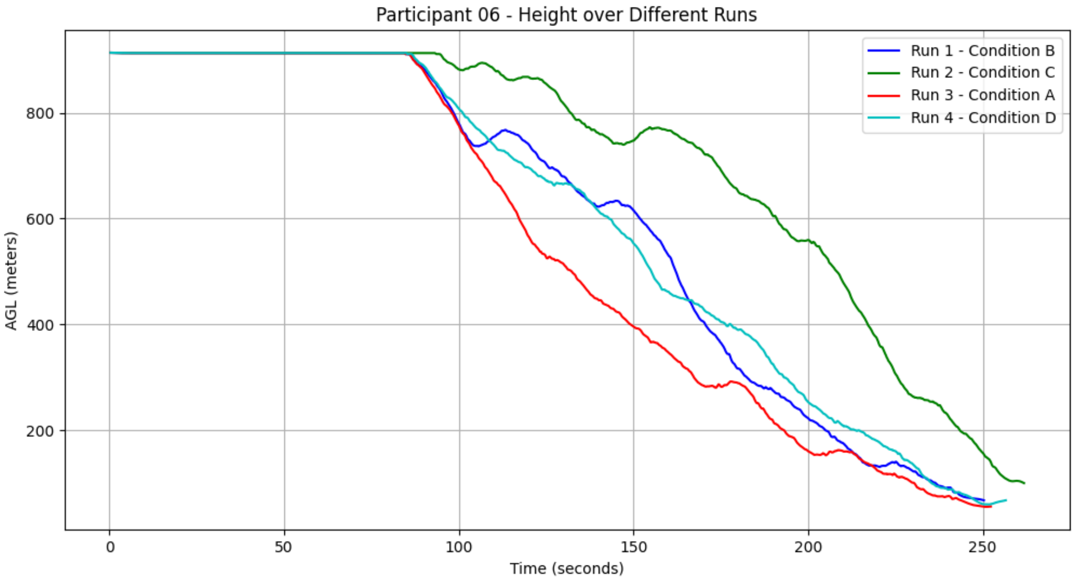

Participant 05 - Heart Rate over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
Heart Rate (bpm)
100
95
90
85
80
0
1
2
3
4
Time (minutes)
1e6

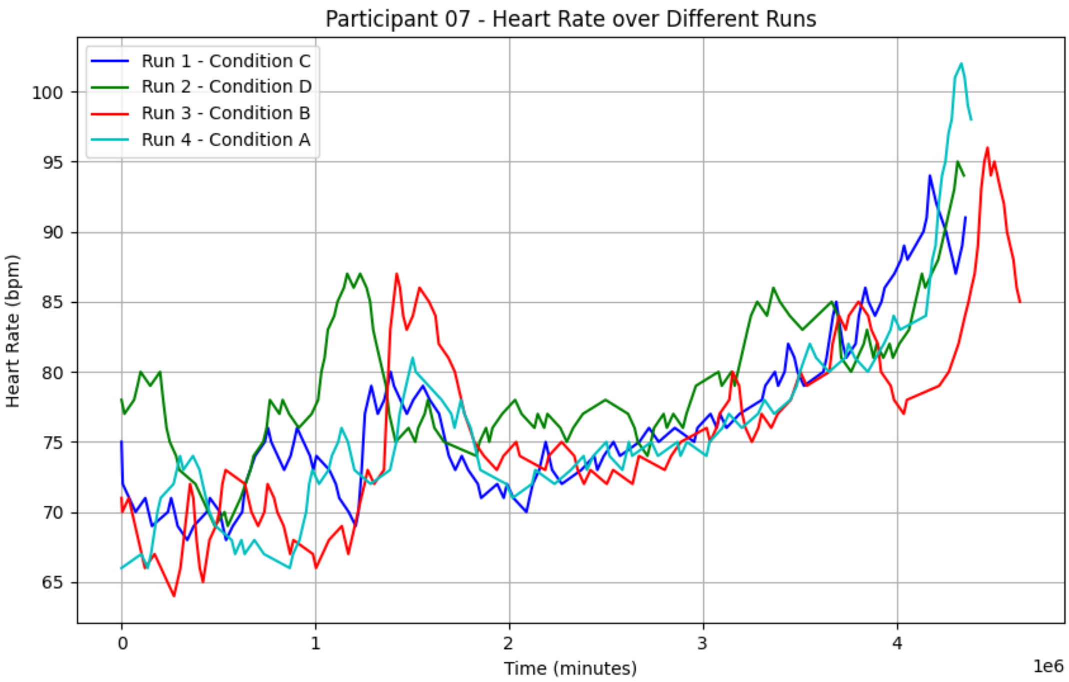

Participant 05 - Skin Conductance over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
Skin Conductance (µS)
8
7
6
5
4
3
0
1
2
3
4
Time (minutes)
1e6

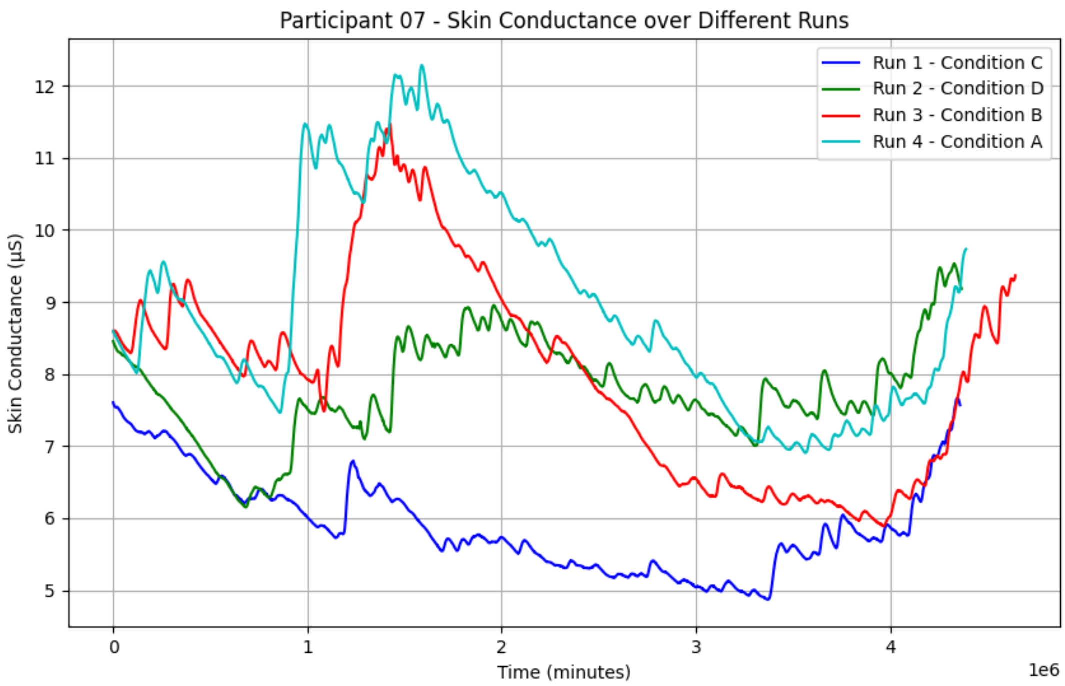

Participant 05 - Height over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
AGL (meters)
800
600
400
200
0
0
50
100
150
200
250
Time (seconds)

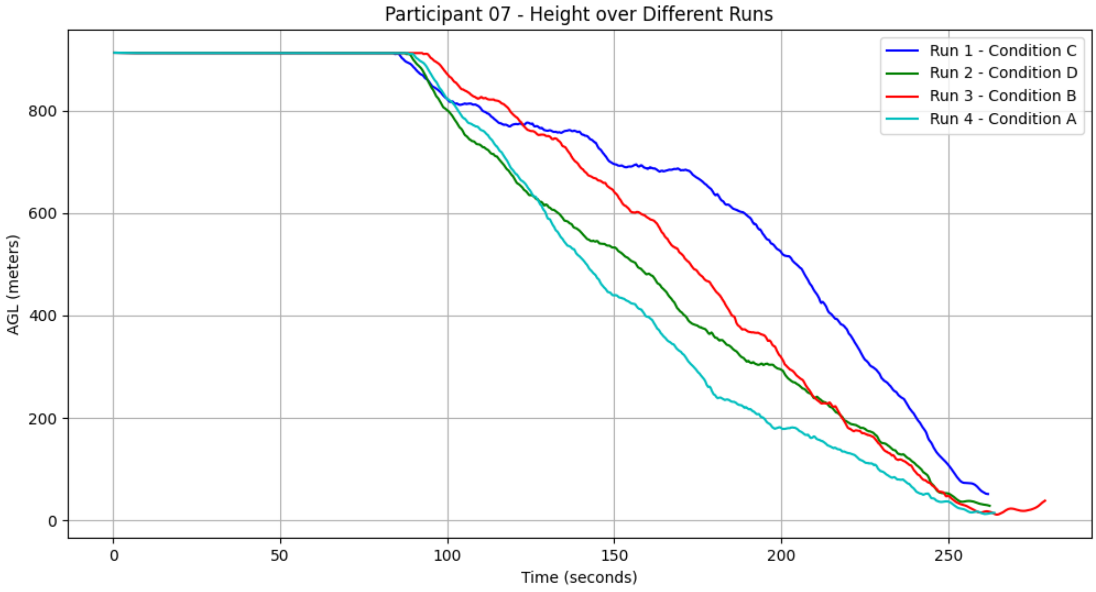

Participant 06 - Heart Rate over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Heart Rate (bpm)
120
110
100
90
80
0
1
2
3
4
Time (minutes)
1e6


Participant 06 - Skin Conductance over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Skin Conductance (µS)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
0
1
2
3
4
Time (minutes)
1e6

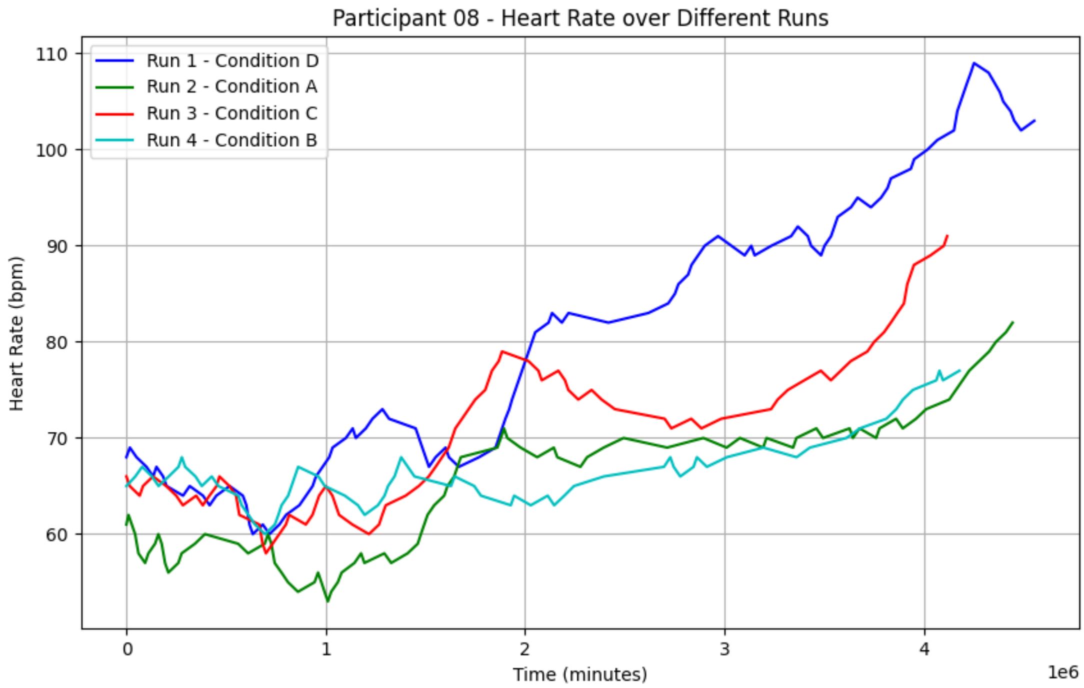

Participant 06 - Height over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
AGL (meters)
800
600
400
200
0
50
100
150
200
250
Time (seconds)

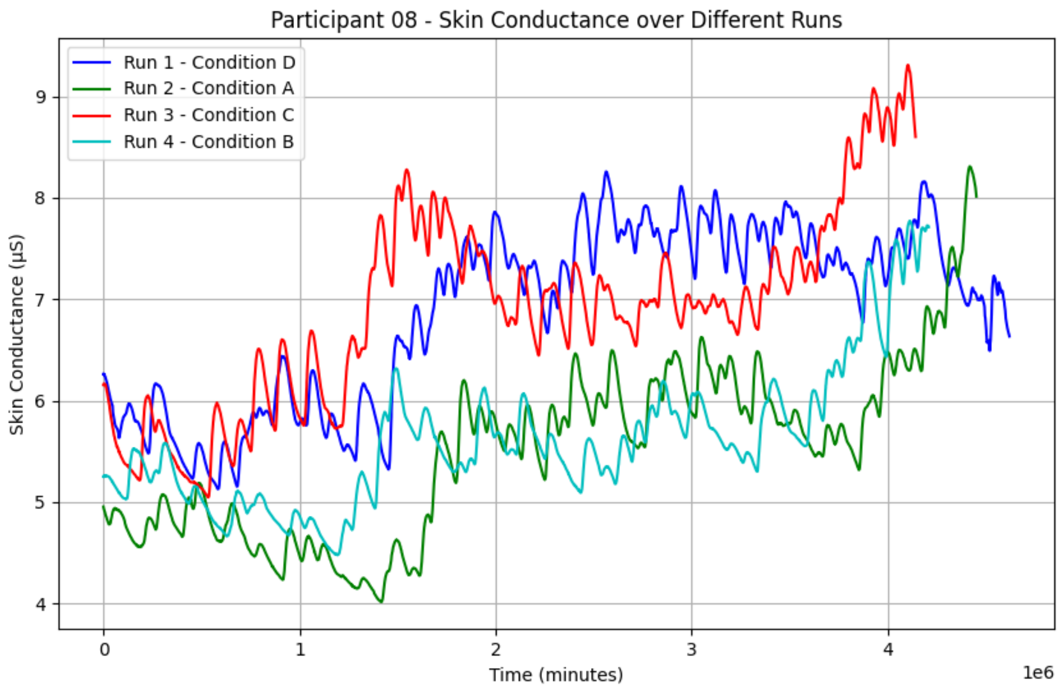

Participant 07 - Heart Rate over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Heart Rate (bpm)
100
95
90
85
80
75
70
65
0
1
2
3
4
Time (minutes)
1e6

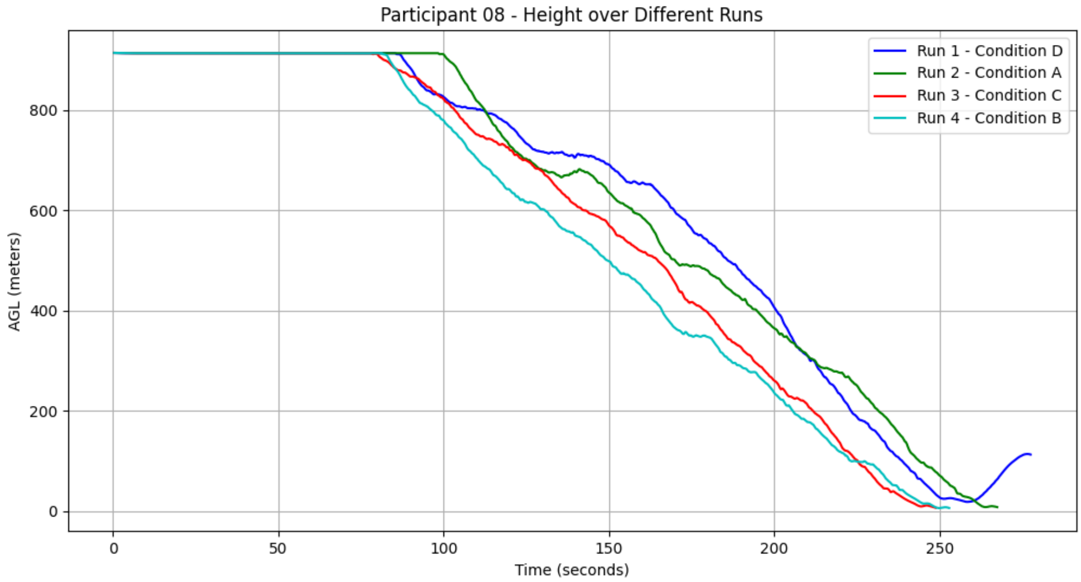

Participant 07 - Skin Conductance over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Skin Conductance (μS)
12
11
10
9
8
7
6
5
0
1
2
3
4
Time (minutes)
1e6

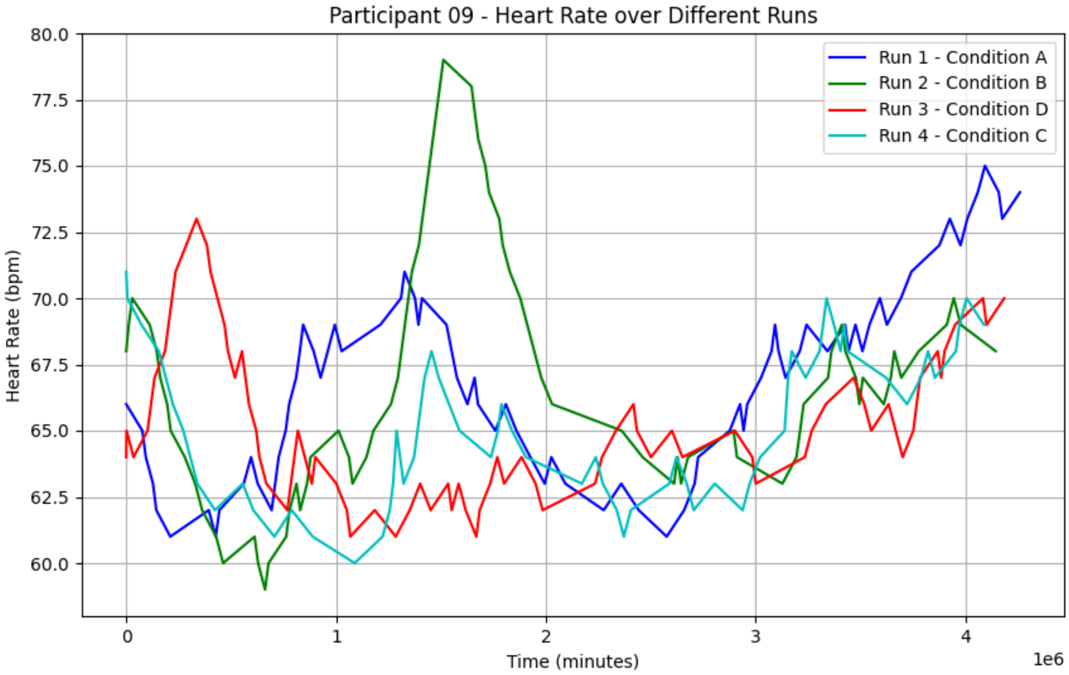


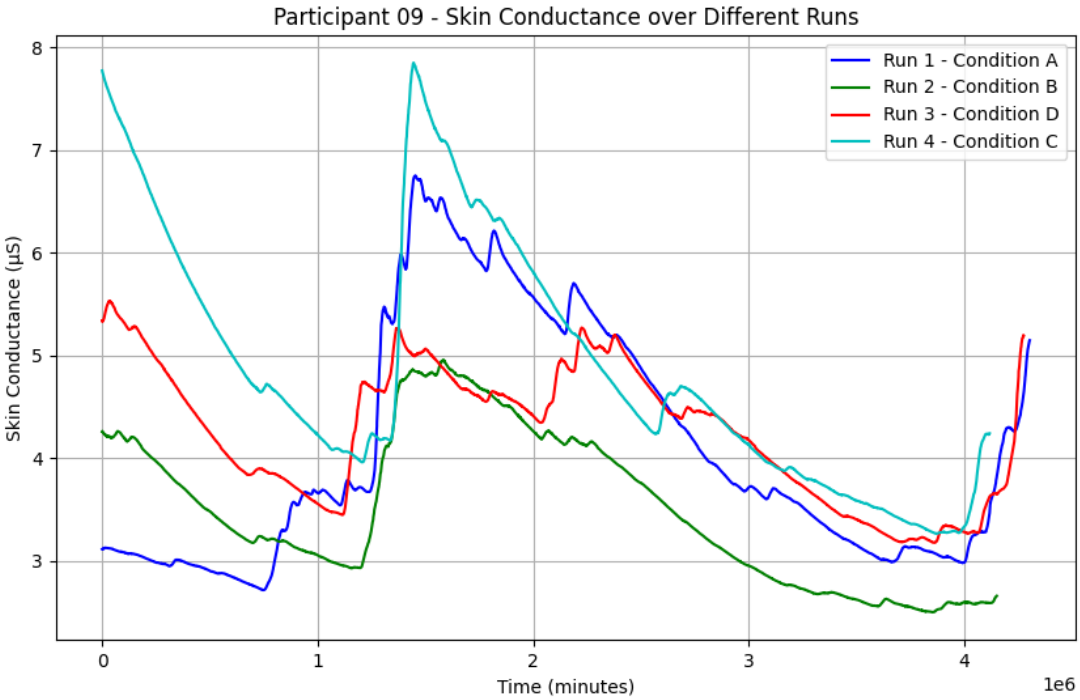
Participant 07 - Height over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
AGL (meters)
Time (seconds)
0
200
400
600
800
0
50
100
150
200
250

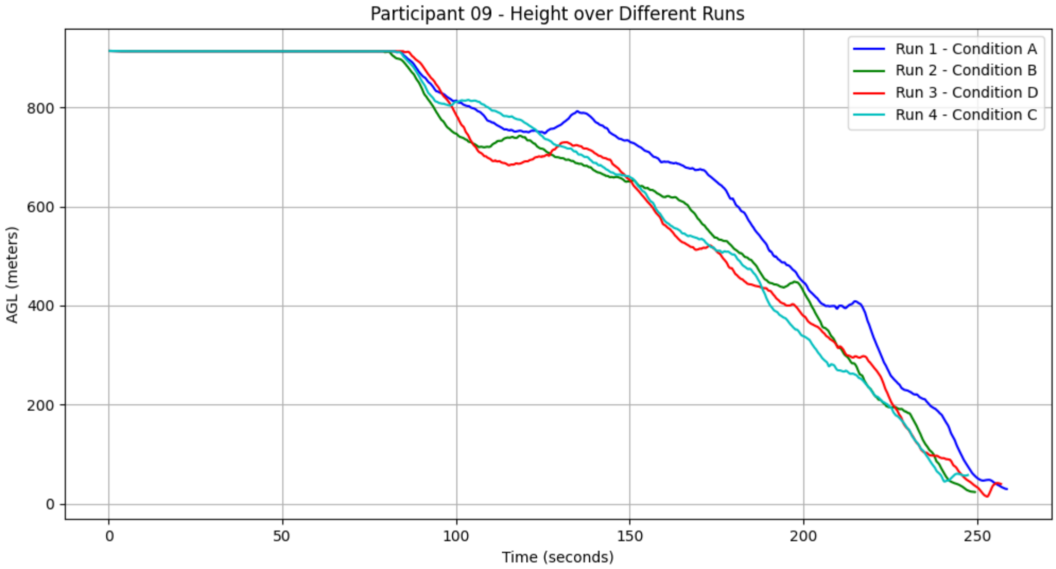

Participant 08 - Heart Rate over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Heart Rate (bpm)
110
100
90
80
70
60
0
1
2
3
4
Time (minutes)
1e6

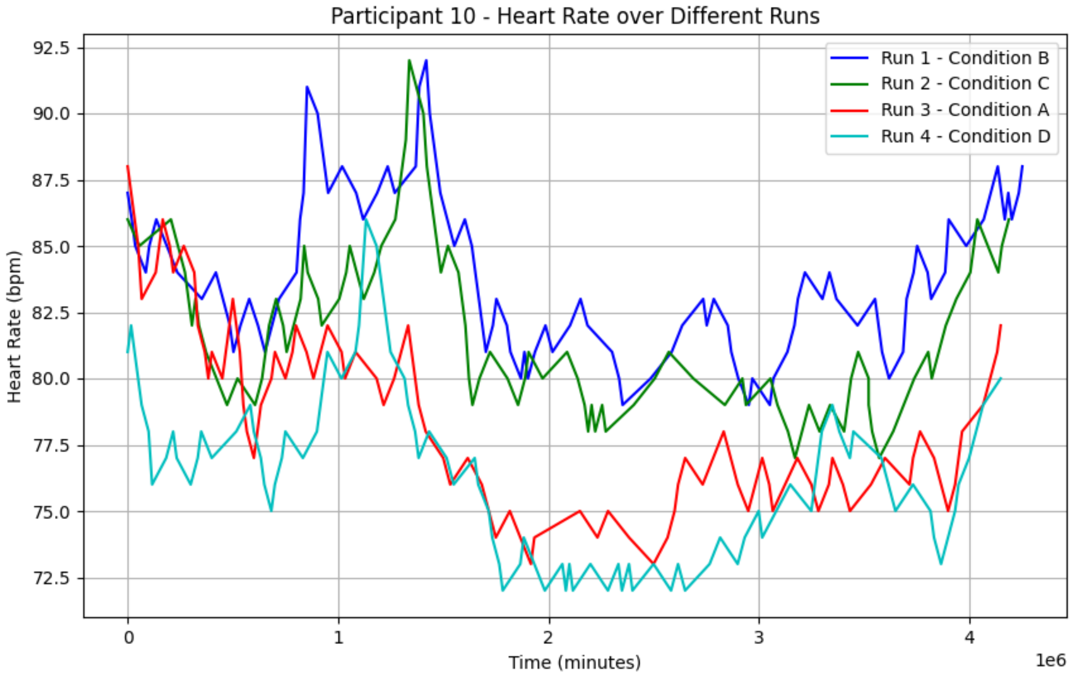

Participant 08 - Skin Conductance over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Skin Conductance (µS)
9
8
7
6
5
4
0
1
2
3
4
Time (minutes)
1e6

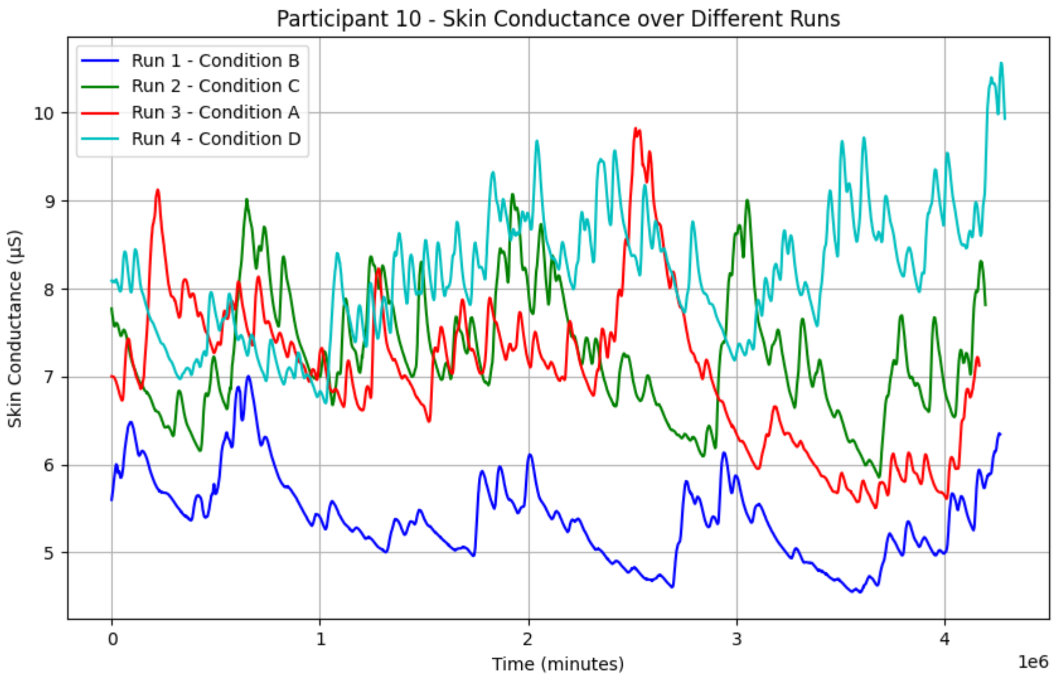

Participant 08 - Height over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
AGL (meters)
0
200
400
600
800
Time (seconds)
0
50
100
150
200
250

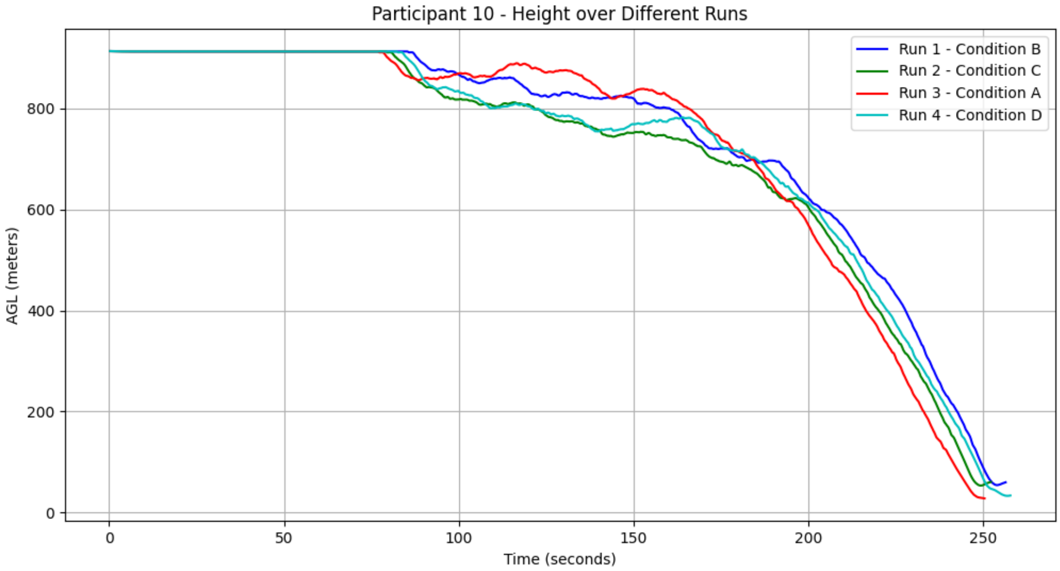

Participant 09 - Heart Rate over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
80.0
77.5
75.0
72.5
70.0
67.5
65.0
62.5
60.0
Heart Rate (bpm)
0
1
2
3
4
1e6
Time (minutes)

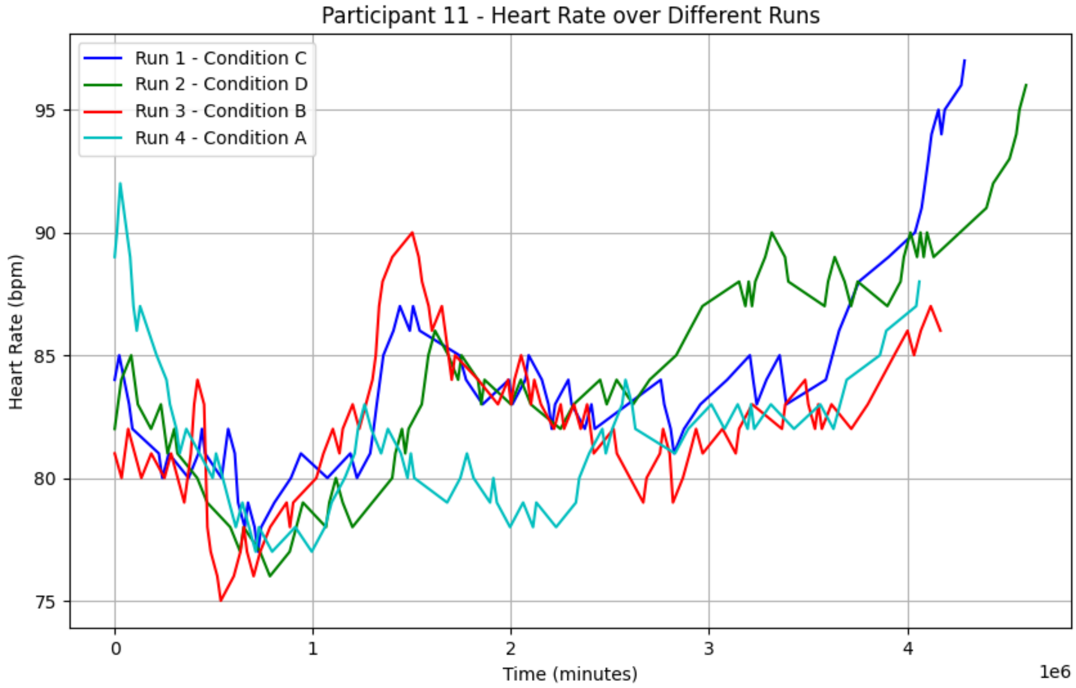

Participant 09 - Skin Conductance over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
8
7
6
5
4
3
Skin Conductance (µS)
0
1
2
3
4
1e6
Time (minutes)

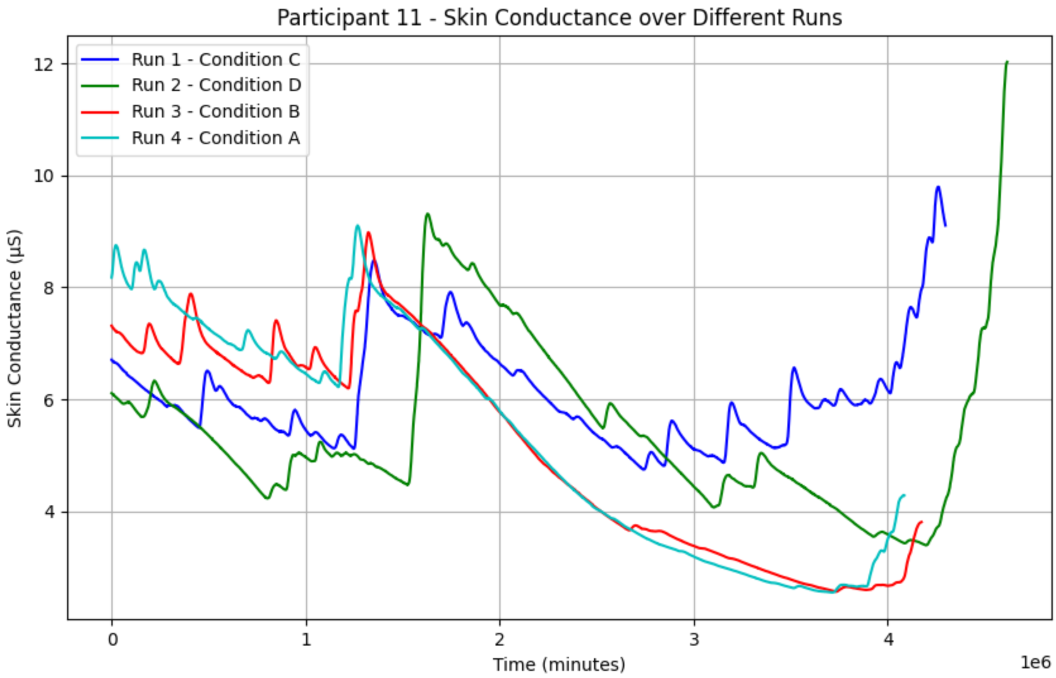

Participant 09 - Height over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
AGL (meters)
0
200
400
600
800
Time (seconds)
0
50
100
150
200
250

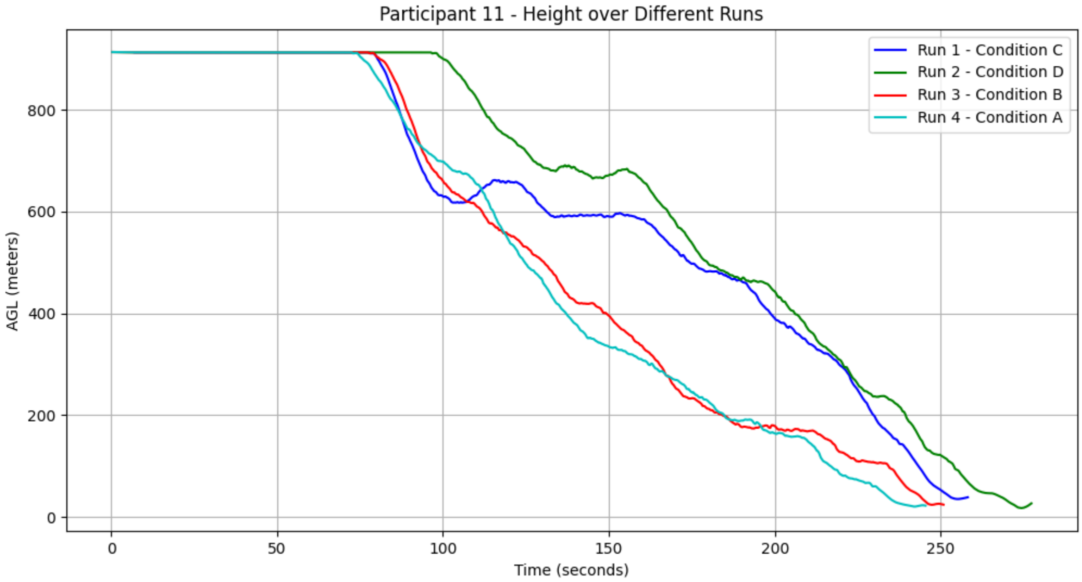

Participant 10 - Heart Rate over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Heart Rate (bpm)
92.5
90.0
87.5
85.0
82.5
80.0
77.5
75.0
72.5
0
1
2
3
4
Time (minutes)
1e6

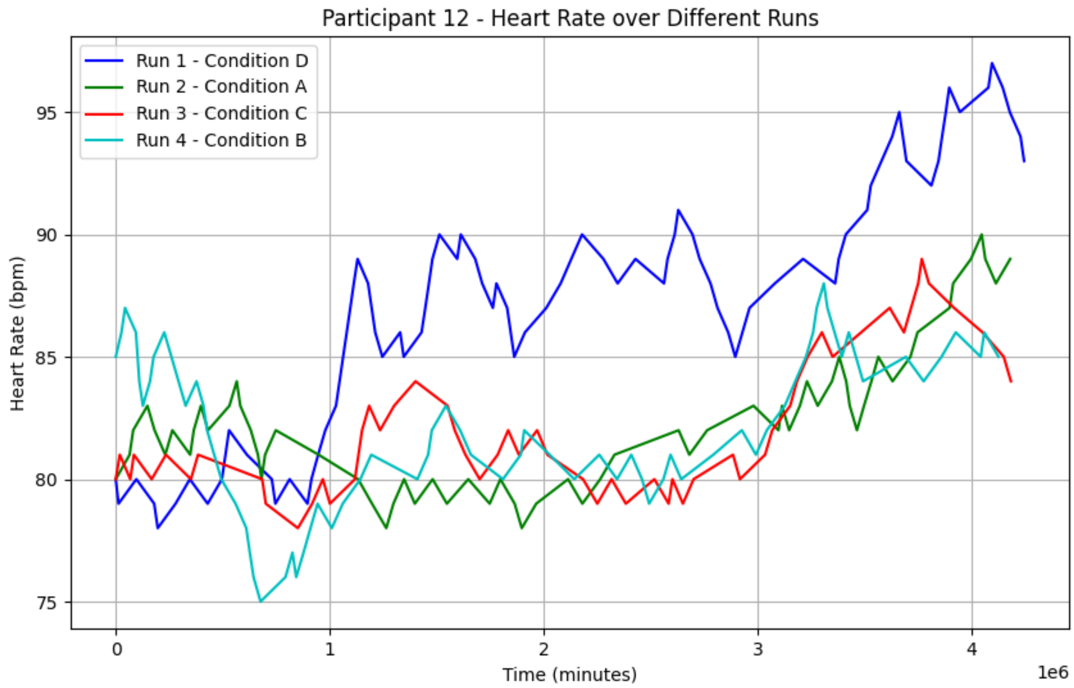

Participant 10 - Skin Conductance over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Skin Conductance (µS)
10
9
8
7
6
5
0
1
2
3
4
Time (minutes)
1e6

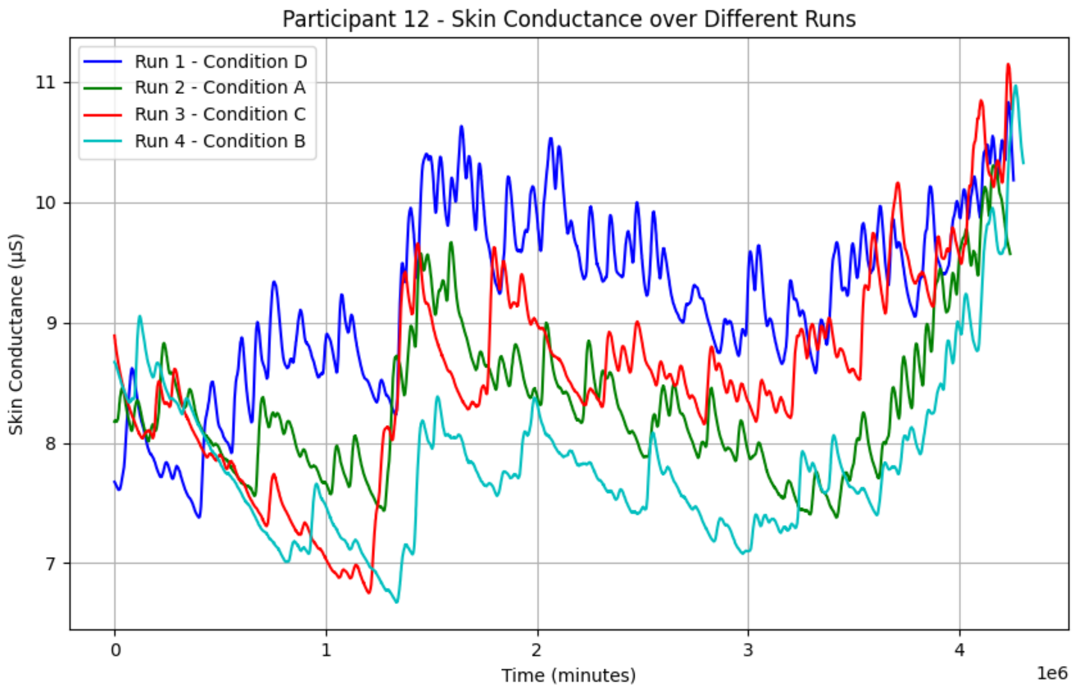

Participant 10 - Height over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
AGL (meters)
Time (seconds)
0
200
400
600
800
0
50
100
150
200
250

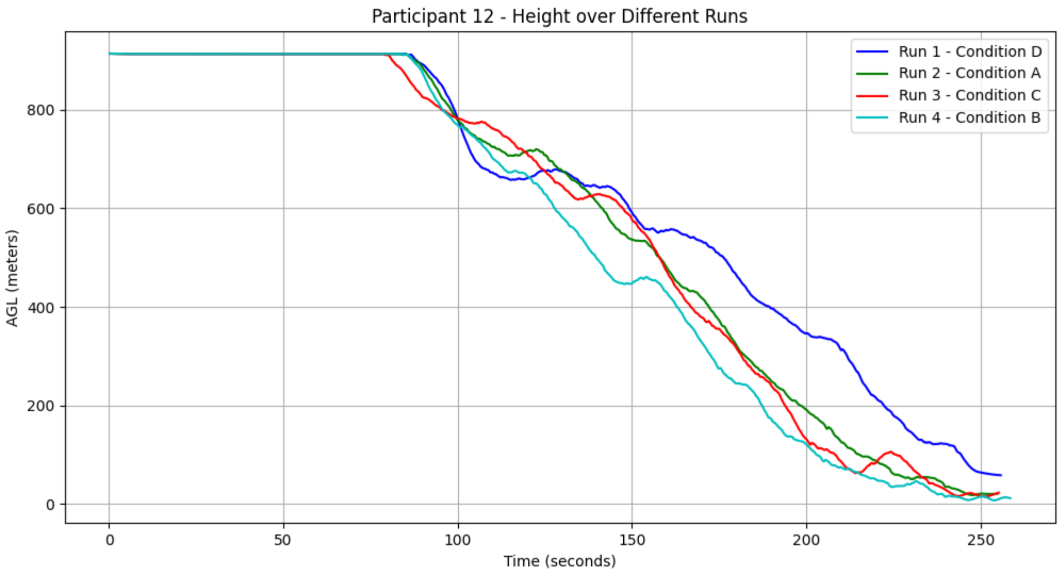

Participant 11 - Heart Rate over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Heart Rate (bpm)
75
80
85
90
95
0
1
2
3
4
Time (minutes)
1e6

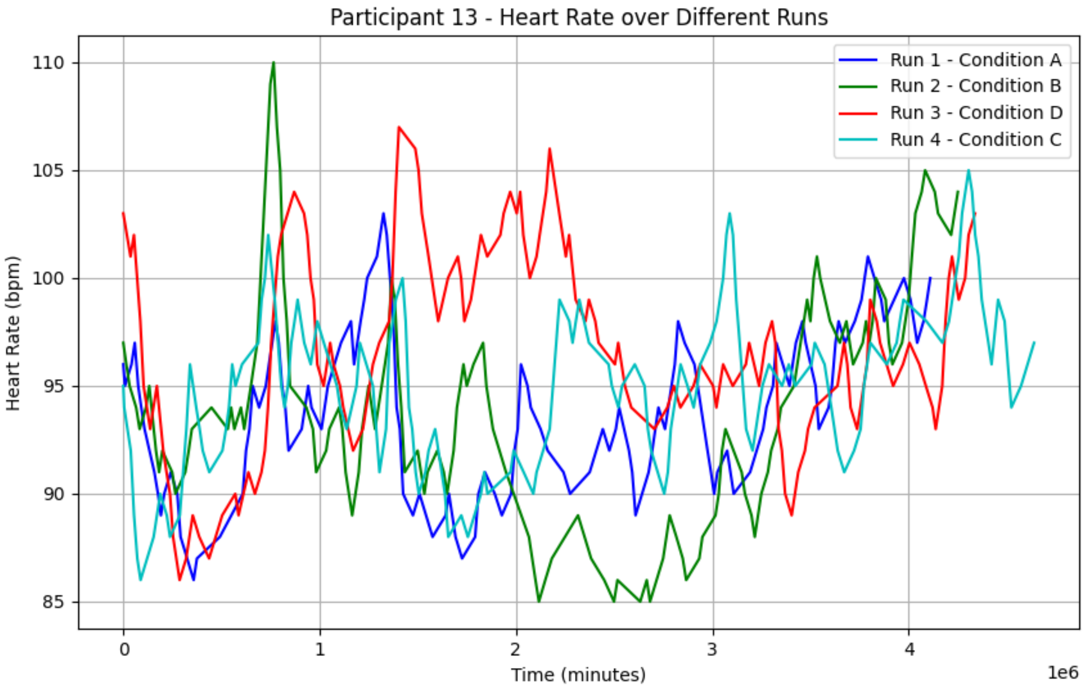

Participant 11 - Skin Conductance over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Skin Conductance (µS)
4
6
8
10
12
0
1
2
3
4
Time (minutes)
1e6

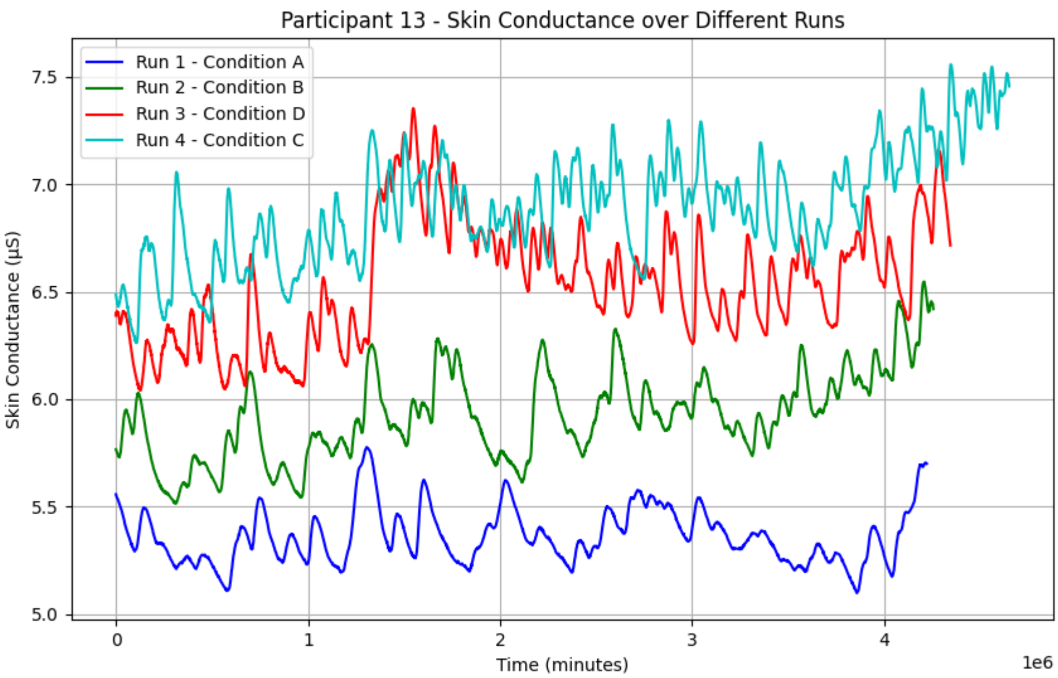

Participant 11 - Height over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
AGL (meters)
0
200
400
600
800
0
50
100
150
200
250
Time (seconds)

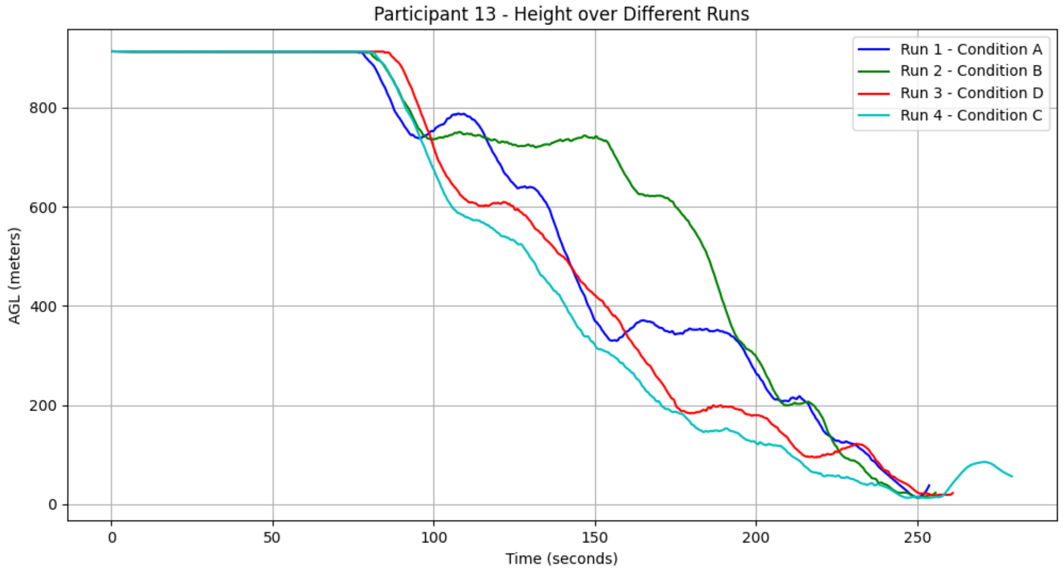

Participant 12 - Heart Rate over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Heart Rate (bpm)
95
90
85
80
75
0
1
2
3
4
Time (minutes)
1e6

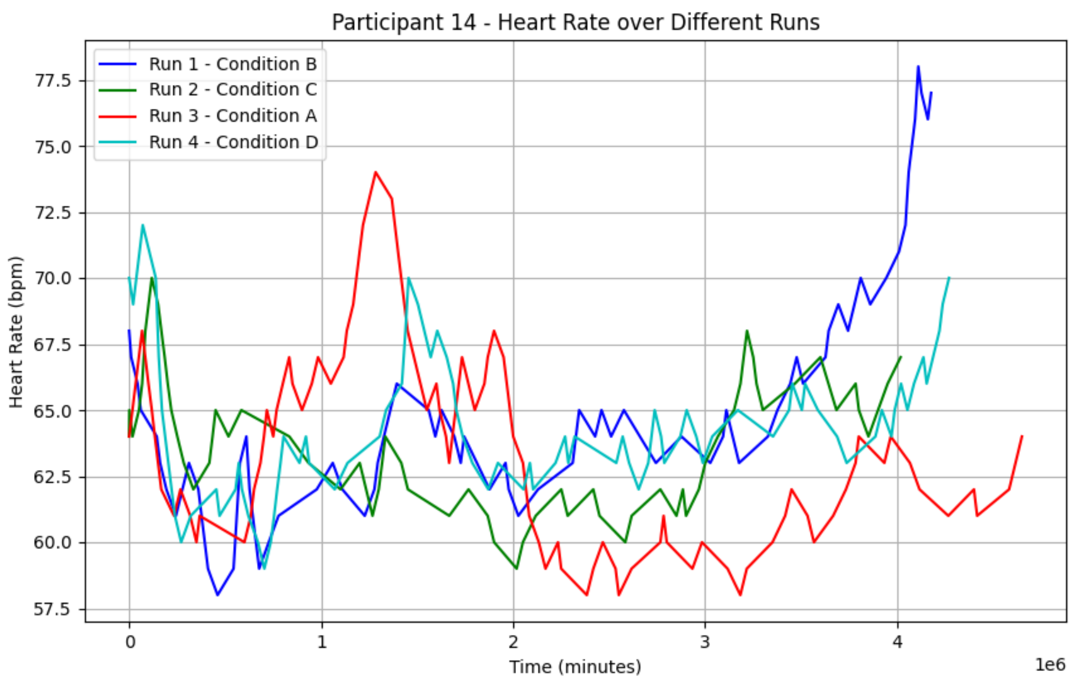

Participant 12 - Skin Conductance over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Skin Conductance (µS)
11
10
9
8
7
0
1
2
3
4
Time (minutes)
1e6

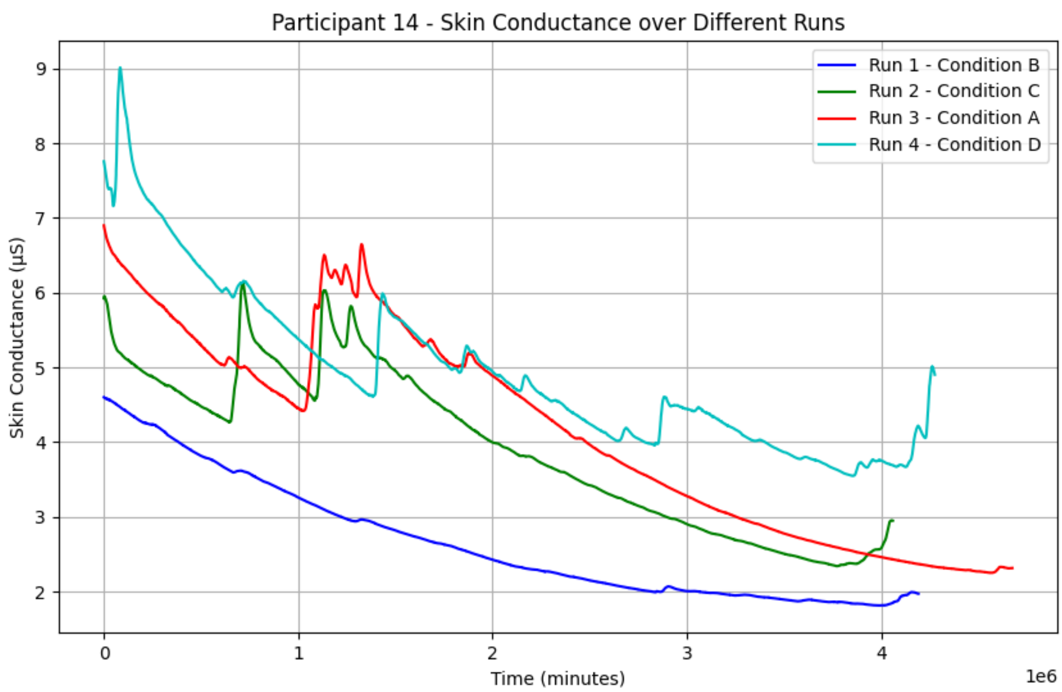

Participant 12 - Height over Different Runs
AGL (meters)
Time (seconds)
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
0
200
400
600
800
0
50
100
150
200
250

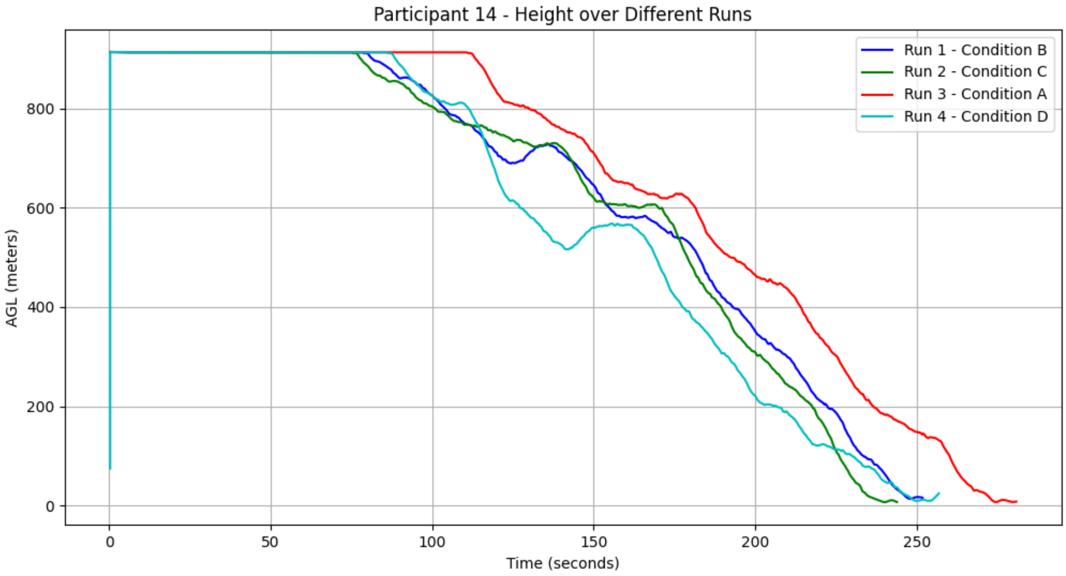

Participant 13 - Heart Rate over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
Heart Rate (bpm)
110
105
100
95
90
85
0
1
2
3
4
Time (minutes)
1e6

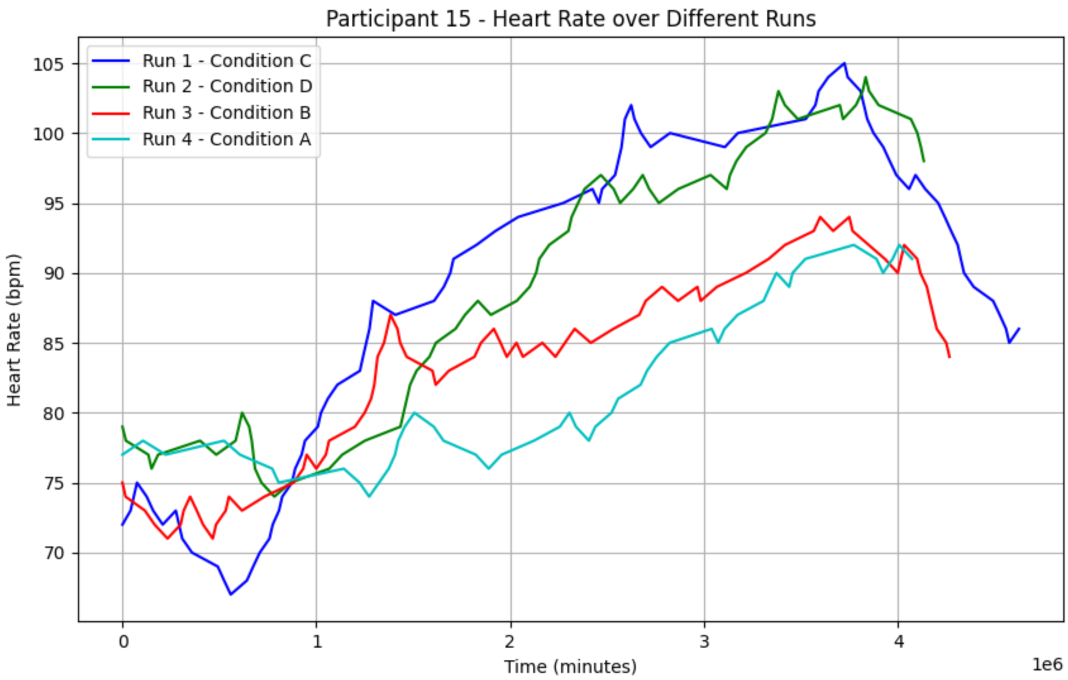

Participant 13 - Skin Conductance over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
Skin Conductance (µS)
7.5
7.0
6.5
6.0
5.5
5.0
0
1
2
3
4
Time (minutes)
1e6

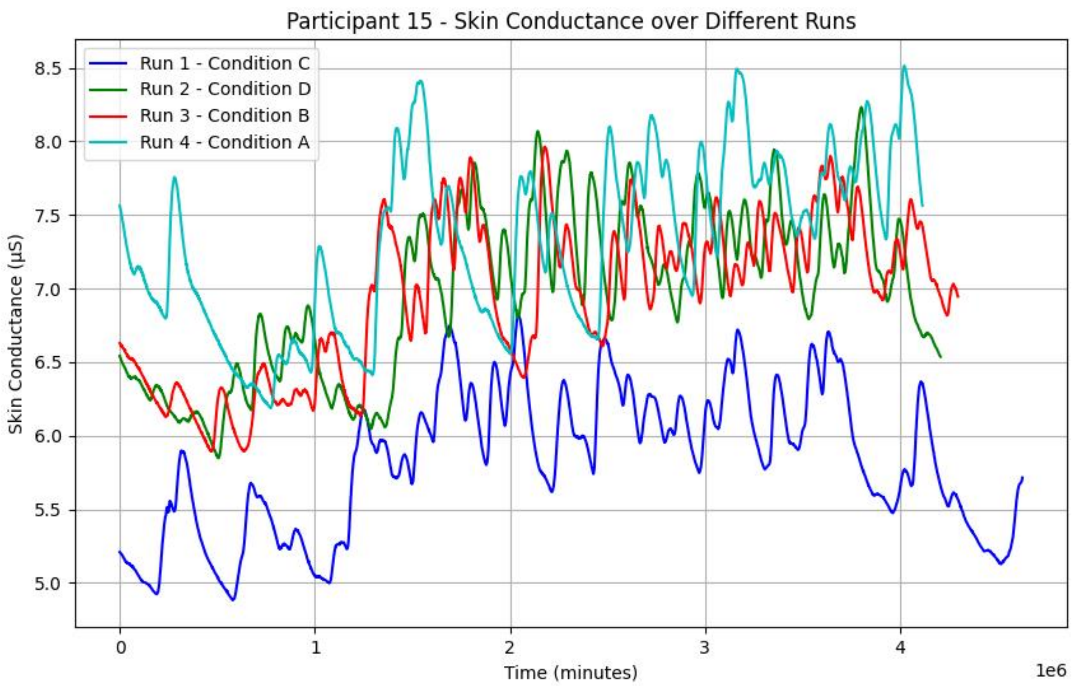

Participant 13 - Height over Different Runs
AGL (meters)
Time (seconds)
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
0
200
400
600
800
0
50
100
150
200
250

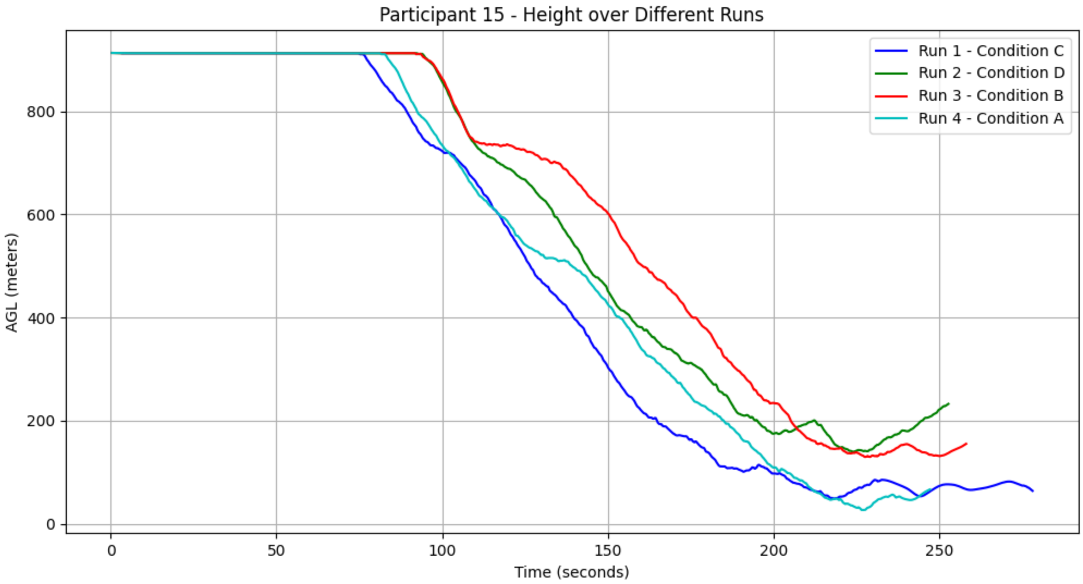

Participant 14 - Heart Rate over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Heart Rate (bpm)
77.5
75.0
72.5
70.0
67.5
65.0
62.5
60.0
57.5
0
1
2
3
4
Time (minutes)
1e6

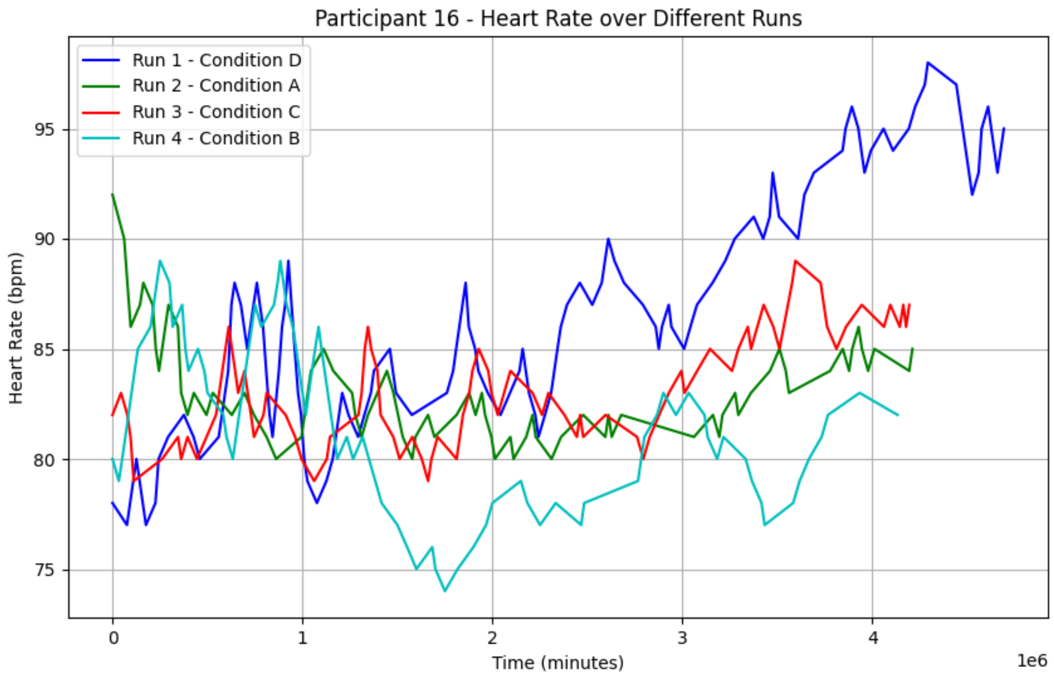

Participant 14 - Skin Conductance over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Skin Conductance (μS)
9
8
7
6
5
4
3
2
0
1
2
3
4
Time (minutes)
1e6

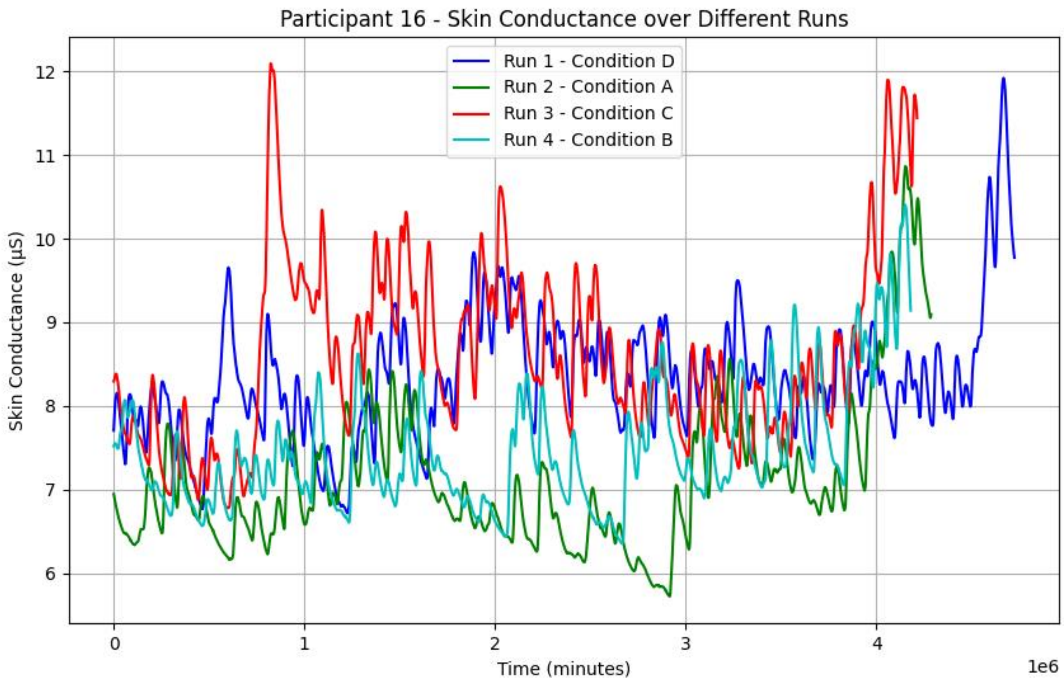

Participant 14 - Height over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
AGL (meters)
800
600
400
200
0
0
50
100
150
200
250
Time (seconds)

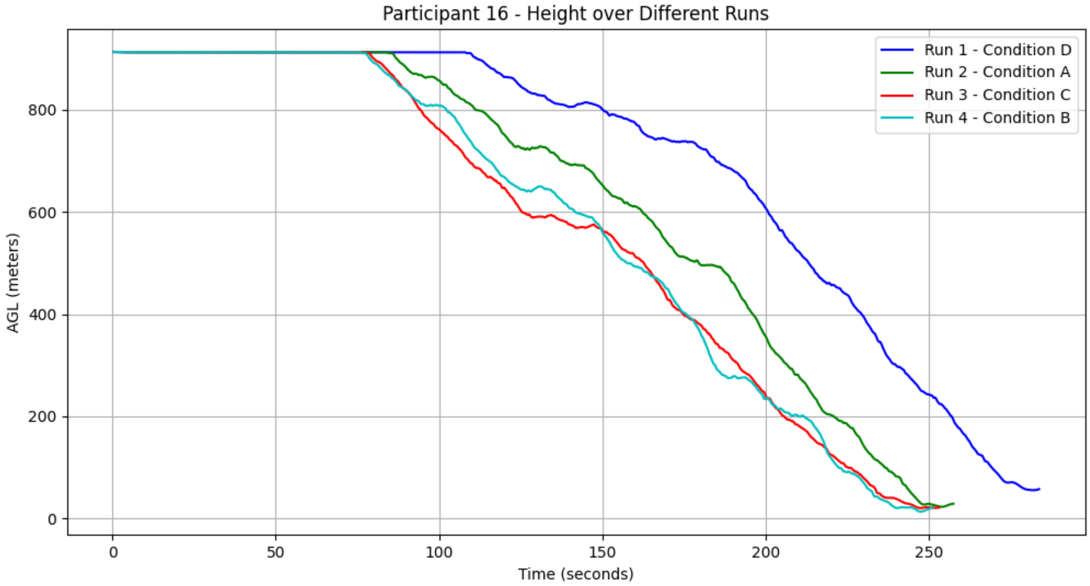

Participant 15 - Heart Rate over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Heart Rate (bpm)
105
100
95
90
85
80
75
70
0
1
2
3
4
Time (minutes)
1e6

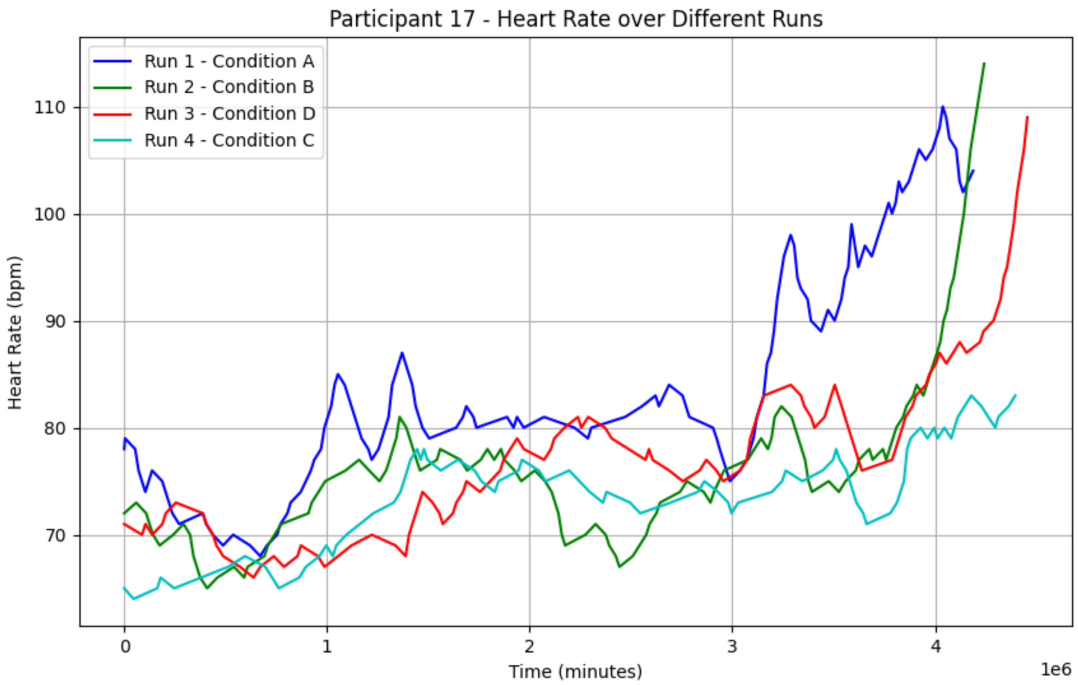

Participant 15 - Skin Conductance over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
Skin Conductance (µS)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
0
1
2
3
4
Time (minutes)
1e6

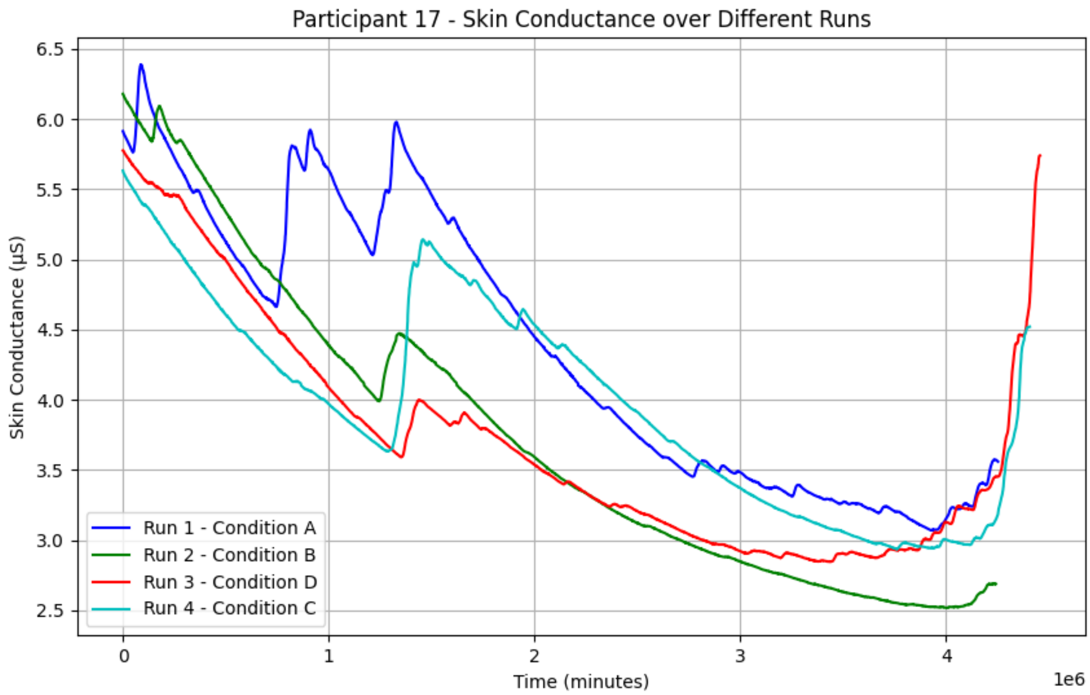

Participant 15 - Height over Different Runs
Run 1 - Condition C
Run 2 - Condition D
Run 3 - Condition B
Run 4 - Condition A
AGL (meters)
0
200
400
600
800
0
50
100
150
200
250
Time (seconds)

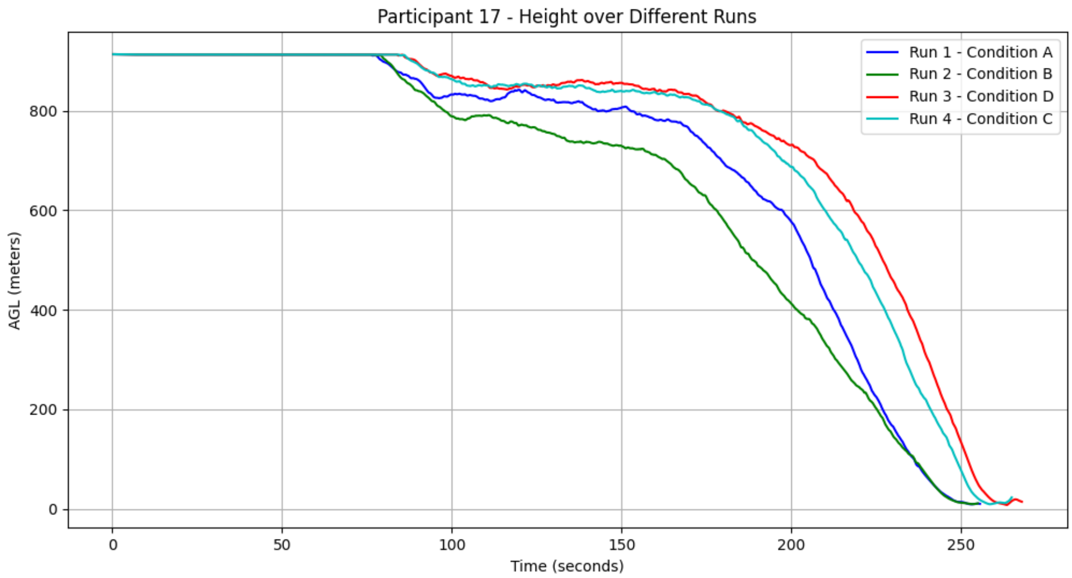

Participant 16 - Heart Rate over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Heart Rate (bpm)
Time (minutes)
1e6

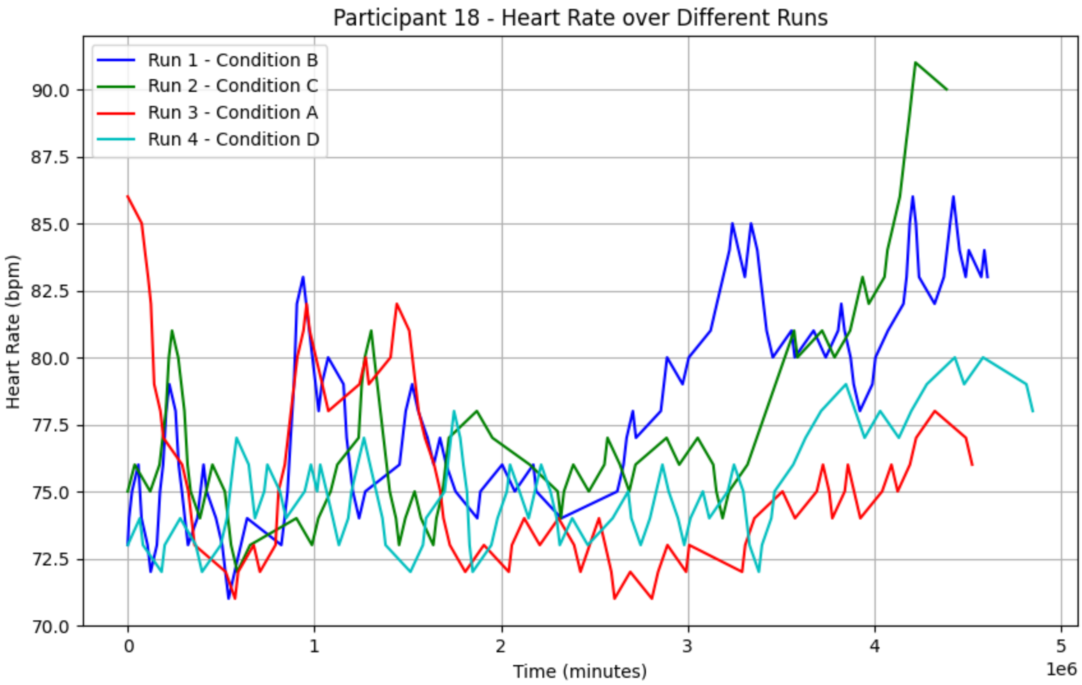

Participant 16 - Skin Conductance over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
Skin Conductance (µS)
Time (minutes)
1e6

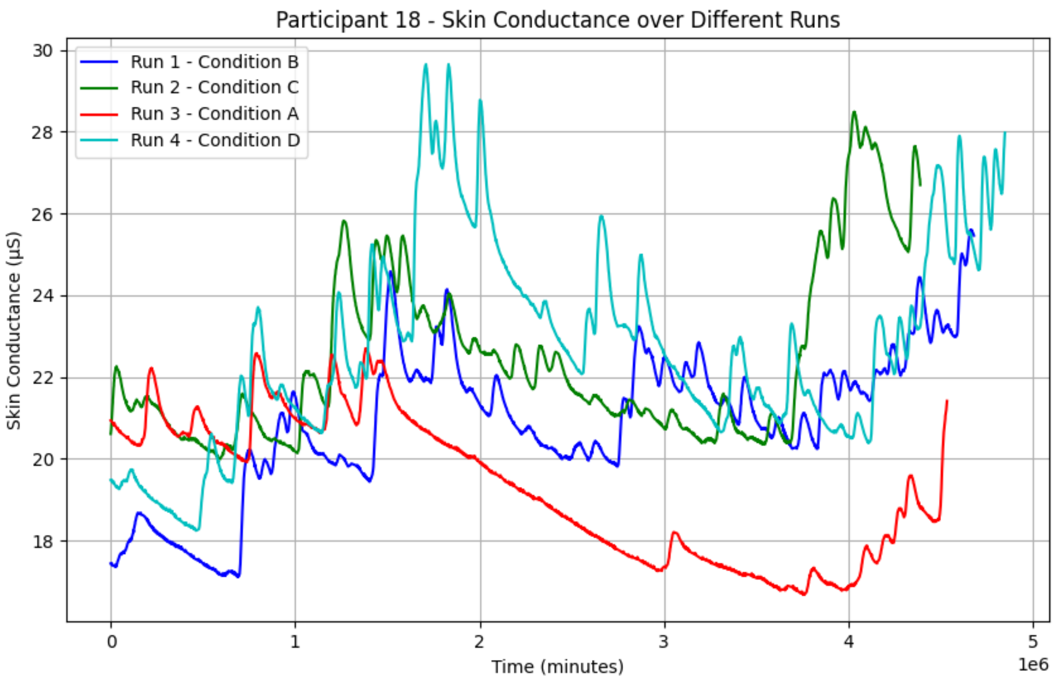

Participant 16 - Height over Different Runs
Run 1 - Condition D
Run 2 - Condition A
Run 3 - Condition C
Run 4 - Condition B
AGL (meters)
0
200
400
600
800
Time (seconds)
0
50
100
150
200
250

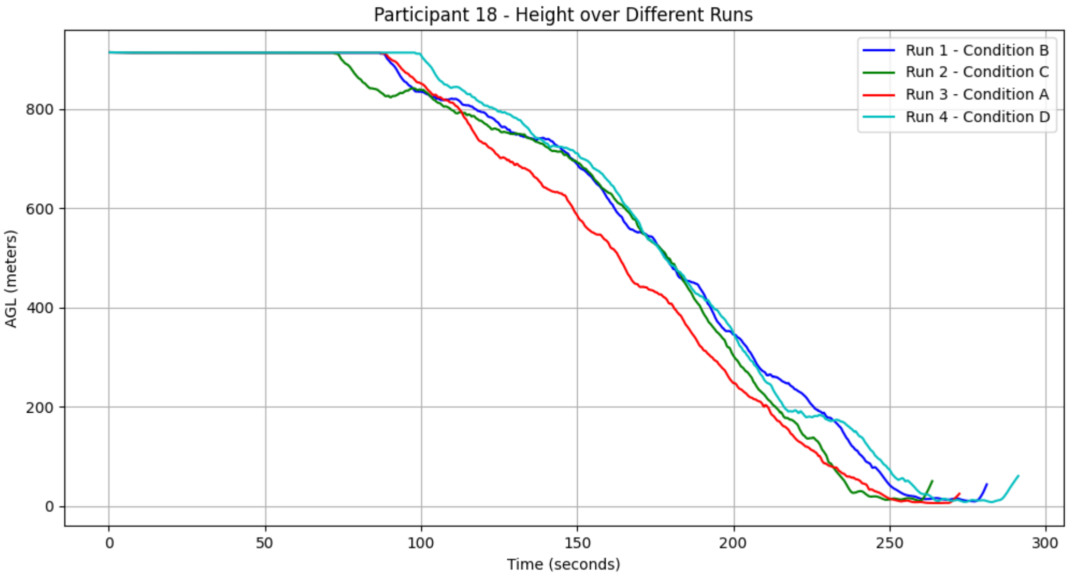

Participant 17 - Heart Rate over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
Heart Rate (bpm)
110
100
90
80
70
0
1
2
3
4
1e6
Time (minutes)


Participant 17 - Skin Conductance over Different Runs
Skin Conductance (µS)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
0
1
2
3
4
1e6
Time (minutes)


Participant 17 - Height over Different Runs
Run 1 - Condition A
Run 2 - Condition B
Run 3 - Condition D
Run 4 - Condition C
AGL (meters)
800
600
400
200
0
0
50
100
150
200
250
Time (seconds)

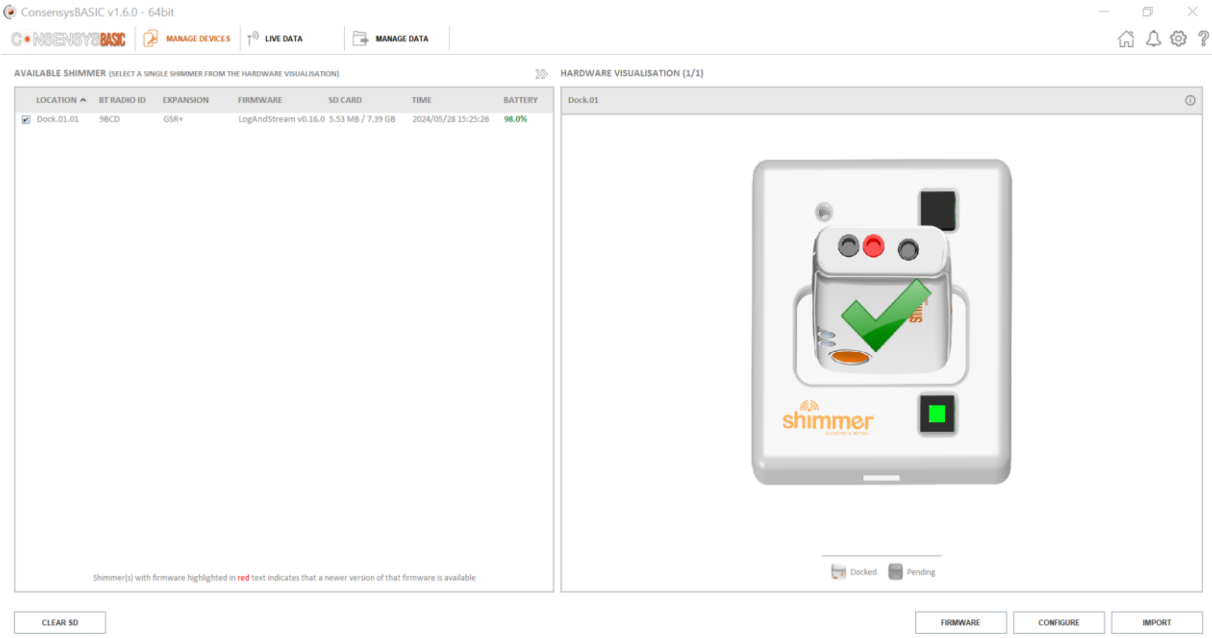

Participant 18 - Heart Rate over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Heart Rate (bpm)
90.0
87.5
85.0
82.5
80.0
77.5
75.0
72.5
70.0
0
1
2
3
4
5
Time (minutes)
1e6


Participant 18 - Skin Conductance over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
Skin Conductance (µS)
30
28
26
24
22
20
18
0
1
2
3
4
5
Time (minutes)
1e6

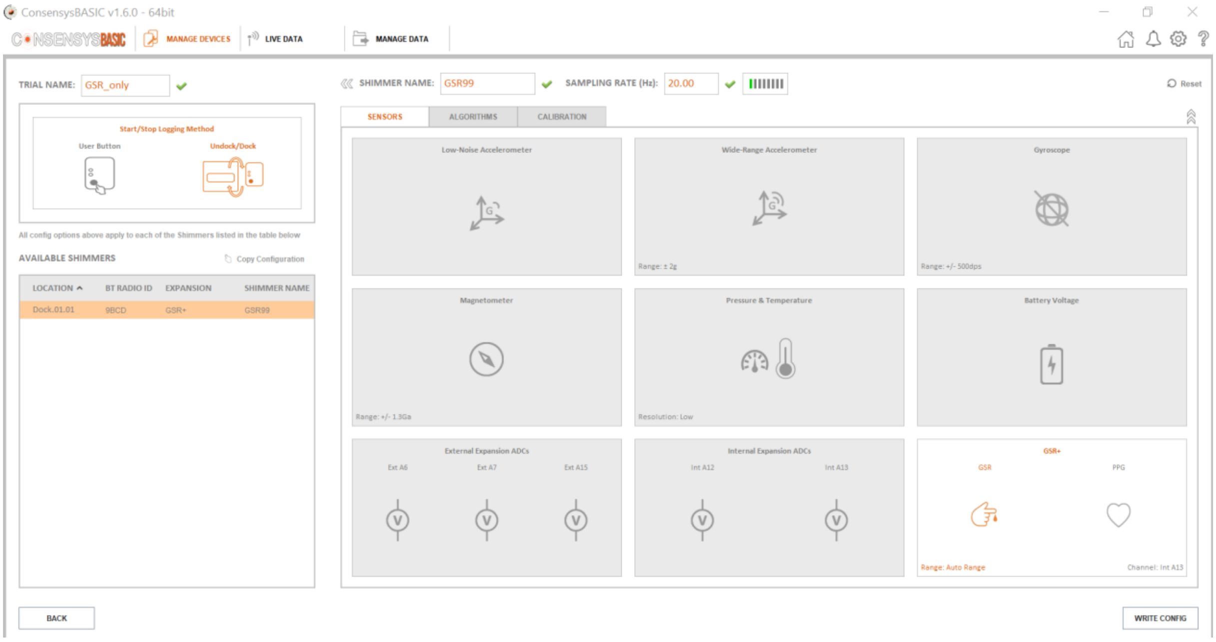

Participant 18 - Height over Different Runs
Run 1 - Condition B
Run 2 - Condition C
Run 3 - Condition A
Run 4 - Condition D
AGL (meters)
Time (seconds)
0
200
400
600
800
0
50
100
150
200
250
300

6.9. Appendix 9: Shimmer to LSL Guide

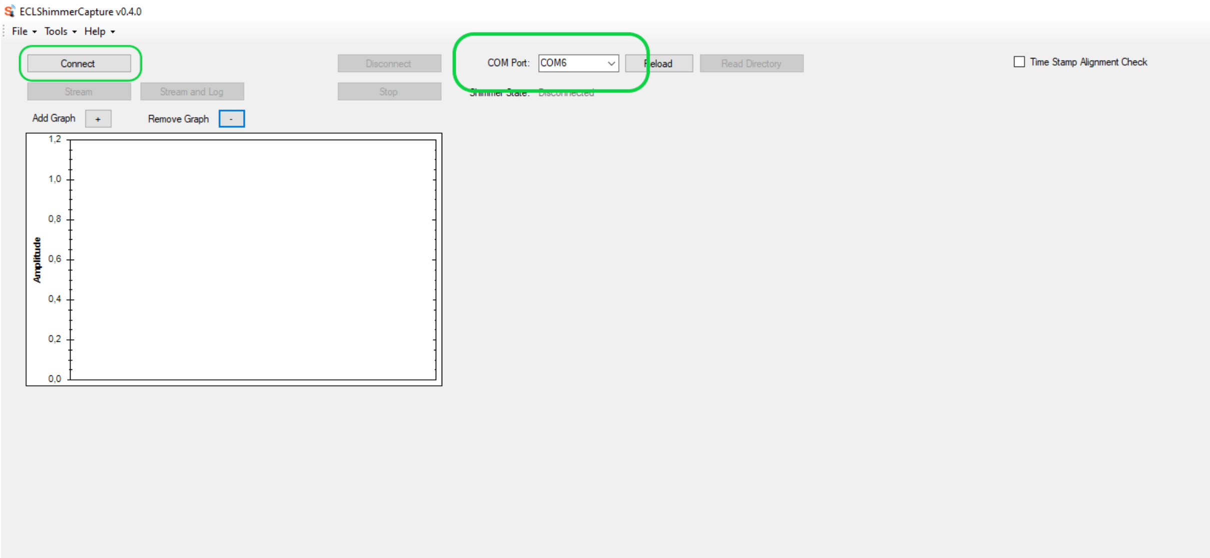
1. Download Consensys by Shimmer, the basic version is sufficient.
2. Connect docking station to laptop to configure selected Shimmer3 GSR+ unit.



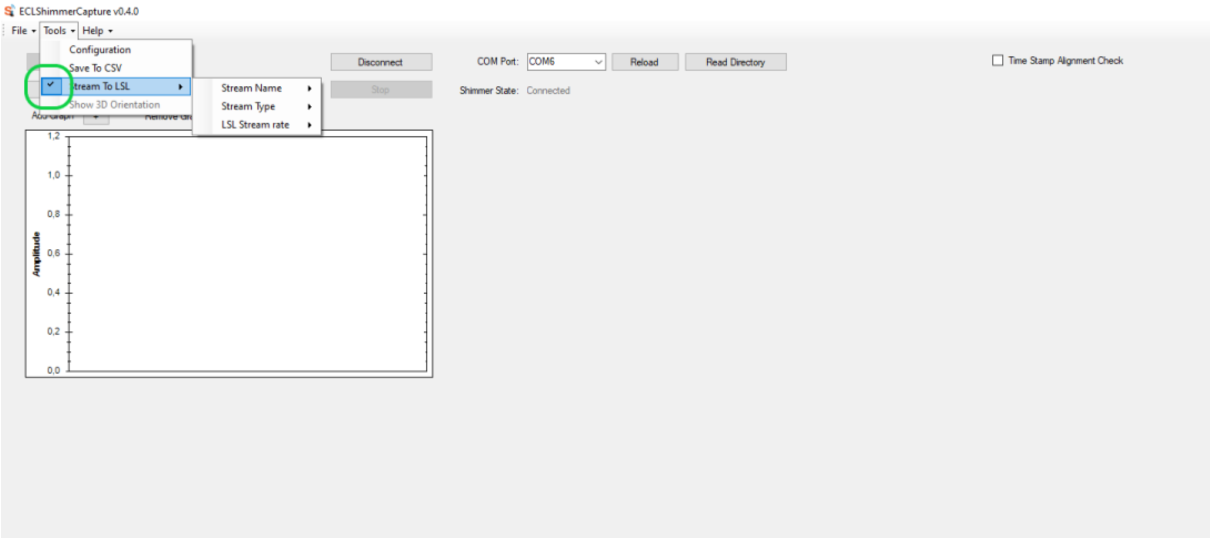
3. Configure unit in Consensys by selecting what you want to measure.



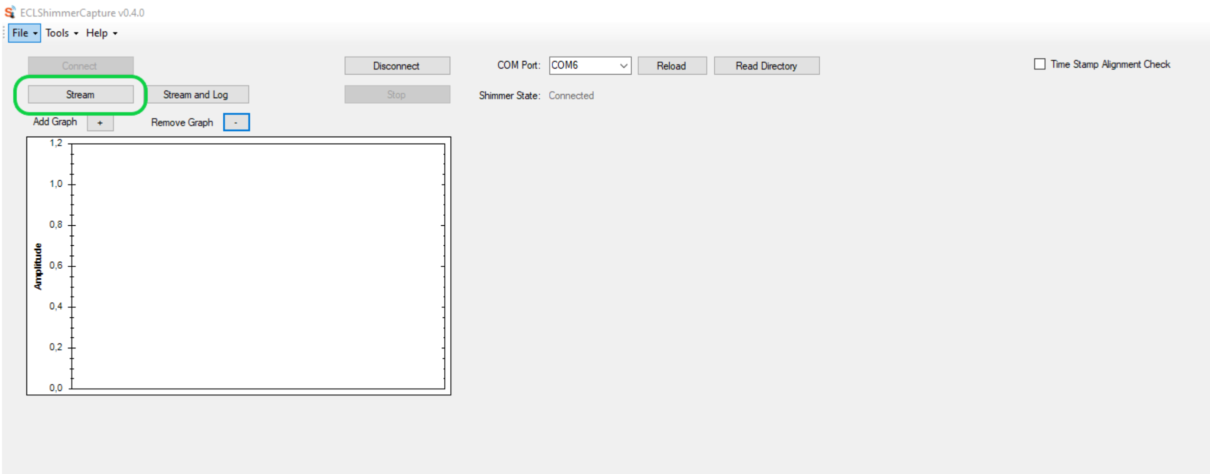
4. Write config to the unit.
5. Download ECL-Shimmer-C-API from GitHub ([GitHub - prasanthsasikumar/ECL-Shimmer-C-API]).
6. Launch "ECL ShimmerCapture".
7. Find the COM Port that belongs to the unit and press connect.



8. Check the box next to “Stream To LSL”.



9. Press “Stream”.



10. The data is now being sent to the LSL.