Analysis of Physiological Effects of Multisensory Stimuli in Automotive Cabin Spaces.

A Graduation Thesis Report

by

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Foreword

I would like to thank my parents for their unwavering support throughout this journey. I am deeply grateful for their patience, encouragement, and kindness.

I am also indebted to my project chair, Dr. Y. (Wolf) Song, for his continuous moral and academic guidance, and to my project mentor, Ir. G. (Gerbera) Vledder, for answering my endless questions and offering steadfast support. This project would not have been possible without the invaluable assistance of both of them.

My sincere thanks go to my good friend and research assistant, Ruida Chen, for standing by me during the most challenging stages of this work and for being a constant source of cheer along the way.

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Abstract

This study explores the effectiveness of a multisensory relaxation program developed for a high performance coupe interior by a German manufacturer. There is a growing need to introduce sensory-rich cabin experiences that bring about stress alleviation coupled with improvement of attention. The aim of this research is to evaluate whether auditory, visual, and tactile stimuli can facilitate relaxation in occupants following a high-arousal driving task.

A total of thirty-three participants were subjected to four therapy program conditions in a counterbalanced Latin Square order: no stimulus (control), auditory-only, auditory + visual, and auditory + visual + tactile (vibratory) stimuli. A custom-built test buck was built for the therapy activities, emulating the interiors of a sports coupe. The therapies were preceeded by a driving simulation stressor. Physiological data such as electrodermal activity, pulse rate, and skin temperature were collected through a wearable device, while subjective responses were collected via questionnaires. A psychomotor vigilance task (PVT) was also paired with the questionnaires to measure response times.

Physiological data analysis reveals no statistical differences between the four therapy conditions. PVT reaction times show minor improvements post-therapy, aligning with expectations. However, subjective data indicates clear preferences among participants. The complete therapy was most frequently rated as effective, though many complained about visual overstimulation. In contrast, the audio-only condition was perceived most balanced. Notably, participants suggested an audio-tactile configuration omitting the visual component.

These findings show that while objective data is still inconclusive, subjective feedback support such multisensory integrations in automotive interiors, particularly during idle EV charging phases or pre/post performance driving.

Keywords:
multisensory, stimulus, automotive, interior, relaxation, therapy, driver, well-being, physiological stress, pulse rate, electrodermal activity, skin conductance, human-centred, design, electric vehicle

Introduction

Analysis of Psychological Effects of Multisensory Stimuli in Automotive Cabin Spaces is a research project aiming to analyse and quantify occupant response, in terms of mental state, when exposed to a relaxatory therapy program. The study seeks to corroborate subjective information with objectively measurable physiological markers to evaluate the effectiveness of the multisensory therapy program under study, as well as the influence of individual sensory stimuli on a human's perceived state of stress and relaxation.

The context of the current experimental study lies within the use case of performance-oriented sports coupes and considers both passenger- and driver-side effects. The relaxatory program aims to alleviate stress and ultimately enhance alertness, with potential use cases including periods while the vehicle - particularly in the case of an electric or hybrid automobile - is charging, or before and after adrenaline-inducing driving sessions involving the driver and occupant. The program is applicable only when the car is stationary.

An automotive interior space is often a passenger's window of contact with the heart of the machine. It offers a plethora of sensory experiences to the occupants that engage and stimulate them in pleasant, comforting ways (Liang et al., 2019). These spaces cocoon the passengers from the brashness of the engineering and the outside world. Therefore, it is essential for the passengers to feel at ease while traveling and to build trust with their personal vehicles.

These spaces play a significant role in influencing occupants on a deeper, more personal level. The myriad of stimuli that a human occupant experiences inside an automotive cabin each have their own qualities - the materials they touch (Ryu et al., 2003; Yun et al., 2004), the sounds they pick up (Cheer, 2020), and even the ambient lighting inside inform them of how to perceive and feel their surroundings at that moment (Kim et al., 2022; Caberletti et al., 2010).

(Source: BMW Pressclub Global)

Fig 1: A BMW M4 CS on the racetrack

Historically, red lighting of button controls and classical music have been used to induce a relaxatory state among occupants. The tasteful use of metals, leather, and soft or hard materials - each with their own unique lustre and texture -

brings a renewed freshness every time one enters a vehicle (Kamp, 2012). Even olfactory factors (Yao et al., 2020a; Gentner et al., 2020b) play a significant role in shaping one's connection to their car - a wave of familiarity and relaxation washes over a person when they catch a waft of their car's unique scent, a blend of upholstery and perfume.

In an era of the increasingly diminishing presence of tactile interfaces and the fading fidelity of cabin design, there arises a need to incorporate smart solutions to substitute the lack of sensory stimuli in modern automotive interiors. What factors play a role in influencing the state of alertness or relaxation of a passenger? Can we predict and control how a person's mind would react to carefully engineered artificial stimuli inside the cabin? And is this an active or a passive effect?

The way a person might perceive such a program is informed by a multitude of factors, but the two predominant ones are the person's prior life experiences and the evolutionary reaction traits shared by all human beings. While the former is not easily predictable, the latter can indeed be tapped into to develop such a program. The sound of a creek, the flickering of a lick of flame, or even the smell of windswept grass have all been found to have universal stress-alleviating effects (C. Liu et al., 2024).

This project thus aims to demonstrate the effectiveness of a digital relaxatory program developed by an automaker - one that utilises carefully crafted audio, strobing lighting, and vibrational seats to stimulate auditory, visual, and tactile sensory perception in the human occupant. The goal is to identify whether these factors are confluential or


(Source: BMW Pressclub Global)

Fig 2: The interior console of a current generation BMW M4 CS detrimental to a passenger's positive mental state.

The possible use cases of such an intervention warrant deeper exploration. In the rapidly hybridising landscape of cars today, a short stop at a charging station after a fatiguing drive could be turned into a focused effort to alleviate stress. Additionally, such an in-car relaxation program could serve as a periodic respite from the constant information overload from the many screens in today's cabins.

This assertion is based on the fact that, over the next 5-10 years, charging times are expected to decrease significantly due to developments in battery chemistry. Currently, vehicles like the Porsche Taycan Turbo GT achieve 5-80% charging in approximately 22 minutes using 270-320 kW chargers (Car and Driver, 2025). However, thermal and battery-aging constraints remain a bottleneck to further reductions in charging time. Developments in silicon-anode XFC batteries by StoreDot (Y. Yao et al., 2025; Z. Yang et al., 2023; StoreDot, n.d.) and solid-state battery (SSB) technologies - led by BMW, Toyota, and Nissan - promise sub-15-minute charging times while maintaining thermal stability (Shah et al., 2024). Stellantis' SSB prototypes have demonstrated 15-90% in 18 minutes, while FIA-derived systems in high-performance EVs from Rimac, Audi, and AMG are projected to enable 60-80% top-ups in under 5 minutes.

As the automotive industry transitions toward increasing automation and hybridization, the interior of a car has become more of a sanctuary than just a workspace. In high-performance, track-focused sports coupes like the car in this study, this presents a unique opportunity - to contrast the car's aggressive mechanical identity with a psychologically calming cabin that serves as a personal retreat between adrenaline-fueled driving instances.

A relaxation program is not only about comfort - it is about mental resetting. A brief relaxation phase before a high-focus driving session not only ensures well-being but also improves driver performance (Meteier et al., 2022). By lowering baseline stress levels and mitigating sensory fatigue, these systems positively influence reaction times and situational awareness. In fact, this exact principle was the foundation of

(Source: BMW Pressclub Global)

Fig 3: The new BMW Neue Klasse is supposed to deliver M performance in an EV package

Mercedes-Benz's ENERGIZING Comfort system - an immersive wellness program, featured primarily in its premium sedans and SUVs, that utilizes music, ambient lighting, seat heating, and even massage functions to curate specific passenger moods (Automotive World, 2023).

Furthermore, in hybrid vehicles, the downtimes during long charging stops could be transformed into positive micro-experiences. These breaks can subtly address mental fatigue while offering engaging sensory input. As modern vehicles continue to abandon tactile-heavy interfaces in favor of sterile minimalism, such sensory stimulations could help bridge the growing disconnect between man and machine. Thus, integrating relaxation tools into automotive cabins - especially in track toys - may yield tangible cognitive and physiological benefits in future applications.

Problem Statement

The impact of controlled audiovisual stimuli on driver comfort, stress reduction, and physiological well-being within the automotive interior remains an intriguing, yet underexplored, area of research. Prior studies have demonstrated positive correlations between relaxation programs and improved comfort levels (Shahid et al., 2011; Liu et al., 2023). Building upon these findings, this study investigates how auditory, tactile, and visual interventions influence physiological and psychological states within real-world driving environments. The results aim to evaluate the potential benefits and limitations of incorporating multisensory design principles in modern automotive interiors.

Research Questions

- How does in-car relaxation therapy influence physiological signals associated with comfort and stress?
- Does a combination of auditory, visual, and tactile stimuli produce stronger or weaker physiological and psychological effects compared to auditory intervention alone?
- How do participants' perceived comfort and relaxation levels vary across different experimental conditions?
- Can multisensory interventions serve as a viable strategy for enhancing future vehicle interior design?

Expected Outcomes

The expected deliverables include empirical data on the physiological and psychological effects of a multisensory relaxation program in automotive environments. The analysis will focus on physiological parameters to assess its impact on comfort and stress. The findings will offer insights into integrating passive comfort-enhancing features into vehicle interiors, along with recommendations for optimizing occupant relaxation.

Literature

While physical ergonomic factors often govern the perceived comfort of an automotive cabin, emerging studies suggest that emotional and sensory dimensions also play a significant role. An experimental study by Kruithof et al. (2020) demonstrated that a passenger's emotional valence notably affects both comfort and well-being. The study highlighted how music and emotion-driven cabin design enhanced passenger comfort, with music showing a stronger positive influence on emotional state than the nature of the activity undertaken by the passenger.

Visual stimuli, being the primary drivers of perception and behaviour, typically take precedence over other sensory inputs, with auditory stimuli following closely. This suggests that carefully manipulating a passenger's visual environment - through elements such as colour, ambient lighting, and spatial quality - can contribute to meaningful relaxation effects (Xie et al., 2022; Elliot, 2015). Likewise, auditory cues play a crucial role in mood regulation, prompting automotive manufacturers to explore relaxation programs that integrate both visual and auditory modalities to enhance well-being (Deng et al., 2020; Liu et al., 2023).

However, while the individual effects of these stimuli have been studied, there remains a critical need to investigate their interaction in a combined multisensory environment. A positive correlation observed when stimuli are presented in isolation does not necessarily guarantee a similar effect when they are experienced simultaneously. Understanding this interaction is therefore central to the present experimental study.

There has been prior testing of such multisensory relaxation programs inside controlled settings, which might be useful for the current exploration. A component of the relaxation therapy program is vibroacoustic stimulation, which uses low-frequency sound coupled with vibration from the seat (MacDonald et al., 2024). Vibroacoustic therapy has been shown to increase parasympathetic activity - usually a physiological indicator of a state of relaxation. In a study of 48 participants subjected to low-frequency sound on a reclined platform, an increased parasympathetic response was found through post-intervention HRV (Fooks & Niebuhr, 2024).

Also, vibroacoustic sound massage (VSM) sessions, where the vibrations along the seated platform follow the auditory cues, have been linked to EEG changes that reflect a reduced level of arousal and increased concentration (Fooks & Niebuhr, 2024). This indicates both a psychological perception of stress relief, along with the high HRV-implied physiological relief. These findings confirm the efficacy of combined audio + tactile stimulation in relaxation.

Another study explored the effect of sounds with or without vibrational stimuli, in order to verify their constructive or destructive interaction in stress alleviation (Kantor et al., 2022). While testing sound playback with low-frequency vibrations, it was found that only the music-plus-vibration condition yielded physiologically significant relaxation. This suggests that audio alone may not be sufficient to elicit the desired result, whereas the addition of tactile stimuli results in a positive symbiosis (Peng et al., 2024).

Music has often been found to be an effective catalyst in attenuating cardiac stress markers - for example, by stabilising HRV levels compared to normative driving ones (Alves et al., 2019; De Witte et al., 2019). Despite such studies showing that audio alone is still effective in stress alleviation, factors such as an occupant's prior experiences and connotations to certain music, or even their personal inclinations, could make the audio-only condition quite difficult to predict, and thus unable to surmount a multisensory approach.

In real life, human beings are constantly subjected to multiple sources of sensory input. Research by Stein & Meredith (1990) and Ernst & Bülthoff (2004) shows that if such sensory inputs are congruent with each other, they can yield a stronger perceptual effect compared to if the same inputs were presented in isolation. This is referred to in these studies as

(Source: BMW Pressclub Global)

Fig 4: BMW "My Modes" Relax Mode in the 7 series, which plays audio from Bowers and Wilkins speakers superadditivity. Also, as seen earlier, the aspect of physical contact through touch is important in influencing emotional impact, especially when the tactile and audio components are in synchronicity (Spence & Gallace, 2011).

In fact, certain studies have been conducted to observe the universality of this exact phenomenon. Haptic cues, such as vibrotactile arrays, harmonic simulators, and such, have been shown to lower heart rate and induce a state of calmness when timed with relaxation audio (MacDonald et al., 2024b).

A combination of in-cabin music plus light has also been found to be significant in improving the relaxation of a passenger compared to audio alone (Deng et al., 2020). Lighting is often a critical effector of comfort, performance, and physiology in the context of an enclosed cabin. Ambient illuminance of around ~284 cd/m² and 5500K - a neutral white light slightly warmer than natural sunlight - was associated with peak comfort and cognitive performance (Zhu et al., 2024). Despite improving performance, it is also interesting to observe that comfort sometimes declines after task completion. This may indicate that lighting affects mood and performance differently.

While natural light may indicate increased comfort, blue ambient light results in three-times faster reduction in physiological stress indicators compared to white light. This effect diminishes after five minutes, so it is especially useful for short relaxation sessions (Minguillon et al., 2017). Red light (~140 lux), though, is observed to incite mild sympathetic activation and elevate arousal levels, thereby aiding more in alertness than relaxation (Pan et al., 2023).

Rhythmic Photic Stimulation (RPS) - or flickering lights at specific frequencies - has been used therapeutically for reducing anxiety and depression. Studies have found that flickering at alpha frequencies (around 10 Hz) improves HRV and the subject's mood (Yang et al., 2025). Similarly, studies have shown that stroboscopic exposure to flickers around 40 Hz induced altered states linked to calmness and also, sometimes, disorientation (Bartossek et al., 2021). Meanwhile, flickers exceeding 50/60 Hz lowered accuracy and increased the speed of office tasks - indicating decreased comfort and increased arousal (Kuller & Laike, 1998).

Relaxation of a seated occupant inside a car is also affected by the number of passengers in the car. The physiological state while driving benefits from a prior short relaxation or meditation session and is also improved by a lack of co-passengers, which has been seen to spike stress levels in drivers (Meteier et al., 2022). Thus, for the sake of uniformity, the present experimental study may look to avoid introducing multiple occupants in a single relaxation therapy session.

Materials and Methods

Experimental Setup

The Test Buck

The test buck is a body frame of the passenger occupancy area of a two-door sports coupe car, complete with a roll cage. It is furnished with both passenger and driver seats, both of which are racing bucket seats. Two fully assembled doors exist on both sides to enable closure of the cabin, and all windows are blacked out in order to create a dark environment suitable for testing.

The therapy program itself is software run through a laptop that sits on a platform replacing the centre console between the two seats. The executable application is called LSV, aptly named for Light, Sound, and Vibration, and this enables control of the various stimuli marking the different therapy programs. The therapy program, labeled Vibe + Deep Dive 20, is a 20-minute long session designed to incorporate audio, pulsating lights, and seat vibrations synchronous with each other.

The laptop is connected by a cable to a Behringer audio interface box, placed on a wooden platform replacing the dashboard. This audio box relays the input from the laptop to the peripherals that interact with the occupant, such as headphones and vibrational seats. Rotary knobs Phones A and Phones B, beside the AUX port, control the audio through to the headphones, while the Main Out 1-2 knob controls the vibrational intensity of the seat.

Fig 5: (a) Frontal view of the test buck from outside the cabin.
(b) Assortment of instruments replacing the central console, for controlling stimuli.
(c) Participant seating area, comprising the driver and passenger seats.
(d) A close-up view of the carbon bucket racing seat.

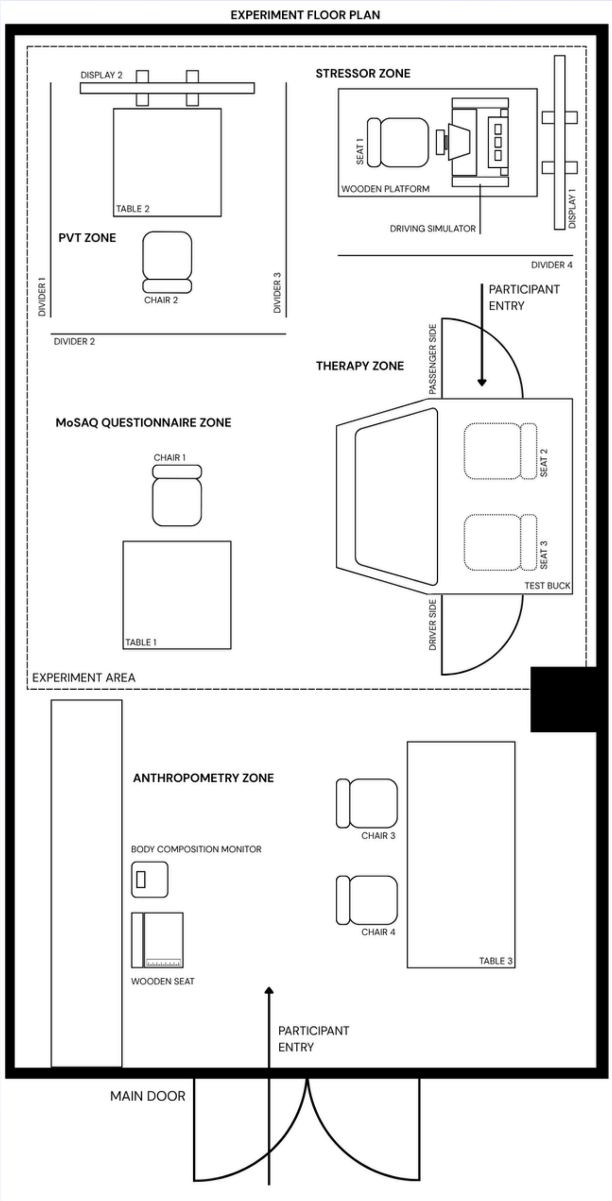


Fig 6: The experimental setup involves four separate zones:

1. *The Test Buck, where the participant experiences the therapy program*
2. *The Driving Simulator setup*
3. *A designated area for the Psychomotor Vigilance Task*
4. *Anthropometric Data Measurement*

Despite the audio interface controlling the intensity of seat vibrations (usually set to around 70%), the motors also require power of their own. For this, there is a voltage box behind the laptop on the central console. Based on whether the participant is to experience a therapy session with or without seat vibrations, the Main Out 1-2 knob and the voltage box can be controlled to turn them on or off.

The audio is heard by the participant via a pair of Sony headphones located on the central console, which the participant wears during therapy sessions involving audio. The volume is set to around 30% via the Phones B knob, as recommended by the operation manual provided by the automaker. The headphone ear cups are covered with disposable, breathable covers for better sanitation between different participant trials.

Visual stimuli are delivered to the participant via LED-fitted wearable goggles. Since the provided goggle units did not have arms, they are affixed to sleep masks with ample padding and adjustable straps that can then be worn over the eyes. The LEDs are turned on and off by switches on the centre console where traditionally an armrest is situated. The intensity or brightness of the lights - which was later seen to be a critical aspect of the therapy experience - can be controlled using a long rotary potentiometer stalk beside the switches.

There is also an infrared camera, a skeletal tracking camera, and an RGB camera to monitor the participant's facial skin temperature, spine posture, and facial emotional markers, respectively. They are mounted on the wooden dashboard using a SmallRig mount.

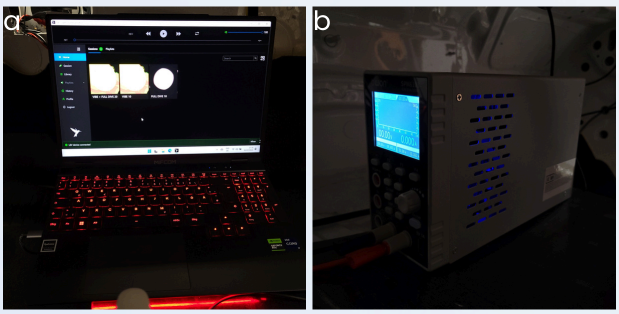


Fig 7: (a) The laptop on the centre console, which runs the LSV application during therapy (b) A voltage control box supplies power to the vibration motors in the car seats

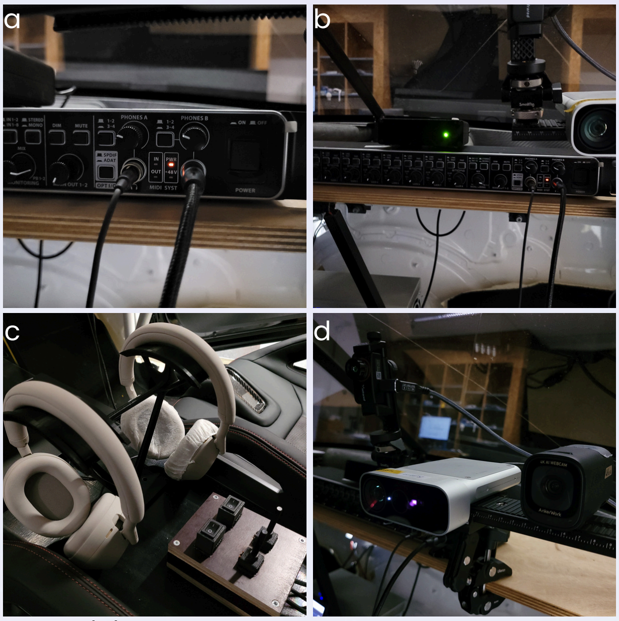


Fig 8: (a) A behringer audio box that controls the intensity of audio and seat vibrations
(b) A light box which supplies signals to the LED goggles from the laptop
(c) A pair of headphones sit beside the power switches and rotary potentiometer of the LEDs
(d) Skeletal tracking and thermal infrared cameras - used for auxilary subject metrics

The Driving Simulator

The driving simulator is an activity that acts as a stressor. In this activity, the participant has to drive a BMW M4 CSL G82 car in the racing simulator game Assetto Corsa Evo for around 15 minutes, in a practice session on a race circuit - Brands Hatch GP or Laguna Seca GP. A numerical target lap time is set for the participant to try to achieve, and over the course of the 15 minutes, they attempt multiple laps around the circuit in both clear and rainy weather conditions.

This game runs on a computer situated behind a 55” TCL television mounted on a floor display stand. This specific TV is chosen for its resolution and its gaming-optimised high screen refresh rate (144Hz) over its HDMI 2.1 port. The size of the TV offers an immersive experience for the participant compared to a traditional 27” monitor.

In front of the television is a rectangular wooden platform on the floor, above which a Next Level Racing Wheel Stand is secured. A Logitech G920 wheel is mounted on top of the stand, whereas the Logitech pedals are attached to the bottom plate of the stand at an appropriate height and orientation.

During the driving simulator activity, the participant operates the accelerator and the brake to move the car, while controlling the wheel for directions. The wheel also has Button LSB for changing the camera view from the default driver’s perspective by cycling through various available options.

In the event of the participant going off track or meeting with a collision in-game, they are instructed to use the left and right paddle shifters to shift into reverse gear and back. But for the rest of the session, the participant does not need to

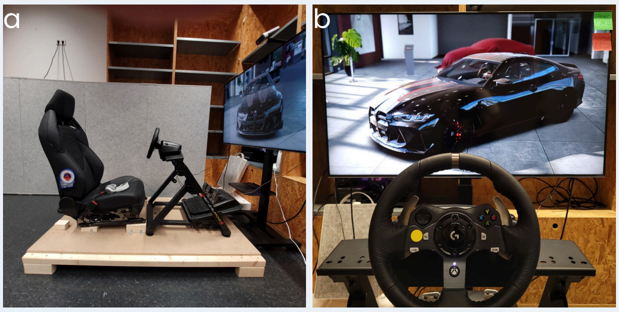


Fig 9: (a) The driving simulator atop a wooden stand, as seen from the side
(b) A participant’s perspective of the screen while in the driving position

operate the paddle shifters for shifting gears, since the car is set to have auto-switching gears inside the game.
Since the chosen car is RWD, in order to make controlling the car easier even for one unacquainted with such racing simulators, the electronic stability control in-game is set to 80 percent, and Button 7 on the Logitech wheel is mapped to enable Traction Control while the participant is on the track.

Audio from the game is routed through a pair of SteelSeries Arctis wired headphones. The choice of the headphones is based on several factors such as latency, weight of the headphone, and also comfort of the ear cushion pads. Similar to the headphones inside the test buck, these ear cups are also covered with disposable, breathable covers for better hygiene protocols between participants.

The participant performs this activity by sitting on an electronic automobile seat, which has controls for to-fro and up-down movement, along with rear backrest inclination. The seat is attached to the wooden base platform and is powered by a portable Anker Power Station.

Fig 10: (a) A close up of the steering wheel. Notice the yellow traction control sticker
(b) The three pedal setup of the simulator - rightmost accelerator, middle brake
(c) Portable power supply for the electronically adjustible driver seat
(d) Headphones used for the stressor - wired but lightweight and unintrusive

Psychomotor Vigilance Task

The Psychomotor Vigilance Task (PVT) is a 5-minute reaction time test in which the participant responds to recurring prompts on a display. Reaction time refers to the interval between the reception of visual stimuli by the retina and the execution of a motor response - typically involving neural processing within the central nervous system and culminating in an action such as a mouse click. Due to the performance-sensitive nature of the software, a 1000 Hz mouse polling rate and a fast LCD panel are required to measure reaction times with an accuracy of 1 to 10 ms.

The designated area for performing the PVT task is enclosed on three sides using IKEA room dividers, creating an isolated space that minimizes external distractions. These dividers also reduce reflections on the display's glossy surface - an issue identified as a pain point during the pilot study. Within this enclosed cubicle are a television display, a table, and a chair, allowing the participant to comfortably perform the PVT activity.

The software used is PC-PVT 2.0, developed by BHSAI (Reifman et al., 2018), running on an Intel NUC connected to the television. Participant registration is conducted using PVT Manager.cmd, while the reaction time test is initiated via PVT Trial.cmd within the PVT directory.

A TCL 55C71B QLED television is used for the task. With an impressively low input lag of 5.7 ms, the display is well-suited for such testing. Although the screen is relatively large, the 4K resolution ensures that the visual prompt appears centrally, allowing the participant to maintain a narrow field of attention that minimizes external distractions (Eriksen & St. James, 1986). The prompt is approximately 15mm in width and is located at ~360mm from the base of the display. The television is positioned at an appropriate distance to prevent eye strain.

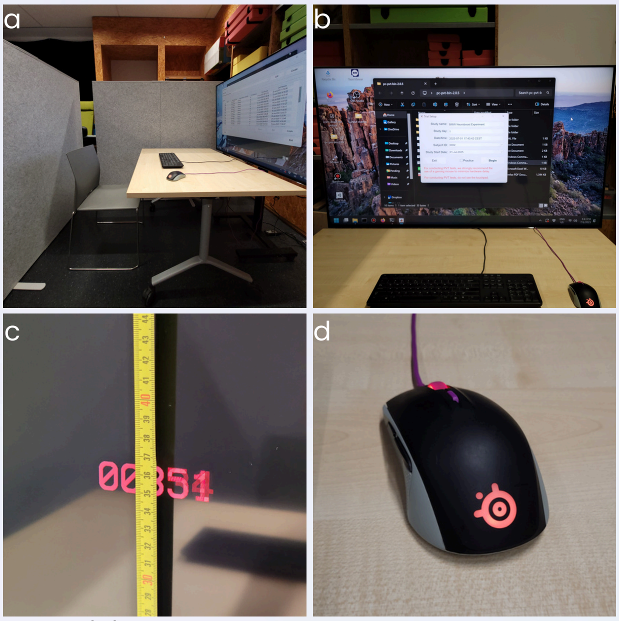


Fig 11: (a) A side view of the PVT setup, isolated one all sides by dividers forming a cubicle
(b) The view a participant would face while performing a PVT task while seated
(c) A measuring tape demonstrating visually the position of a visual prompt on screen
(d) The gaming mouse used for the PVT task - wired ensures minimum input latency

Placed between the participant and the television is a table equipped with a wired keyboard and mouse. The only action required during the task is clicking the mouse in response to an on-screen prompt. The chosen device is a SteelSeries Rival 100 - a gaming mouse with a 1000 Hz polling rate. Its click latency, reported at 17 ms (RTINGS.com, 2021), falls well within the error tolerances of the PC-PVT software.

Similar to the setup for the PVT task, a separate table and chair are placed outside the cubicle for the participant to complete the Momentary State Assessment Questionnaire. The questionnaire is administered in physical (paper) format to avoid potential biases that could arise from using a non-traditional, digital interface - even though the paper-based format takes slightly longer to complete.

Anthropometric Data Measurement

For the experiment, it is also important to measure key anthropometric data of the participants. These body measurements are taken using two apparati - an OMRON BF511 KaradaScan and a wooden platform.

The OMRON BF511 is a full-body measurement device that measures the participant's body composition, including body weight, visceral fat, body fat percentage, muscle percentage, and metabolism rate.

It uses a method called Bioelectrical Impedance Analysis (BIA). There are electrodes on where the participant stands, and also on the grab handle. A tiny amount of electricity is then passed through the participant's body, and the resistance or impedance the current faces is measured. Muscle has more water, so is more conductive than fat, which offers a higher resistance to current flow.

The unidimensional anthropometric length measurements of the participant,

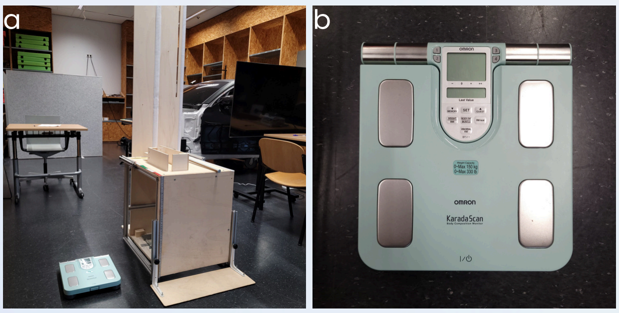


Fig 12: (a) The wooden measurement platform
(b) An OMRON device used for measuring body composition of each participant

such as sitting height, popliteal height, shoulder breadth, hip breadth, etc. are taken using the wooden platform, which has length gradations on required axes.

The participant's stature (standing height), sitting height, eye height, shoulder height, and popliteal height are measured in such a manner. For the measurement of hip breadth, shoulder breadth, elbow-to-elbow width, and popliteal-to-knee width, a calliper is used that has a resolution of 1 mm.

The stature and weight of the participant with their shoes are also measured in order to account for real-life automotive cabin interior usage conditions.

Experimental Protocol

Data Aquisition

For the quantitative identification of participant relaxation states and the analysis of relaxation levels, previous experimental research involved the extraction of physiological metrics such as Heart Rate Variability (HRV), Heart Rate (Pulse), Electrodermal Activity (EDA) / Skin Conductance Response (GSK), Oxygen Saturation (SpO_2), and Blood Volume Pulse (BVP) (Shahid et al., 2011). This combination of data provides a comprehensive physiological profile for assessing participants' relaxation levels.

A critical requirement for data collection was ensuring high data quality, specifically whether the extracted data met medical-grade standards - thereby ensuring the clinical validity of the study - while also being minimally intrusive to participants throughout the experiment. To meet these criteria, the Empatica EmbracePlus, a watch-like wearable with a 64 Hz sampling rate, is selected for its familiar form factor, ease of initial fitting, and high-quality medical-grade data acquisition capabilities (Empatica, n.d.).

Therefore, the physiological markers that align with the experimental objectives include Heart Rate Variability (HRV),

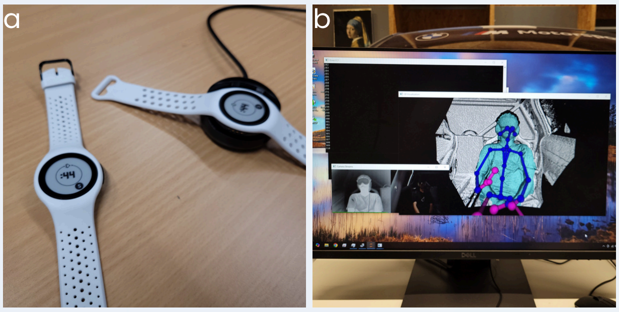


Fig 13: (a) A pair of Empatica EmbracePlus wearable devices used in the experiment (b) A display showing skeletal mapping of a participant. Potential for use in a future study

Electrodermal Activity (EDA) / Skin Conductance Response (GSK), Skin Temperature, and Peripheral Temperature. With the exception of Peripheral Temperature - measured using infrared cameras to track temperature changes in regions such as the ears, nose, and fingertips - these markers are recorded using a single Empatica EmbracePlus device.
While it is true that wrist-worn measurement devices are more susceptible to motion-induced artifacts, the design constraints of this experiment necessitate a solution that would not interfere with the freedom of movement or comfort of the participant. Since the core aim of the study is focused on relaxatory stimuli, it is counterintuitive for

a data acquisition method to skew the participants' perception of the effectiveness of the setup.

Therefore, rather than restricting movement, consistent skin contact and signal stability through minimizing sensor displacement is prioritized. To achieve this, participants are asked to initially rub the contact skin area with WaterWipes, and once the surface is dry, wear the EmbracePlus as tightly as comfortably possible to eliminate play while moving. The participant is also optionally provided a soft, elastic, breathable athletic band to wrap over the EmbracePlus to secure it snugly around the wrist if it felt loose at any point. This low-intrusion intervention reduces the likelihood of discontinuous signals.

Other, more extensive stabilization measures were also investigated and remain viable for future studies:

1. Replacing the strap to provide a more secure and snug fit and reduce slippage, such as through the use of the Velcro EmbracePlus band accessory.
2. Adjusting the placement of the wearable on the participant's wrist, such as shifting to the supine side of the participant's wrist to avoid bony regions and improve contact.
3. Applying conductive gel between the sensor and the skin to enhance signal quality.

The detachment capability of the EmbracePlus sensor module allows for exploratory alternative placements such as the neck or ankle. While the neck offers superior HRV and SpO_2 signals due to richer blood perfusion, it poses issues in terms of comfort and participant intrusion. The ankle, although less intrusive, may suffer from reduced signal strength due to its distal position and lower blood flow. Each of these placements introduces unique trade-offs, with the wrist still remaining the best compromise between signal quality, comfort, and practicality.

The use of conductive gel was evaluated, particularly in improving EDA data by reducing impedance. However, as this might interfere with optical sensors - particularly in the context of Pulse Rate and HRV - it was not implemented in the final study setup.

Other potential tools, including electroencephalography (EEG) with dry electrode headbands like Muse or BrainBit, were assessed for their ability to track alpha brain waves associated with relaxation. These were ultimately rejected due to their obtrusiveness and the risk of breaking immersion. Similarly, respiratory rate belts from manufacturers such as ADInstruments or Biopac were excluded despite their data accuracy, due to their physical intrusiveness and potential to introduce discomfort.

Further alternatives - such as facial EMG or pupillometry using Tobii Eye Tracking - were considered as well. Facial EMG, while capable of tracking subtle changes in forehead muscle tone, required cumbersome electrode bands, thus clashing with the low-intrusion design goals. Pupillometry, though potentially valuable, introduced excessive complexity and integration demands.

Therefore, despite exploring a variety of alternative physiological monitoring methods, the final implementation using the modest Empatica EmbracePlus proves to be the most suitable solution - both technically and contextually - for this particular study. Unlike other sensor systems that impose a certain degree of intrusiveness, the EmbracePlus offers a minimally invasive, familiar form factor which can capture a comprehensive array of data.

Skeletal tracking and facial emotion tracking are also captured during the experiment, but due to the computationally intensive nature of such 3D coordinate data, and the time-constrained nature of the project, inferences from the analysis of those data are currently beyond the scope of what this report has to offer.

Subjective data from participants is collected through several questionnaires interspersed between each stressor or therapy activity. After beginning their first experimental session, participants fill out a pre-questionnaire that collects personal information relevant to the context of the study, such as dominant hand, ancestral ethnicity, driving experience, and music preferences.

The Momentary State Assessment Questionnaire (MoSAQ), which participants complete multiple times during the course of the experiment, placed before, between, and after each stressor and its succeeding therapy activity, consists of three sections: comfort rating, sensory rating, and discomfort rating (refer to Appendix F).

The comfort rating section requires participants to evaluate (on a 0-10 scale) their current levels of comfort, fatigue, and stress, as well as the perception of body temperature (0 = hot, 6 = cold) across multiple body zones, including the head, upper body, arms, buttocks, thighs, and legs.

The sensory rating section is the most critical for this experimental analysis, as it provides vital insights into the participant's mental state at that moment. It assesses emotional tone (happy to sad), arousal level (drowsy to energised), and sense of presence (detached to immersed) on a scale from 0 to 6. This section also includes questions that evaluate cognitive state (cognitive clarity, sensory distraction, focused state, temporal distraction, and sensory intensity) and general mood/awareness

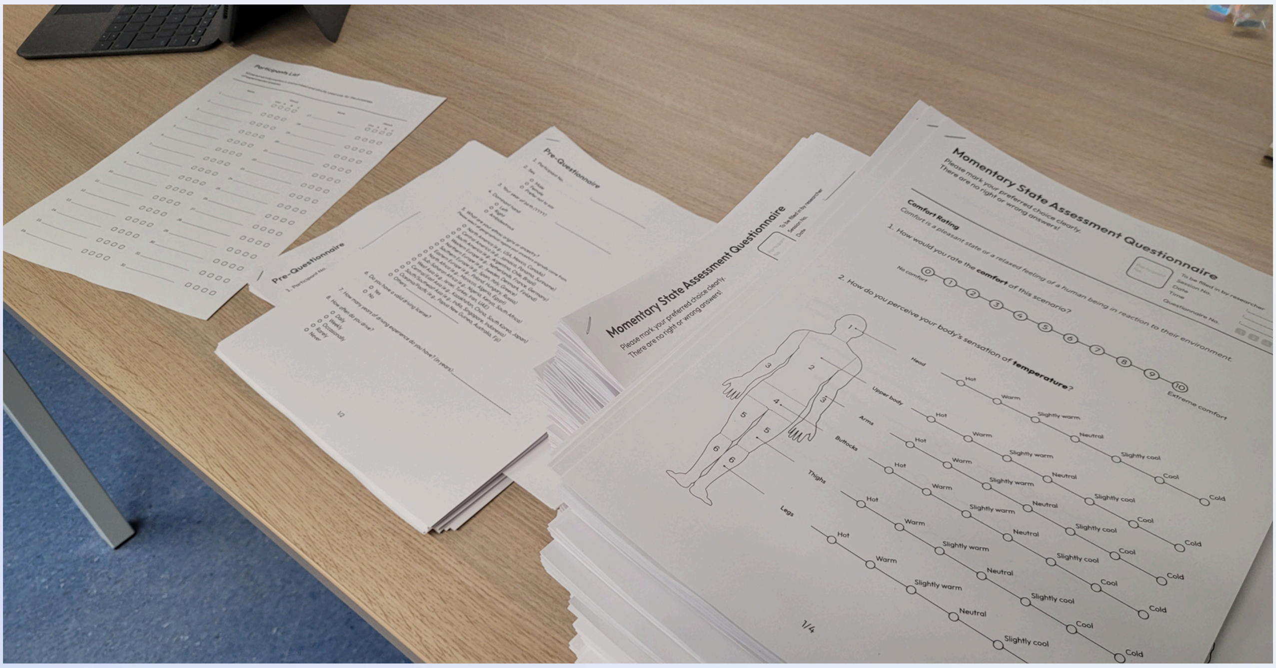


Fig 14: A stack of questionnaires that each of the 33 participants complete over the course of both sessions of the experiment

(alertness level, relaxation level, emotional salience/affection, immersion level, and autonomy perception), each on a 0-4 scale.

The discomfort rating section captures both overall perceived discomfort and localised postural discomfort across specific regions - such as the neck, shoulders, upper back, upper arms, mid back, lower arms, lower back, buttocks, left thigh, right thigh, lower left leg, and lower right leg - using a 0-10 scale.

The Post-Session Reflection is an interview-style questionnaire completed after participants have experienced all four therapy conditions (see Appendix F). It allows them to provide open-ended feedback and personal insights that may not be captured by structured questionnaires.

Experimental Setup

Flow of Experiment

The experiment began with a pilot study involving two participants to evaluate the feasibility of the protocol and determine whether measurable differences could be observed. Adjustments were made based on the pilot results. For example, logging the start and end timestamps of participant activities by hand was found

Fig 15: A sketch showing various activities involved with the experimental setup
(a) Participant arrives at the lab and is introduced to the experiment
(b) Participant wears the EmbracePlus wearable to start physiological data collection
(c) Participant completes the pertaining physical paper questionnaire(s)
(d) Participant performs the psychomotor vigilance task (PVT)
(e) Stressor - Participant participates in a stimulating driving activity
(f) Therapy - Participant experiences the relaxation program in the test buck

to be difficult; therefore, a more accurate and faster user interface was developed using a short Python code. Additionally, the pilot participants expressed a need for dividers around the PVT zone so that reflections of other movement within the lab on the display would not be distracting.

Experimental Trials (for each participant) is as follows:

- Control
- A - Auditory Stimuli (Music) Only
- B - Auditory Stimuli + Visual Stimuli (Ambient Lighting)
- C - Auditory Stimuli + Visual Stimuli + Tactile Stimuli (Massage)

There are a few reasons why this particular set of therapy conditions was chosen. A control scenario was necessary to act as a baseline against which the other therapies could be compared. Therapies A to C were devised such that the level of sensory input increased step by step. Therapy A was kept audio-only rather than visual-only because, as noted earlier, visual stimuli occupy 60-70% of the human cognitive range (Xie et al., 2022) and could easily overpower the other senses, making it harder to notice their effects. Therapy B added visual stimuli to the audio, while leaving tactile out for now. This was because the seat vibration motors used for tactile input tend to produce a low-level buzzing noise that can interfere with the audio. For that reason, tactile stimuli were kept for the final condition, Therapy C, which combined all three sensory inputs. Interestingly, as seen from participant feedback later, there was considerable interest in a setup with only auditory and tactile stimuli.

The breakdown of flow of a single stressor-therapy pair is as follows:

The experimental procedure began with a baseline measurement phase, during which participants first completed a Psychomotor Vigilance Task (PVT) followed by a questionnaire.

Next, an arousal induction stage was carried out. Participants engaged in a driving simulation activity designed to elevate arousal levels (Johnson et al., 2011). Electrodermal activity and pulse rate were measured during this stage to confirm the increase in arousal (Daviaux et al., 2019).

Following the arousal induction, post-arousal measurements were taken. This included another round of the PVT and the same questionnaire administered earlier, allowing for a direct comparison with baseline values.

Participants then underwent the relaxation intervention according to their assigned trial condition - Control, Therapy A, Therapy B, or Therapy C. Throughout this stage, relevant physiological data were recorded, and an alertness test was conducted after both the stressor session and the relaxation program.

Finally, the experiment concluded with the final measurement phase. This consisted of one last PVT and the completion of the questionnaire, ensuring a consistent dataset across all stages of the study.

A visual flowchart has been provided in Appendix D for ease of understanding this sequence of events. For a more detailed, step-by-step experimental protocol, refer to Appendix E.

Participant Recruitment

GPower Analysis

The number of participants required for the experiment was determined by a GPower analysis (GPower, 2025). It indicated that, for a within-subject experiment using a two-tailed setup (with α set at 0.025), a sample size of 33 participants is needed to detect large effects (effect size dz = 0.8) with a power (1-β error probability) of 0.98 (Figure 16).

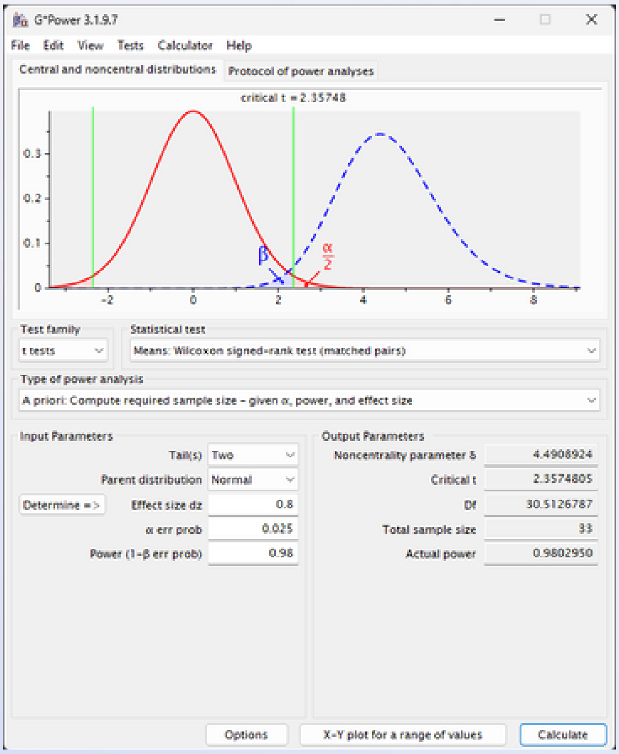


Fig 16: *GPower analysis window for the given analysis recommends 33 subjects or more*

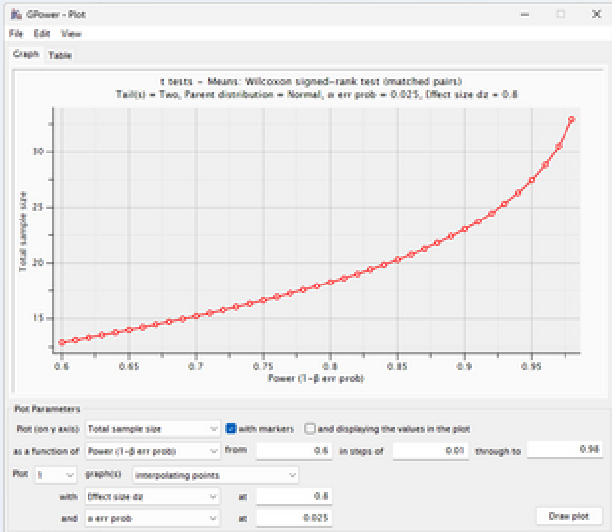


Fig 17: *GPower plot between sample size and statistical power (1-β error probability)*

In order to account for order biases in data acquisition and participants' perception of the four therapy conditions, a Latin Square arrangement was devised to randomise the order of therapy scenarios each participant experienced, as illustrated in Appendix A. This ensured that successive participants did not follow the same progression of therapy conditions across their two sessions.

Participant Profile

Participants were recruited through physical posters (see Appendix H) placed around the TU Delft university campus, as well as through application links shared in public WhatsApp groups. Among the applicants, viable candidates for the experiment were selected based on the client's target demography, with priority given to European participants.

In accordance with the automotive client's request, participants were intentionally selected to reflect a predominantly European demographic in terms of regional background. The largest group came from Western Europe (13 participants), followed by Eastern and Southern Europe (8 each), South/Southeast Asia (3), and Northern Europe (1) (see figure 18).

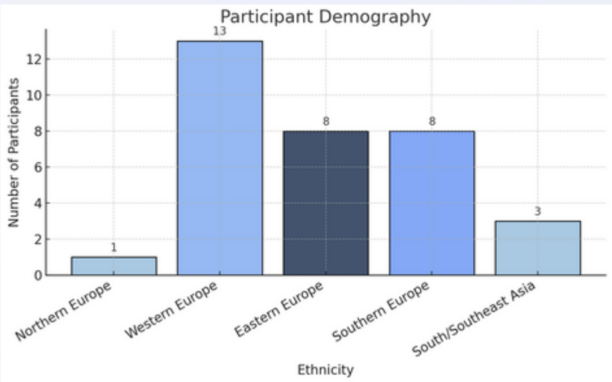


Fig 18: Participant distribution by ethinicity

The participant sample in this experiment consisted of a relatively balanced group in terms of gender, with 54.5% male and 45.5% female subjects. This near-even split ensures that the findings are not likely to be skewed due to gender imbalance, although gender itself is not a focus of this analysis.

In terms of body composition, most participants had a Body Mass Index (BMI) within the normal range. Specifically, 83.9% were classified as normal weight,

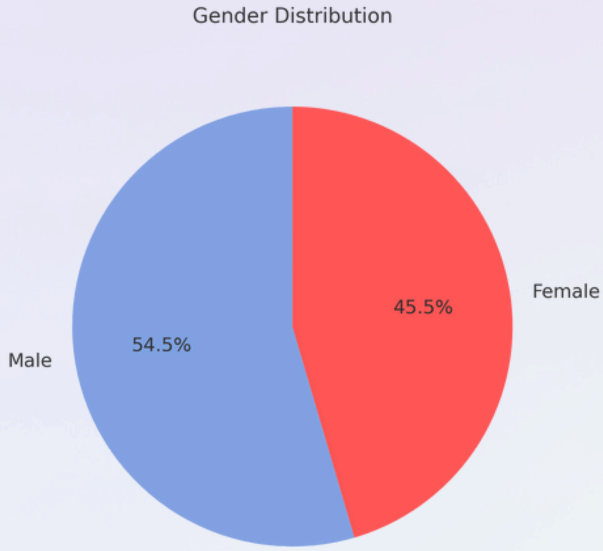


Fig 19: Pie-chart showing an almost equal gender distribution within the sample space

while 12.9% fell into the pre-obese category, and only 3.2% were considered obese. This indicates that the sample generally reflects a healthy adult population, minimizing the potential influence of weight-related health factors on the results.

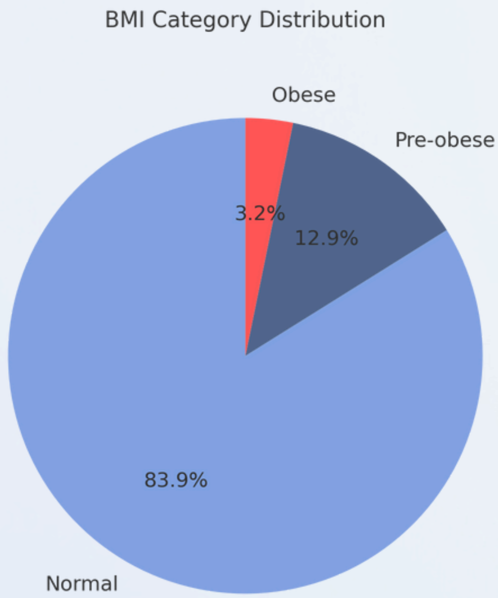


Fig 20: Pie-chart showing BMI distribution

Body measurements showed a natural correlation between height and weight across the sample. Participants ranged from approximately 1500 mm to 1900 mm in stature, with corresponding body weights from around 50 kg to over 100 kg. This spread supports a reasonable anthropometric diversity, which is beneficial for studies that may relate to comfort, perception, or physiological responses.

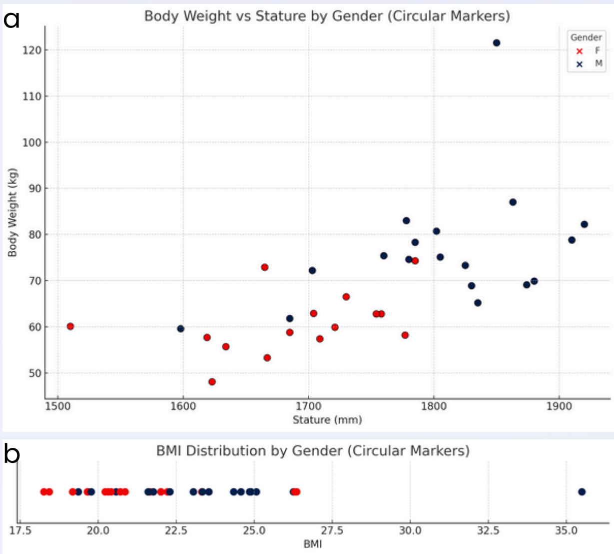


Fig 21: (a) Body Weight versus Stature shows a uniformly distributed population
(b) BMI distribution by gender shows a lesser average BMI for women compared to men

The participants ranged in age from 19 to 29 years, with a mean of 23.5 years and a standard deviation of 2.5, indicating a youthful and relatively homogeneous sample. Among the 33 participants, 75.8% held a valid driving license, with an average driving experience of 3.4 years - suggesting moderate familiarity with

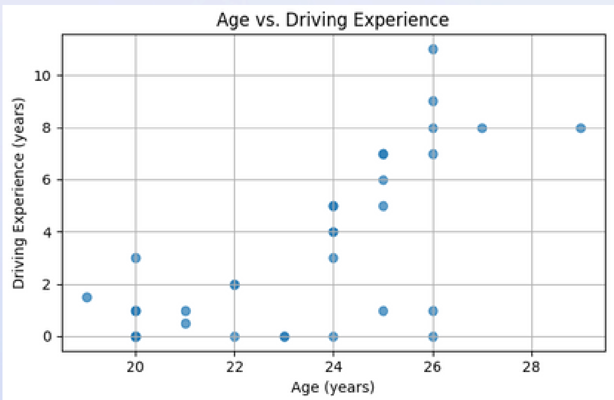


Fig 22: Participant age versus driving experience shows a linear upward trend

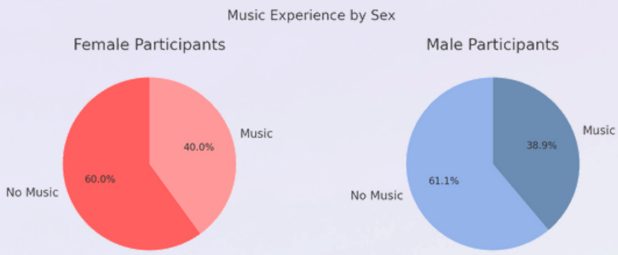


Fig 23: Pie-charts of music experience categorised between genders

vehicle operation. Moreover, 84.8% were right-handed, 9.1% left-handed, and 6.1% ambidextrous, reflecting a predominantly right-dominant sample. Additionally, 39.4% reported experience with music-related activities such as playing instruments or singing.

Data Analysis

Comparing the data collected after high arousal and post-relaxation therapy will enable us to assess the statistical significance of the therapy's effect on participant relaxation. Differences between trials with combined stimuli will be analyzed based on the various recorded physiological parameters.

The Empatica Embrace Plus collects data at a sampling rate of 64 Hz, but the physiological marker data is logged only once per minute. Given that the stimulating task and each experimental trial (Control, A, B, C) last 20 minutes, we obtain physiological readings at time points t0,..., t19 per activity.

With 33 participants, each experiencing all four scenarios, the dataset for each participant can be represented as a 4 × 20 matrix. Extending this across all

Participant	Sex	Therapy	Time	Reading
1	M	Con	t0	X(1,1)
1	M	Con	t1	
...	...	...	...	...
1	M	A	t0	X(1,21)
1	M	A	t1	X(1,22)
...		...	...	...
1	M	C	t19	X(1,80)
2	F	Con	t0	X(2,1)
...		...	...	...
33	F	C	t14	X(33,80)

Fig 24: Sample representation of raw data from the EmbracePlus in a matrix

participants results in a three-dimensional 4 × 20 × 33 matrix, containing a total of 2640 elements.

Since, at present, the stimulus response varies between participants and even within individual trials (as only the stimuli are predetermined, not the response), a potential approach could be to average the heart rate response for each participant across the four trials. The measured data for each scenario can then be represented relative to this averaged stimulus data.

Each scenario lasts 20 minutes, with the Empatica polling at one reading per second. Let Con, A, B, C represent the four scenarios, and let the measured reading at any given time be one of Heart Rate Variability (HRV), Electrodermal Activity (EDA), or Skin Temperature (ST). These measurements are represented by X(i, j), where i denotes the participant ID and j represents the consolidated temporal datapoint (see figure 24).

The dataset includes 3 factors - Participant, Therapy, and Time. Each of the 33 participants undergoes four paired sessions, each consisting of a stressor followed by a corresponding therapy session. From both the stressor and therapy phases of each pair, the first five minutes (start) and the last five minutes (end) of physiological data are extracted, resulting in 10 rows per session. Therefore, the factor Time is recorded at 10 total points.

In order to assess whether different therapy conditions produced distinguishable effects on physiological responses, a One-Way Independent Measures ANOVA was employed to compare data across the participant population.

Although the broader experimental design was within-subjects, this specific analysis treated the four therapy conditions (Control, Therapy A, Therapy B, Therapy C) as independent groups, with measurements standardized (via z-scores) and aggregated across participants.

This approach allows for a simplified comparison of group-level differences between therapy conditions using a single-factor model:

$$X_i = \mu + A_i + \varepsilon_i$$

where:

- X_i = observation from therapy condition i
- μ = grand mean across all conditions
- A_i = effect of therapy condition i
- ε_i = residual error for group i

The null hypothesis (H_0) posits that all therapy groups come from the same population:

$$H_0: \mu_{Control} = \mu_A = \mu_B = \mu_C$$

The One-Way Independent Measures ANOVA tests whether there also exists a significantly large between-group variance, which is of importance for this study.

ANOVA is chosen over a t-test due to the presence of multiple groups (or factors) in the dataset. Unlike a t-test, which compares only two groups at a time, ANOVA allows us to analyze all four factors simultaneously using a single F-statistic. Performing multiple t-tests instead would lead to the compounding of Type I errors, increasing the likelihood of false positive correlations between groups.

Considering the possibility that the

distribution of any of the groups is not normal, the Kruskal-Wallis H-Test, a non parametric alternative to the one-way ANOVA, is also used.

The Kruskal-Wallis H-Test compares multiple groups at a time, and compares the rank order of one group's distribution with another rather than actual values. Therefore it is not sensitive to normality of the data.

In order to pinpoint exactly which therapies differ from each other after determining significant difference somewhere either through One-Way ANOVA or Kruskal-Wallis H-Test, either Welch's pairwise t-Test (assuming normally distributed data) or Mann-Whitney U Test (aka Wilcoxon Rank-Sum Test) which is a non parametric alternative.

Welch's pairwise t-Test is used over the standard t-Test because it is robust and doesn't assume equal variance between the groups compared (often the case with human physiological data).

The Mann-Whitney U Test is a non parametric alternative to the pairwise t-test, which also compares two independent groups without assuming normal distribution. Similar to the Kruskal-Wallis H-Test, it is also based on rank ordering of values, rather than means, making it useful for confirming whether the results from the Welch's t-test holds even if the data is slightly skewed and not normal.

Z-Score is a way to normalise the data points of each activity subset so that comparison between the therapies is performed at a common scale. Since all Z-scores are relative to the entire experiment's population mean and variance, this method is great for group-level interpretations of effect size and direction. The global z-scores are calculated using the time window method of data aggregation.

$$Z = (X - \mu_{global}) / \sigma_{global}$$

where:

- X = observed value from specific activity (averaged over 33 participants at a particular minute)
- μ_{global} = global mean of all physiological marker values across all stressors & therapies
- σ_{global} = global standard deviation of that dataset

Each activity is divided into a start time window and an end time window, each lasting 5 minutes. Since data points are sampled at one per minute, there are 5 start rows and 5 end rows in the physiological data matrix per activity for a single participant, resulting in 10 rows.

For each stressor-therapy pair, this yields 20 rows: 10 from the stressor and 10 from the corresponding therapy. Across all participants, this results in 660 rows per therapy condition (33 participants × 20 rows).

To prepare the data for analysis, rows corresponding to the same temporal position across participants are averaged. That is, all first rows across participants are averaged into a single mean row, followed by all second rows, and so on, producing 20 averaged rows per therapy condition.

This process is repeated for all four therapy types - Therapy A, Therapy B, Therapy C, and Control - yielding a total of 80 averaged rows (4 therapy conditions × 20 rows each) for statistical comparison.

Each participant undergoes two sessions. Within each session, there are two relaxation therapy sessions, meaning that each participant experiences a total of four therapies.

Each relaxation therapy lasts 20 minutes and is preceded by a 15-minute stressor (such as a driving simulator or other stimuli) and a 5-minute Psychomotor Vigilance Task (PVT) (Reifman et al., 2018). Following the therapy, participants also complete another 5-minute PVT to assess post-intervention effects.

Two Empatica EmbracePlus watches, designated E1 and E2, will be worn by participants for physiological data acquisition. Throughout the experiment, the experimenter will manually document the timing of each activity in an Excel file. For example, the Excel file structure could be as seen in figure 25.

To ensure repeatability, participants will undergo the therapies in a randomized order, meaning the sequence of therapies (Con, A, B, and C) will vary for each participant. The planned arrangement is outlined in Table 1 (refer Appendix A).

The raw data from the Empatica EmbracePlus wearable is recorded in a .csv (comma-separated values) file with the following format:

timestamp_unix, timestamp_iso, participant_full_id, pulse_rate_bpm, missing_value_reason

Since data is collected using either device E1 or device E2, the participant_full_id remains constant across all participants, making it redundant for analysis. Instead, each participant's data will be identified using timestamp information from the manually documented Excel log.

- The Empatica device with serial number 3YK3J151LD is designated as E1.
- The Empatica device with serial number 3YK3H151FM is designated as E2.

The folder containing the raw data from these devices will be named according to the corresponding serial number, ensuring clear identification of the measurement source.

participant_no	sex	device	date (yyyy-mm-dd)	start_time (hh:mm:ss)	end_time (hh:mm:ss)	activity_type
1	M	E1	Jun 1, 20...	09:55:00	10:10:00	Stressor 1
1	M	E1	Jun 1, 20...	10:10:00	10:15:00	PVT 1
1	M	E1	Jun 1, 20...	10:20:00	10:35:00	Therapy 1
...			...	...	...	...
1	M	E2	Jun 2, 2...	09:55:00	10:10:00	Therapy 3
...			...	...	...	...
33	F	E2	Jun 30, ...	11:10:00	11:25:00	Therapy 4

Fig 25: Sample structure of the manual activity timestamp log maintained for each subject

In this experiment:

- The independent factor is the type of activity (e.g., stressor test, PVT, therapy).
- The dependent variable is the measured physiological parameter (pulse_rate_bpm in this case).

To process the data:

- Trim the raw .csv data by aligning it with the corresponding time slots from the excel file.
- Note that raw data is recorded in UTC, while manual logs are in CEST (i.e. UTC+2). This has to be accounted for while slicing data.
- Append and consolidate the cleaned data into a single sliced file.
- Perform a Mixed-Design Repeated Measures ANOVA to analyze relationships between different experimental factors and physiological responses.

At the end of this activity, a total of five different file outputs are obtained, each containing the sliced raw data of electrodermal activity, pulse rate, and skin temperature for a participant's stressor and therapy sessions.

Since the order of therapy sessions (one to four) varies per participant according to the Latin Square pattern described in table1.xlsx, the generic labels Therapy 1, Therapy 2, Therapy 3, and Therapy 4 are renamed to their corresponding actual therapy conditions - Therapy A, Therapy B, Therapy C, and Con (Control) - for each participant.

However, another dilemma arises: each therapy session is always paired with a preceding stressor activity (still labeled as Stressor 1 to Stressor 4), so the data files must include information that links each stressor to its corresponding therapy session. To address this, a new column named pair_id is introduced. This pair_id encodes both the participant number and the therapy number, ensuring that the correct stressor-therapy pairs can be referenced accurately.

Pair ID	Participant No.	Activity Type	Timestamp	Reading
P001-T1	1	Con	t0	X(1,1)
P001-T1	1	Con	t1	
...	...	...	...	...
P033-T4	33	C	t0	X(33,1)
...	...	...	...	...

Fig 26: Corrected sliced data file structure of a physiological marker used for further analyses

Results and Discussion

Inferences of Study

This section consolidates the observations from the results and proposes probable interpretations in the context of comparing the four therapy conditions (Audio-only, Audio + Visual, Audio + Visual + Vibration, and Control). For detailed results and data visualisations, refer to the Appendix.

Physiological Markers

Physiological markers such as Electrodermal Activity (EDA), Pulse Rate, and Skin Temperature were analysed statistically under three configurations. The first configuration used the full raw data, i.e., all data points from the sliced data file for each therapy session. To narrow the scope of observation and provide distinct comparison points, time-windowed data - using the first and last five-minute windows of each therapy session - was also used, as described in the previous Data Analysis section. Thirdly, to reduce the effects of random factors and ensure a uniform baseline for comparison of the four therapies, z-score data based on the above time-window data was used.

As discussed in the Data Analysis section, the techniques deployed for statistical analysis included a combination of One-Way ANOVA/Kruskal-Wallis H-tests, Pairwise Welch's t-tests, and Mann-Whitney U tests (i.e., Wilcoxon rank-sum tests). Both parametric and non-parametric comparisons were applied to eliminate the possibility of incorrect interpretations arising from the assumption of normal distribution in the data.

Despite performing various types of statistical analyses, no statistically significant differences were observed between the four therapies. This result was consistent across all three data configurations. In each case, the p-values were well above the 0.05 threshold - often even exceeding 0.90 - indicating that none of the therapies produced a strong enough physiological change to differentiate itself from the control scenario in a statistically meaningful way.

One pattern, however, appeared repeatedly: EDA values across all data configurations showed a consistent, though still non-significant, difference between Audio + Visual stimuli and Audio + Visual + Vibration, with p-values hovering around 0.058. While not low enough to be considered statistically significant, this might suggest that Therapy B had a slightly better relaxatory effect on sympathetic arousal compared to Therapy C. Alternatively, this could be due to random variation in the data, and is therefore not conclusive.

Overall, the results suggest that all three therapy conditions performed similarly to the control, with no therapy condition emerging as a clear outperformer. Any subtle effects may become evident with a larger sample size.

PVT Reaction Time

Reaction times (RT) of participants were measured across ten Psychomotor Vigilance Task (PVT) trials performed before and after every stressor or therapy activity. For this analysis, delta values - calculated as the value at the end of an activity minus the value at the start of the same activity - were used instead of absolute measures. This approach was chosen to introduce uniformity and account for individual baseline variability, while also directly reflecting the magnitude of the effect of the stressor or therapy.

When comparing Δ Median RT values in the post-stressor phase, the medians were close to 0 ms, indicating negligible change in RT. However, there was a slight positive shift, representing an increase in RT. This suggests that after performing a strenuous task, participants may be in a fatigued state, leading to slower reaction times.

In the post-therapy phase, Δ Median RT values were positive for Therapy B and Therapy C, indicating higher (slower) reaction times after therapy - possibly due to participants remaining in a passive state. Therapy A, the auditory-only condition, showed the lowest median increase, making it the most balanced in stabilising median reaction times.

For Δ Mean RT values in the stressor phase, medians again remained close to 0 ms, with a slight positive shift consistent with the intended design of the stressor.

In the therapy phase, the first signs of differentiation appeared. Control and Therapy A showed a slight decrease in median RT, indicating improved mean RT values, while Therapy B and Therapy C still showed higher positive medians. This


(Source: BMW Pressclub Global)

Fig 27: Vibrant visuals and audio within the new BMW 7 series Artist Mode increase for Therapies B and C suggests that reaction times worsened (slowed) post-therapy, possibly due to certain elements of these conditions disrupting participant alertness. From this analysis, Control and Therapy A appear to slightly improve mean RTs.

Median values for all Δ Maximum RT results were very close to zero, indicating no clear advantage in reducing the longest reaction time delays. However, Therapy C displayed a tighter spread of values with fewer outliers, which may imply consistency.

Whereas, Δ Minimum RT appeared least affected by either the stressor or therapy. The fastest reaction times may be an inherent individual quality, with no therapy condition showing a distinct central tendency.

Overall, Therapy A (auditory stimuli only) may have a slight advantage in stabilising both mean and median reaction times. Therapies B and C displayed greater variance and occasional slowdowns in RT post-therapy, suggesting they may be less effective at enhancing attentiveness in the intended use case of such a program.

MoSAQ Questionnaire

Sensory Rating

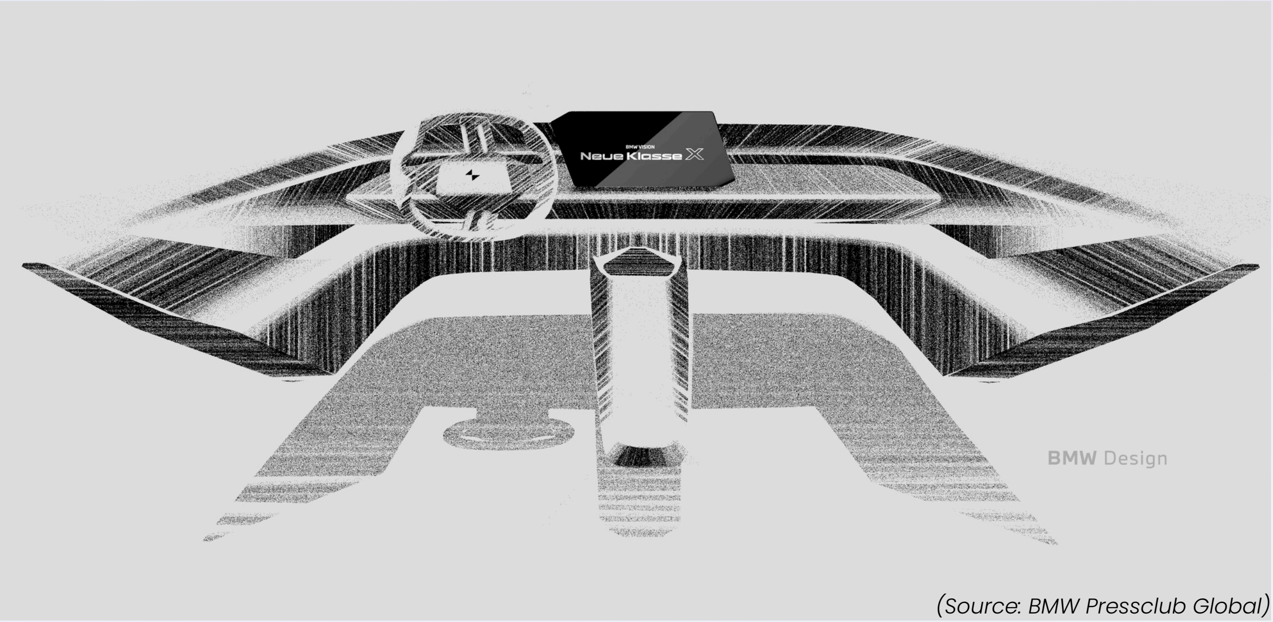
Therapy B was the only condition that consistently shifted emotional valence from negative to positive after therapy, indicating a clear improvement in mood. This aligned with its reductions in stress and higher comfort ratings. Therapies A and C showed more variable or neutral changes, suggesting they may influence physiological responses without strongly altering emotional tone.

Arousal levels declined in all therapies, but the drop was steepest and most consistent in Therapy B, followed by Therapy C. This pattern suggests that Therapy B was most effective in downregulating heightened alertness and promoting a parasympathetic-dominant state ideal for post-performance recovery. Therapy A showed only a mild decline, indicating a gentler calming effect.

Presence levels decreased most in Therapies B and C. While this might appear to signal disengagement, it could instead reflect a shift toward internal focus and reduced environmental

(Source: Rolls Royce Pressclub Global)

Fig 28: Rolls Royce The Starlight Headliner looks to emulate a starry night sky



(Source: BMW Pressclub Global)

Fig 29: Sketch of the Neue Klasse interior shows a minimalistic design approach

scanning — consistent with a relaxed state. In Therapy B, this pattern may indicate a meditative form of absorption, whereas in Therapy C it could point to detachment or overstimulation. Therapy A maintained a steadier presence, balancing engagement with ease.

Across sensory dimensions, Therapy B reduced distraction, emotional salience, and temporal distortion more consistently than the others, indicating a stabilizing influence on perception. It also produced the largest gains in cognitive clarity, autonomy perception, and focused state. Therapy C showed mixed results, with improvements in some measures but variability and occasional increases in sensory intensity or alertness, hinting at overstimulation. Therapy A generally improved relaxation, alertness, and immersion, but with more moderate effects.

The Control condition produced no meaningful changes in any of the ten sensory variables, reinforcing the role of multisensory input in post-stressor recovery. Overall, Therapy B demonstrated the most consistent and restorative effects, combining reductions in stress, arousal, and distraction with improvements in mood, clarity, and focus.

Comfort Rating

Therapy B produced the strongest comfort recovery, showing a marked improvement from post-stressor levels to well above the pre-stressor baseline. This improvement clearly outpaced all other conditions. Therapy A provided moderate recovery, while Therapy C showed little change and appeared to plateau. The Control group improved slightly, suggesting some natural recovery without intervention, but it remained less effective than any therapy condition.

Fatigue increased across all phases in every group, but Therapy B had the smallest rise, suggesting better energy preservation despite experimental demands. Therapy C produced the highest post-therapy fatigue, possibly reflecting overstimulation or limited recuperative capacity. Control and Therapy A followed similar moderate trajectories.

Stress ratings peaked after the stressor, as expected. Therapy B achieved the sharpest reduction, lowering stress to below pre-stressor levels. Therapy C offered moderate relief, while Therapy A and Control showed smaller declines, with Control remaining relatively elevated.

Thermal ratings indicate that Therapy B provided the most balanced redistribution of warmth after stress. It restored moderate warmth to the limbs, which are often cooler during stress responses, without causing excessive heat in the buttocks, back, or thighs. This suggests a return to a physiological baseline without discomfort. Therapy C consistently increased warmth in core seating areas, which could contribute to fatigue or sensory overload. Therapy A produced mild warming in the extremities and remained neutral in core areas, indicating moderate recovery without thermal strain.

Overall, Therapy B supported the most effective post-stressor comfort restoration, combining improved subjective ratings with balanced physiological recovery patterns.

Discomfort Rating

Discomfort peaked uniformly after the stressor in all groups, confirming effective stress induction. Therapy B produced the largest reduction post-therapy, lowering discomfort to well below pre-stressor levels. Therapy A and Control produced only slight improvements, while Therapy C showed minimal change, leaving participants with the highest residual discomfort.

Local discomfort data showed that Therapy B reduced strain across most body regions, particularly the lower back, shoulders, upper arms, and thighs — areas commonly affected in seated conditions. These results suggest effective physical relief, possibly from reduced muscle tension or decreased sensory

(Source: BMW Pressclub Global)

Fig 30: Interior of the BMW M4, showing the contoured bucket seats

distraction. Therapy A offered modest relief in areas like the lower arms and upper back. Therapy C often maintained or increased discomfort in the mid back, neck, and thighs, potentially due to overstimulation, postural rigidity, or heat buildup.

The Control condition displayed minimal improvement across all regions, reinforcing that passive seated recovery without stimuli is insufficient for relieving postural strain.

Reported discomfort sources included bucket seats, headphone pressure, and sleep masks with or without LED goggles. The process of entering and exiting the compact cabin likely added strain, especially to the lower back, neck, and thighs. In Control and Therapy C, either the absence of stimuli or overstimulation may have prevented these effects from being counteracted. In contrast, Therapy B's balanced sensory input seemed to ease these constraints, lowering both overall and specific areas of discomfort.

Post Session Reflection

The rankings of therapy conditions from the previous subsection show a clear tilt in favour of multi-modal sensory experiences, especially those that include auditory and tactile elements.

Overstimulation due to visual stimuli in therapy conditions B and C resulted in a few participants independently suggesting that removing the visual stimulus from Therapy C - leaving only synchronised audio and seat vibrations - would offer an ideal experience which still is immersive and relaxatory without becoming overwhelming.

This indicates a crucial possibility of refinement - the medium in which the light module delivers visual stimuli may need to be redesigned or removed. Since visual cognition occupies a lion's share of a human's perception (Xie et al., 2022), better brightness control or adaptive personalization based on each individual user's sensitivity could be viable areas of interest.

Participant reflections also suggest overall support for better customization - vibration intensity, audio volume, and LED brightness were all cited as parameters they'd want to adjust. There's a case for developing a responsive system too, one which adapts to the user's state in real-time or collects preferential or habitual data in advance, like a learning feedback loop. Other constructive suggestions included presets for "soothing", "energizing", or "neutral" modes.

While some participants loved the full-body immersion, others described the same sessions as "overstimulating", "confusing", or "too much input". Whether that was caused by the visual sensory component, or due to the tonal whiplash of performing a stressor in quick succession of a therapy session - intended by the design of the experiment - remains to be seen in further experimentation with larger sample sizes. But current takeaways highlight a need for a personalizable therapy configuration inside the automotive cabin.

Some participants felt that relaxation sessions helped them perform better in the stressor tasks due to a relatively calmer state of mind. Interestingly, contrary to expectation, many found it easier to focus during the therapy sessions than during the stressor phase.

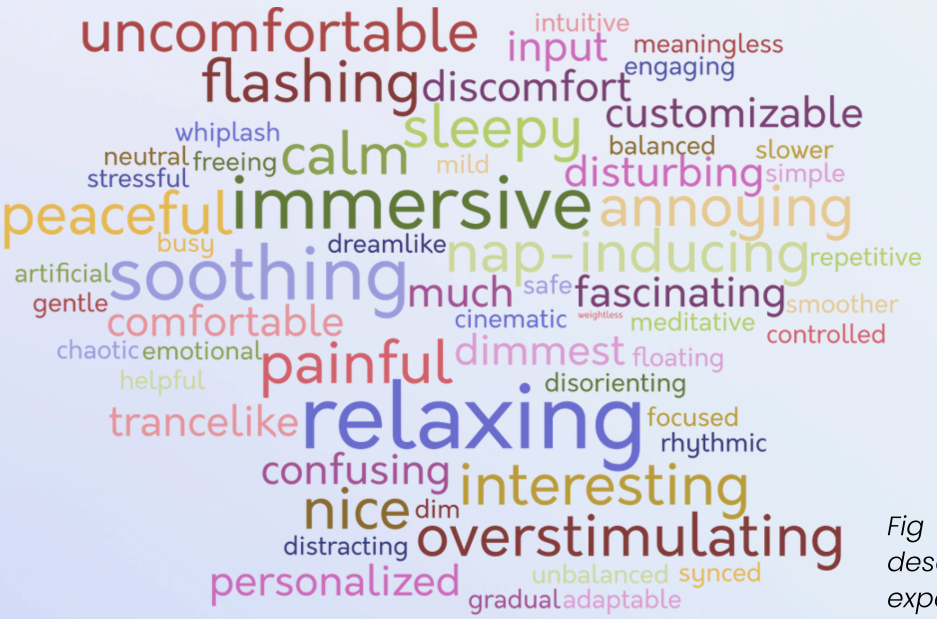


Fig 31: A word cloud with descriptor words used by the experiment participants

Limitations of Study

Several factors limit the scope and interpretation of this study. Some participants reported feeling disoriented immediately after therapy sessions, especially when required to transition directly to subsequent tasks. While this could be an intentional effect of entering a deeply relaxed state, it raises the question of whether a brief recovery period should be incorporated, or whether the therapy itself requires adjustment to support smoother re-engagement.

Although skeletal tracking and infrared thermal imaging data were collected, these were not processed within the scope of this report due to the extensive computational resources required. Incorporating these datasets in future analyses could provide richer insights into posture dynamics and detailed thermal responses during therapy.

A further limitation lies in the interpretation of the objective physiological data. The chosen biomarkers - electrodermal activity, pulse rate, and skin temperature - were analysed using aggregated measures across relatively short time windows, which may have masked more transient or subtle responses to the therapies. Additionally, wrist-worn devices such as the Empatica EmbracePlus are inherently prone to motion artefacts and contact variability, potentially reducing signal fidelity. While these measures were selected to minimise participant intrusion, this trade-off may have reduced the sensitivity of the analysis in detecting small but meaningful changes.

The delivery of visual stimuli via a fitted sleep mask also emerged as a discomfort source for many participants. This suggests a need to rethink how visual elements are integrated, possibly through more ergonomic designs or alternative ambient delivery methods. Environmental factors presented another limitation; as the sessions were conducted under varying seasonal conditions, with some days hot and others cold and rainy, the absence of controlled ambient temperature may have influenced both thermal comfort ratings and physiological measures.

The psychomotor vigilance task, used to assess cognitive performance, was a standard five-minute mouse-clicking exercise. While reliable, several participants found it monotonous and disengaging. More interactive approaches, such as using physical targets or tactile response mechanisms, could help maintain attention while preserving measurement accuracy.

The sensory programme itself also faced design constraints. Light pulses in the goggles were not synchronised with the accompanying audio and vibration patterns, creating a jarring rather than cohesive sensory experience for some users. Synchronisation of these elements could enhance immersion and comfort. The participant sample was predominantly drawn from the client's target demographic, with few individuals at the extreme ends of height and weight. While this aligns with the intended market, it limits the generalisability of findings to a broader anthropometric spectrum.

Finally, the driving simulator stressor may not have consistently triggered sympathetic arousal, with some participants responding more in a parasympathetic manner. A stressor capable of reliably inducing a comparable stress baseline across participants would improve the robustness of subsequent therapy evaluations (details in Appendix B).

Conclusion

This study examined the effects of four therapy program conditions on participants' physiological and mental states within an automotive cabin setting. Physiological markers showed no statistically significant differences between conditions, though subtle patterns suggested Therapy B may have had a slightly greater calming influence.

Cognitive performance, measured through psychomotor vigilance tasks, indicated that Therapy A best supported attentional stability, with minimal changes in reaction times post-therapy. In contrast, Therapies B and C produced slight slowdowns, likely reflecting deeper relaxation or reduced sensory engagement.

Subjective sensory ratings consistently favored Therapy B. Participants reported the most positive shifts in mood, the greatest reductions in arousal, and improvements in perceptual clarity. It also reduced sensory distraction and emotional intensity. Therapy A showed moderate benefits and maintained attentional presence, while Therapy C, despite providing full-body immersion, yielded mixed outcomes and occasional signs of overstimulation or fatigue.

Comfort and thermal ratings again pointed to Therapy B as the most balanced, promoting relaxation without overheating or sensory saturation. Discomfort, both general and region-specific, improved most under this condition. Although some participants initially experienced visual overstimulation, many adapted over time and responded positively to the overall sensory profile.

In summary, Therapy B offers the strongest option when emotional and sensory relaxation are the primary goals, while Therapy A is better suited for preserving cognitive focus. Therapy C provided immersive depth but was less consistent across both subjective and objective measures.

Fig 32: A three-quarter angle view of the front facade of the test buck

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Appendix

Appendix A

Latin Square

participant_no	Therapy 1	Therapy 2	Therapy 3	Therapy 4		
1	Therapy A	Therapy B	Therapy C	Con		
2	Con	Therapy A	Therapy B	Therapy C		
3	Therapy C	Con	Therapy A	Therapy B		
4	Therapy B	Therapy C	Con	Therapy A		
5	Therapy A	Therapy B	Therapy C	Con		
6	Con	Therapy A	Therapy B	Therapy C	■	Session 1
7	Therapy C	Con	Therapy A	Therapy B	■	Session 2
8	Therapy B	Therapy C	Con	Therapy A		
9	Therapy A	Therapy B	Therapy C	Con		
10	Con	Therapy A	Therapy B	Therapy C		
11	Therapy C	Con	Therapy A	Therapy B		
12	Therapy B	Therapy C	Con	Therapy A		
13	Therapy A	Therapy B	Therapy C	Con		
14	Con	Therapy A	Therapy B	Therapy C		
15	Therapy C	Con	Therapy A	Therapy B		
16	Therapy B	Therapy C	Con	Therapy A		
17	Therapy A	Therapy B	Therapy C	Con		
18	Con	Therapy A	Therapy B	Therapy C		
19	Therapy C	Con	Therapy A	Therapy B		
20	Therapy B	Therapy C	Con	Therapy A		
21	Therapy A	Therapy B	Therapy C	Con		
22	Con	Therapy A	Therapy B	Therapy C		
23	Therapy C	Con	Therapy A	Therapy B		
24	Therapy B	Therapy C	Con	Therapy A		
25	Therapy A	Therapy B	Therapy C	Con		
26	Con	Therapy A	Therapy B	Therapy C		
27	Therapy C	Con	Therapy A	Therapy B		
28	Therapy B	Therapy C	Con	Therapy A		
29	Therapy A	Therapy B	Therapy C	Con		
30	Con	Therapy A	Therapy B	Therapy C		
31	Therapy C	Con	Therapy A	Therapy B		
32	Therapy B	Therapy C	Con	Therapy A		
33	Therapy A	Therapy B	Therapy C	Con		
34	Con	Therapy A	Therapy B	Therapy C		
35	Therapy C	Con	Therapy A	Therapy B		
36	Therapy B	Therapy C	Con	Therapy A		
37	Therapy A	Therapy B	Therapy C	Con		
38	Con	Therapy A	Therapy B	Therapy C		
39	Therapy C	Con	Therapy A	Therapy B		
40	Therapy B	Therapy C	Con	Therapy A		
41	Therapy A	Therapy B	Therapy C	Con		
42	Con	Therapy A	Therapy B	Therapy C		
43	Therapy C	Con	Therapy A	Therapy B		
44	Therapy B	Therapy C	Con	Therapy A		
45	Therapy A	Therapy B	Therapy C	Con		
46	Con	Therapy A	Therapy B	Therapy C		
47	Therapy C	Con	Therapy A	Therapy B		
48	Therapy B	Therapy C	Con	Therapy A		
49	Therapy A	Therapy B	Therapy C	Con		
50	Con	Therapy A	Therapy B	Therapy C		
51	Therapy C	Con	Therapy A	Therapy B		
52	Therapy B	Therapy C	Con	Therapy A		
53	Therapy A	Therapy B	Therapy C	Con		
54	Con	Therapy A	Therapy B	Therapy C		

Fig 33: Latin Square counterbalancing order for participant therapy conditions.

Appendix B

Stressor Design

To prepare participants for the relaxation therapy sessions, the experimental design requires them to first be brought to a heightened physiological and psychological state. A pre-therapy activity is therefore introduced as a deliberate stressor. Initially, a 15-minute driving simulator using a steering wheel and pedal setup was chosen. Not only does this method align well with the real-world application context of the therapy, but it also provides an immersive and sufficiently engaging task to elevate participant stress levels.

However, two critical limitations arise - predictability and repeatability.

While simulated driving has indeed been shown to raise stress indicators (Kruithof et al., 2020), participant responses vary widely. Variables such as driving experience, familiarity with simulation environments, and even motion sickness susceptibility introduce inconsistencies in the induced stress levels. This variance, in turn, limits the interpretative clarity of the post-therapy data. Though contextually relevant, the simulator's uncontrolled factors compromise its reliability as a uniform stressor - at least in its current form. Refinement and thoughtful task design, however, could help mitigate these issues.

The second concern is repeatability within a single session. When exposed to the same simulated driving environment over multiple trials, participants begin to habituate - resulting in a decline in stress responses over time. Prior studies have reported a decrease in HRV between successive trials, confirming this effect. As the stressor's potency diminishes, so too does the ability to meaningfully contrast pre- and post-intervention states. This poses a serious risk to the experiment's internal validity.

To address these concerns, the Cold Pressor Test (CPT) was evaluated as an alternative (Castellani & Young, 2016). While it theoretically offers consistent physiological stress marker output within a shorter duration, achieving the required test conditions proved unsuitable in the current testing environment (see Appendix C).

Given these constraints, the experiment reverts to the original stressor - the 15-minute driving simulation. Despite its flaws, it remains the most feasible

(Source: BMW Pressclub Global)

Fig 34: BMW M4 CS alloy wheels in bronze solution, providing immersive engagement, fitting naturally into the experimental flow, and maintaining high relevance to real-world applications of post-stress relaxation therapy.

However, the simulator setup itself has undergone substantial refinement. The earlier version, which used a timed delivery mission in Euro Truck Simulator 2, did yield elevated stress initially - but participants quickly adapted, resulting in diminished stress responses in repeated trials. The updated design instead implements Assetto Corsa EVO, offering a structured 15-minute practice race session. Notably, the selected in-game car, a BMW M4 CSL (G82) closely mirrors the physical vehicle used in the actual relaxation test buck, creating a direct bridge between stress and therapy.

Tracks such as Brands Hatch (GP) and Laguna Seca (GP) were chosen for their sweet spot between accessibility and cognitive load. Their mix of wide straights and moderately technical corners make them challenging enough to stimulate stress while remaining manageable for drivers with varying skill levels. To maintain pressure, participants are asked to aim for clean laps - introducing a subtle yet effective layer of performance anxiety.

By improving immersion, reducing habituation, and tightly coupling the stressor to the context of the therapy, this new setup offers a more reliable and reproducible stress induction protocol - laying a more stable groundwork for evaluating the effectiveness of the multisensory relaxation intervention that follows.

(Source: BMW UK)

Fig 35: A BMW M4 driving on Brands Hatch

Appendix C

Cold Pressor Test

The Cold Pressor Test (CPT) involves immersing the non-dominant hand into near-freezing water (0–4 °C) and is extensively validated in literature as a reliable and standardised means of inducing acute stress (Castellani & Young, 2016). Compared to driving simulation, it offers shorter duration, greater reproducibility, and more consistent physiological output across subjects.

Fig 36: Equipment used for CPT

Experimental Protocol:

1. Ask the subject to put a pulse oximeter (Kruidvat FRO-104) on the index finger of their dominant hand. Turn on the device.
2. (Optional) Ask the participant to wear the Empatica EmbracePlus watch on the wrist of their dominant hand. Verify that the watch synchronises with the Care Portal.
3. Preparatory Steps
    a. Place two microfibre cloths on the table adjacent to each other.
    b. Place two metal bowls on top of the microfibre cloths.
    c. Fill water in an electric kettle (Royalstar YSH8088).
    d. Turn on the kettle using the On/Standby button.
    e. Navigate to number 8 (Keep Warm) in the menu options using the menu button, and set the temperature to 40 °C using the adjustment button.
    f. Transfer the water from the kettle to bowl A (left).
    g. Cool the water to 32 °C through natural convection. Monitor temperature using a K-Type Thermometer (RS 1319A).
    h. Add 500 g of ice cubes to bowl B (right).
    i. Add 1 L water at ambient temperature (~25 °C) to bowl B. Stir for 2-3 minutes.
    j. Immerse probe in water and monitor temperature using the K-Type thermometer.
    k. Once the water temperature reaches ~5 °C, begin the experiment.
4. Procedure
    a. Ask the subject to immerse their non-dominant hand into bowl A for one minute, with freedom to move fingers.
    b. Monitor the pulse rate and record after retraction.
    c. Ask the subject to retract their hand from bowl A and immerse it in bowl B.
    d. Set a mechanical kitchen timer (TFA Dostmann) to 3 minutes - maximum permissible immersion duration.
    e. The subject may withdraw their hand at any time if discomfort is felt.
    f. Monitor pulse rate changes and record after retraction.
5. Ask the subject to dry their hand using a microfibre cloth.
6. Remove the pulse oximeter (and Empatica watch, if used).

Since the CPT lasts only 3 minutes by design, the Empatica's sampling rate (one reading per minute) would yield only 3 readings - insufficient for conclusive testing. A pulse oximeter was therefore used for instantaneous pulse measurements.

Limitations in Implementation

Maintaining water temperature consistently below 4 °C was not viable with the available infrastructure. Prior research indicates that even small deviations above this threshold (e.g., 5 °C) significantly reduce test efficacy (Mitchell et al., 2004), which was reflected in the negligible and statistically insignificant pulse rate changes observed.

Additionally, the CPT requires pre-screening for cardiovascular conditions, Raynaud's syndrome, hypertension, epilepsy, and recent injuries - criteria that are neither rare nor easy to control for in a general university participant pool. Such screening would have drastically narrowed the sample size and complicated the study timeline.

Given these constraints, the CPT, despite its methodological strengths, was deemed impractical in this context.

Fig 37: (a) and (b) Testing the efficacy of the Cold Pressor Test using multiple participants

Appendix D

Experiment Flowchart

Session 2 follows the same activity flow, with different therapy programs and an initial step for recording participant anthropometric data.

Appendix E

Detailed Experiment Protocol

Participant Recruitment

- Send email to participants a week prior to provide information about the experiment sessions and to give them time to comprehend the information.
- The information email must contain the following:
  - The information_brochure.pdf contains general instructions for the test, and also a video tutorial for PC-PVT software.
  - Ask participants to not develop exercise induced muscle pain.
  - Ask participants to wear comfortable, but not layered clothing.
  - Ask participants to avoid wearing high heels. Shoes are preferred.
  - Ask participants to choose their preferred schedule of the sessions in schedule.xlsx.
  - Request information about the participant's banking name and IBAN for reimbursements after the experiments.
  - Provide participants with the consent_form.pdf.
  - Inform participants about data handling policy.
  - Ask participants to fill the preliminary self-assessment questionnaire participant_info.docx, which enquires about age, height, weight, driving licence status and music preference among other relevant info.
- Ensure that every participant has non conflicting slots in schedule.xlsx.
- Assign participant_no to each participant based on table_1.xlsx and ensure that participants paired according to similar relaxation therapy sessions.
- Consolidate information of the participants banking details and information received from participant_info.docx in participant_info.xlsx.

Preliminary Preparation

- The following list of documents are readied:
  - pre_questionnaire.docx for subject data self-reporting.
  - excel_log.xlsx for recording start- and end-time of each activity.
  - table1.xlsx (converted to table1.csv) containing every participant.
  - schedule.xlsx data corroborated with therapy sequence from table1.xlsx.
  - checklist_s1.docx and checklist_s2.docx for both sessions.
  - ant_data.xlsx with critical anthropometrics for all participants.
  - comfort-fatigue-discomfort questionnaire.docx.
  - pvt_log.xlsx for recording reaction times.
  - interview.docx for post-experimental feedback.
- Documents pre_questionnaire.docx, checklist_s1.docx, checklist_s2.docx, questionnaire.docx, interview.docx are prepared as physical copies for each subject.
- Skeletal tracking / facial recognition start-up instructions:
  - Switch on Computer A.
  - Run BMW.bat.
- Prepare anthropometric measurement tools.
  - Body Composition Monitor - OMRON BF-511.
  - Physical measurement platform.

    - Callipers.
- Preparation of the stressor setup
    - Ensure that the portable battery for the seat is fully charged to 100%.
    - Replace the disposable headphone cover with a new one.
    - Start Assetto Corsa EVO on Computer A before the arrival of participants.
    - Configure the Race Session
        - Go to: Single Player → Quick Race
        - Set up the session with the following parameters:
            - Race Duration: 15 minutes
            - Include Practice Session: Yes
            - Weather: Default or clear conditions
            - Circuit: Brands Hatch / Laguna Seca
    - Under Vehicle Setup → Electronics, set
        - TC1 (Traction Control 1): 8
    - Set Stability Control (ESC) to 80%.
- Start-Up of Test Buck
    - Switch on the main power outlet at the front, outside of the chassis.
    - Switch on all hardware devices inside:
        - Behringer audio interface (on passenger side)
        - Black box on top of the Behringer, responsible for the light (shows a green light once turned on)
        - Turn on ON/OFF switch on the back and front of the voltage device behind the laptop.
        - The switches on the middle console on the wooden board, which connect the light and the glasses.
    - Plug in the Sony headphones into the AUX outputs of the Behringer interface on the right side.
    - Replace the disposable headphone cover with a new one.
    - The right settings for the sessions are to be set on the Behringer interface:
        - Phones A/B (volume control): 30-40% (adjust if needed)
        - Main Out (vibration intensity control): 70% (adjust if needed)
    - Start the main laptop using the password provided.
    - Set the laptop at 100% volume and select outputs 1-10 (or output 1-2 if output 1-10 does not work)
- Setup of PC-PVT:
    - Open folder pc-pvt-bin-2.0.5.
    - Run PVT Manager.cmd
    - Under the Active Study option, create a new study with total trial time as 300 seconds.
    - Create a new subject for each participant. Exit window.

Start of Study

- Provide basic introduction to participants about the objective of the experiment.

Introduction

- Subject/s arrive at the lab - welcome the participant.
- Brief the participants about experiment research and protocol. Refer to script.docx.

    - Verify again for musculoskeletal disorders and visual sensitivity. Ensure that subjects are in accordance with the selection criteria.
    - Ensure that female subjects have their hair tied before commencement.
    - Ask the subject to use the provided skin wipe to clean the wrist region of their non-dominant hand. This helps hydrate the skin and removes any oils or creams from the surface.
    - Put on Empatica EmbracePlus watch on the corresponding location on the subject's wrist. Secure with a kinesiological elastic band for a snug fit.
    - Anthropometric Data Measurement:
        - Ask consent of the subject for making minimal physical contact during measurement.
        - Measure height of subject w/ and w/o shoes.
        - Measure body weight and body composition of subject w/o shoes.
        - Record data in ant_data.xlsx.
    - Ask the subject to read through the pre-questionnaire and answer any queries they have regarding the form.
    - Inform that the participant can choose to discontinue the experiment at any instance of time, without the requirement of any reason.
    - Psychomotor Vigilance Task (Reference):
        - Brief subject on how PVT test works.
        - Start PVT Manager.cmd and ensure that the correct subject no. is chosen.
        - Exit PVT Manager.cmd.
        - Start PVT Trial.cmd and instruct the subject to wait for instructions.
        - After logging start_time in excel_log.xlsx, ask the subject to click anywhere to begin the test.
        - Reaction Time data is automatically recorded by PVT software.
        - Log end_time in excel_log.xlsx.

Principal Test Session

- Stressor:
    - Ask the subject to sit in the seat of the driving simulator.
    - Ask the subject to adjust the seat to a comfortable position.
    - The subject is instructed to drive while minimising collisions and off-track movement. Assure that faster lap-times aren't a necessity for the task.
    - Instruct the subject to utilize the practice session to familiarise themselves with handling the car in-game.
    - The subject is asked to wear the headphone connected to the setup.
    - Ensure that the Stability Control (ESC) is at 50% to ensure ease of control.
    - Start the driving simulation, after selecting the track and weather.
    - Record start_time and end_time of the stressor in excel_log.xlsx.
    - Psychomotor Vigilance Task (Stressor):
        - Start PVT Trial.cmd and ask the subject to begin the test.
        - Record start_time and end_time in excel_log.xlsx.
    - Provide the subject with questionnaire.docx (MoSAQ) concerning comfort-fatigue-discomfort ratings and ask them to complete.
- Therapy:
    - Test buck operation:

        - Start the LSV Software on the laptop. Select the session - Vibe + Deep Dive 20.
        - Ask the seated participant to put on the headphones and the glasses to begin the therapy session. Adjust light intensity if needed.
        - Record start_time and end_time of the therapy session in excel_log.xlsx.
        - Psychomotor Vigilance Task (Therapy):
            - Start PVT Trial.cmd and ask the subject to begin the test.
            - Record start_time and end_time in excel_log.xlsx.
        - Provide the subject with questionnaire.docx (MoSAQ) after PVT and ask them to complete.

Repeat Principal Test Session for Therapy Sessions A, B, C, and Control.

End of Study

- Terminate script running for skeletal tracking and infrared face cameras.
- Collect feedback (optional) from subjects.
- Thank the subjects for their cooperation.
- Remove Empatica Embrace Plus from participant's wrist.
- Update participant_data.xlsx with their BSN.
- Provide gift card compensation based on the hours of participation in the experiment.
- Lead participants to the door.

Post-Experiment

- Verify that HRV, EDA and Skin Temperature have been recorded properly in Empatica Care Portal.
- Verify that skeletal data has been logged properly in Computer A.
- Exit Assetto Corsa EVO and turn off the PC running the driving simulator.
- Switch-down of Test Buck:
    - Shut down the laptop inside the cabin
    - Switch off the following in order:
        - Switches on the middle console on the wooden board
        - Front and back switches on the voltage device.
        - Black box atop the Behringer audio interface.
        - Finally, the Behringer audio interface.
- Export data from excel_log.xlsx, table1.xlsx to .csv format for data analysis.
- Export reaction time (RT) data in .csv format from PVT Manager.cmd

Appendix F

Pre-Questionnaire

Pre-Questionnaire

1. Participant No. :_________________________

2. Sex
   - O Male
   - O Female
   - O Prefer not to say

3. Your year of birth (YYYY) :_________________________

4. Dominant hand:
   - O Left
   - O Right
   - O Ambidextrous

5. What are your ethnic origins or ancestry?
   Please select all geographical regions your ancestors originally came from.
   - O North America (e.g., USA, Mexico, Canada)
   - O Central America (e.g., Jamaica, Panama, Suriname)
   - O South America (e.g., Argentina, Chile, Brazil)
   - O Western Europe (e.g., Netherlands, France, Germany)
   - O Northern Europe (e.g., Sweden, Denmark, Finland)
   - O Southern Europe (e.g., Spain, Italy, Greece)
   - O Eastern Europe (e.g., Poland, Hungary, Russia)
   - O North Africa (e.g., Morocco, Algeria, Egypt)
   - O Sub-Saharan Africa (e.g., Nigeria, Kenya, South Africa)
   - O West Asia (e.g., Israel, Turkey, Iran, UAE)
   - O Central/East Asia (e.g., Kazakhstan, China, South Korea, Japan)
   - O South/Southeast Asia (e.g., India, Singapore, Indonesia)
   - O Oceania/Pacific (e.g., Papua New Guinea, Australia, Fiji)
   - O Others: _________________________

6. Do you have a valid driving license?
   - O Yes
   - O No

7. How many years of driving experience do you have? (in years):_________________________

8. How often do you drive?
   - O Daily
   - O Weekly
   - O Occasionally
   - O Rarely
   - O Never

1/2

Appendix F

Pre-Questionnaire

9. What are your preferred music genres?:_________________________

10. Do you listen to music regularly?
    - Yes
    - No

11. Do you have any musical training or play any instruments?
    - Yes
    - No
    - If yes, please specify:_________________________

12. How often do you play Racing Simulator video games?
    - Daily
    - Weekly
    - Occasionally
    - Rarely
    - Never

13. How often do you play First Person Shooter (FPS) video games?
    - Daily
    - Weekly
    - Occasionally
    - Rarely
    - Never

14. Do you have any of these medical conditions? (Please choose all that apply)
    - Cardiovascular issues
    - Epilepsy
    - High or Low Blood Pressure
    - Migraines or frequent headaches
    - Other (please specify):_________________________

15. Do you snore regularly during your sleep?
    - Yes
    - No

16. Do you have any other comments you would like to share?:

Appendix F

MoSAQ Questionnaire

Momentary State Assessment Questionnaire

Please mark your preferred choice clearly.
There are no right or wrong answers!

Participant No.

To be filled in by researcher
Session No. :________________
Date :________________
Time :________________
Questionnaire No. 1 2 3 4 5

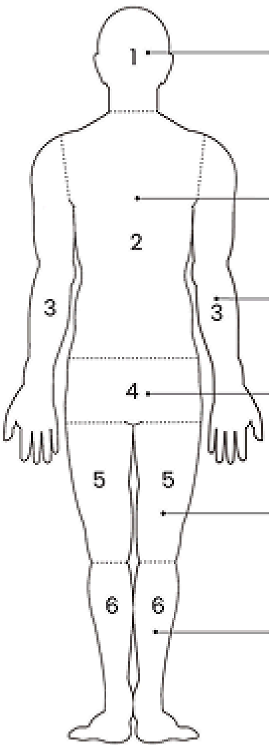
Comfort Rating

Comfort is a pleasant state or a relaxed feeling of a human being in reaction to their environment.

1. How would you rate the **comfort** of this scenario?

No comfort 0 1 2 3 4 5 6 7 8 9 10 Extreme comfort

2. How do you perceive your body's sensation of **temperature**?



	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
Head	○	○	○	○	○	○	○
Upper body	○	○	○	○	○	○	○
Arms	○	○	○	○	○	○	○
Buttocks	○	○	○	○	○	○	○
Thighs	○	○	○	○	○	○	○
Legs	○	○	○	○	○	○	○

1/4

Appendix F

MoSAQ Questionnaire

3. How **fatigued** due you feel at this moment?

0 — 1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9 — 10

Not at all ... Extremely

4. How **stressed** due you feel at this moment?

0 — 1 — 2 — 3 — 4 — 5 — 6 — 7 — 8 — 9 — 10

Not at all ... Extremely

Sensory Rating

Sensory State is the subjective awareness of a human being's senses in response to their environment.

5. What best reflects your **overall state** of mind?

Emotional Tone: Sad ○ ○ ○ ○ ○ ○ ○ Happy

Arousal: Drowsy ○ ○ ○ ○ ○ ○ ○ Energised

Sense of Presence: Detached ○ ○ ○ ○ ○ ○ ○ Immersed

2/4

Appendix F

MoSAQ Questionnaire

6. What is your **Cognitive** State?

	Not at all	Slightly	Moderately	Very	Extremely
My thoughts were clear	○	○	○	○	○
I was distracted by external sensations	○	○	○	○	○
I was fully focused	○	○	○	○	○
Time felt slower or faster than usual	○	○	○	○	○
I had a vivid sensory experience	○	○	○	○	○

7. General Mood and **Awareness**

	Not at all	Slightly	Moderately	Very	Extremely
I feel alert	○	○	○	○	○
I feel relaxed	○	○	○	○	○
I feel emotionally affected	○	○	○	○	○
I feel immersed in my surroundings	○	○	○	○	○
I feel in control of myself	○	○	○	○	○

3/4

Appendix F

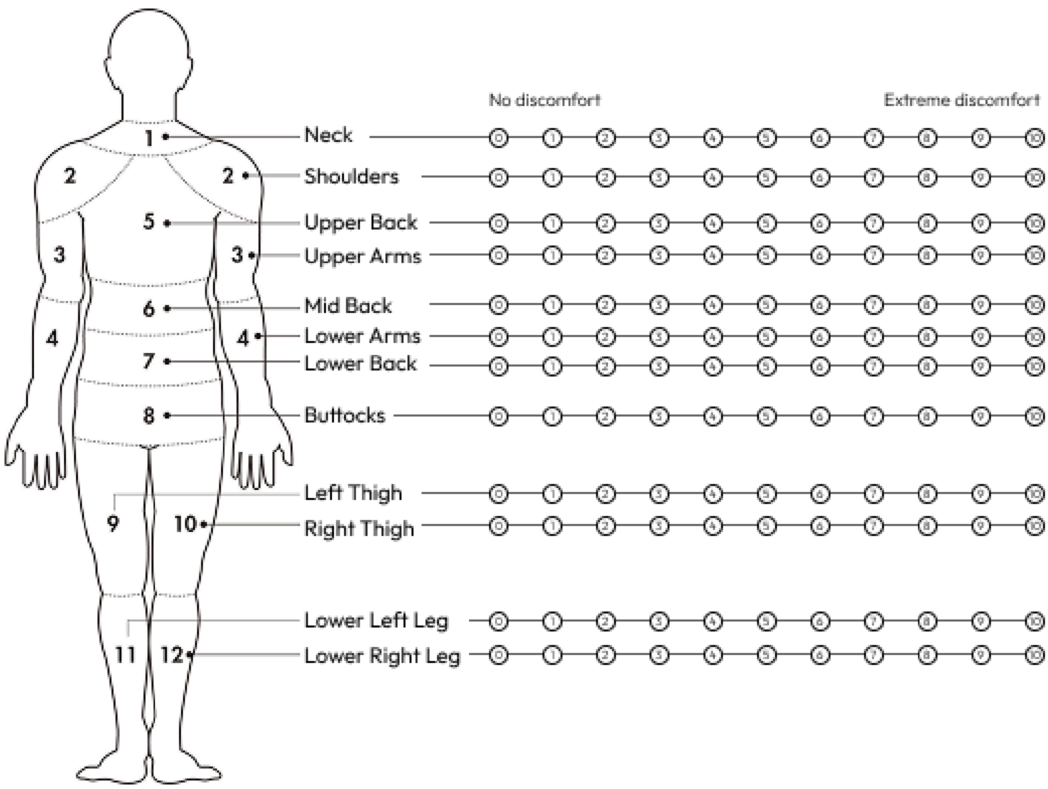
MoSAQ Questionnaire

Discomfort Rating

Discomfort is an unpleasant state of the human body in reaction to their physical environment.

8. Local postural discomfort

   Please rate the **discomfort** in these body regions.



9. How would you rate the overall **discomfort** you felt in this scenario?

(0) (1) (2) (3) (4) (5) (6) (7) (8) (9) (10)

No discomfort — Extreme discomfort

4/4

Appendix F

Post-Session Reflection

Post-Session Reflection

1. Can you rate the therapy sessions on their effectiveness in stress alleviation? (1-4)

	most effective 1	2	3	4 least effective
No Stimulus				
Only Audio				
Audio + Visual				
Audio + Visual + Vibration				

2. Across all four sessions, which experience impacted you the most, and why?

3. If you had to describe the entire experience in one word or feeling, what would it be?

4. Would you like to experience this again? Do you think it would be helpful for you (or others)?

5. Did you find it easy to stay focused during the stressor and therapy?

6. Was there any particular instance that stood out to you?

Appendix G

Experimenter Script for Participant Introduction

This section outlines the standardized script used by the experimenter to brief and guide participants through each stage of the study. It ensures procedural consistency across all sessions.

Introduction

- Greet participants and invite them to take a seat at the preparation table.
- Confirm that they have completed and submitted the informed consent form.
- Ask which hand they use for writing (important for PVT setup).
- Offer water and allow the participant(s) to indicate when ready to proceed.

Wearing the Empatica EmbracePlus

- Clean the wrist area of the non-dominant hand using a skin wipe; allow to dry completely.
- Position the device one finger-width from the wrist bone and fasten as tightly as comfortable to ensure proper data collection.
- If the fit remains loose, provide an elastic athletic band for additional securing.

General Briefing

- Explain the experiment structure: two tasks — a 15-minute driving simulation (stressor) followed by a 20-minute in-car relaxation therapy.
- Inform participants that they will experience two of the four therapy conditions per session, with the remaining conditions in a second session.

Stressor Task: Driving Simulation

- Purpose: induce mild physiological and psychological arousal prior to therapy.
- Setup: BMW M4 CSL in Assetto Corsa EVO, Brands Hatch GP circuit.
- Objective: complete at least one lap within the target lap time during the 15-minute session.
- Controls:
  - Pedals: Right – accelerator; Middle – brake; Left – clutch (gear changes not required).
  - Paddle shifters: Left paddle (×2) – reverse; Right paddle (×2) – first gear.
  - Traction control: Press the yellow-sticker button before starting.
  - Camera view: Press LWB button to cycle views.
- Driving aids:
  - Guiding line color changes: Yellow/Orange = slow down; Red = excessive speed.
  - Corner markers are visible on grass edges.
- Emphasis on maintaining clean laps; recovery allowed after crashes.

Therapy Session

- Participant sits in the passenger seat of the test buck.

- Wears headphones and a sleep mask.
- Stimuli vary depending on therapy condition (audio, visual, and/or tactile).
- Participants may remain awake or nap during the 20-minute session.
- Experimenter will signal the end of therapy.

Psychomotor Vigilance Task (PVT) and Questionnaires

- Conducted before and after each driving or therapy activity.
- Duration: 5 minutes; participants respond to visual stimuli via mouse click.
- Combined with a short questionnaire (~10 minutes total).
- If two participants are present:
  - One performs the PVT while the other completes the questionnaire, then they switch.
  - Second participant begins driving 15 minutes after the first, during which anthropometric measurements are taken.

Appendix H

Participant Recruitment Poster

Appendix I

Personal Project Brief - IDE Master Graduation Project

TU Delft

DESIGN FOR our future

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME
Complete all fields and indicate which master(s) you are in

Family name	[redacted] [redacted]	IDE master(s)	IPD ✔ DfI ☐ SPD ☐
Initials		2nd non-IDE master	
Given name	[redacted]	Individual programme *(date of approval)*	
Student number	[redacted]	Medisign	☐
		HPM	☐

SUPERVISORY TEAM
Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	[redacted]	dept./section	[redacted]
mentor	[redacted]	dept./section	[redacted]
2nd mentor			
client:			
city:		country:	
optional comments			

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

[redacted]

Name [redacted] Date [redacted] Signature

Appendix I

Personal Project Brief - IDE Master Graduation Project

CHECK ON STUDY PROGRESS
To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total ______ EC

Of which, taking conditional requirements into account, can be part of the exam programme ______ EC

★	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

[redacted]

Name [redacted] Date [redacted] Signature

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

[redacted]

Name [redacted] Date [redacted] Signature

Appendix I

Personal Project Brief - IDE Master Graduation Project

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student [redacted] **Student number** [redacted]

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Analysis of Psychological Effects of Multisensory Stimuli in Automotive Cabin Spaces

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The automotive cabin environment plays a crucial role in shaping the driver's experience, influencing cognitive functions, psychological states, and overall well-being. While extensive research has explored the effects of visual, auditory, and haptic stimuli in isolation within vehicular contexts, the impact of their convergence in a multisensory environment remains relatively under examined.

A previous collaborative project at TU Delft, conducted with an automotive manufacturer, demonstrated a relationship between a relaxation program and participants' perceived comfort levels. Physiological data—such as reduced pulse rates and lower electrodermal activity—corroborated these findings, reinforcing the potential of incorporating relaxation therapy features into vehicle design. These results suggested that such interventions could be particularly beneficial for optimizing short breaks, such as those taken during charging stops.

Given this context, automotive manufacturers have also shown interest in understanding how various stimuli interact to enhance comfort, reduce stress, or, in some cases, produce negative effects. This project aims to investigate the effects of four different setups within a real vehicle environment. The experimental conditions will include:
1. A control scenario without therapy
2. Relaxation therapy with only auditory stimulus
3. A combination of auditory and tactile stimuli (massage seat)
4. A multisensory setup incorporating auditory, visual, and tactile stimuli

The study seeks to identify physiological changes across these scenarios, particularly in relation to comfort and discomfort. The findings are expected to provide scientific insights into the measurable physiological effects of systems designed to promote relaxation or enhance energy levels in vehicle occupants.

→ *space available for images / figures on next page*

Appendix I

Personal Project Brief - IDE Master Graduation Project

introduction (continued): space for images

Group	# Control	# A - Audio Only	# B - Audio + Tactile	C - Audio + Tactile + Visual
Pilot	1	1	1	1
	2	2	2	2
Group 1	3	4	5	6
	6	3	4	5
	5	6	3	4
	4	5	6	3
Group 2	7	8	9	10
	10	7	8	9
	9	10	7	8
	8	9	10	7
Group 3	11	12	13	14
	14	11	12	13
	13	14	11	12
	12	13	14	11
Group 4	15	16	17	18
	18	15	16	17
	17	18	15	16
	16	17	18	15
Group 5	19	20	21	22
	22	19	20	21
	21	22	19	20
	20	21	22	19
Group 6	23	24	25	26
	26	23	24	25
	25	26	23	24
	24	25	26	23
Additional Group	27	28	29	30
	30	27	28	29
	29	30	27	28
	28	29	30	27

Purple	Session 1
Green	Session 2

image / figure 1 Experimental Structure

image / figure 2

Appendix I

Personal Project Brief - IDE Master Graduation Project

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The impact of controlled audiovisual stimuli on driver comfort, stress reduction, and physiological well-being within the automotive interior remains an intriguing yet underexplored research area. Previous studies have shown positive correlations between relaxation programs and improved comfort levels. Building on these findings, this study investigates how auditory, tactile, and visual interventions influence physiological and psychological states in real driving environments. The results will help evaluate the potential benefits and limitations of incorporating multisensory design principles in automotive interiors.

The following research questions are of interest in this project:
1. How does in-car relaxation therapy influence physiological signals associated with comfort and stress?
2. Does a combination of auditory, visual, and tactile stimuli produce stronger or weaker physiological and psychological effects compared to auditory intervention alone?
3. How do participants' perceived comfort and relaxation levels vary across different experimental conditions?
4. Can multisensory interventions serve as a viable strategy for enhancing future vehicle interior design?

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Investigate the effects of multisensory interventions in enhancing comfort and relaxation in automotive cabin environments by evaluating the effectiveness of auditory, visual, and tactile stimuli on the physiological and psychological well-being of vehicle occupants.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The experiment will be conducted in collaboration with an automotive manufacturer, which will provide a seat integrated into a test buck, along with supporting systems such as music and lighting, to facilitate the execution of the therapy programs. The objective is to determine whether the addition of these sensory stimulus systems produces measurable physiological effects in vehicle occupants, and whether these stimuli interact constructively with one another.

A sample of 24 participants will be exposed to different therapy scenarios, with both quantitative physiological data and qualitative feedback being collected. Comparative analysis using a Mixed Design Repeated Measures ANOVA between high-arousal states and post-relaxation conditions will enable the assessment of the statistical significance of the therapy's impact on participant relaxation. Differences between trials involving combined stimuli will be examined based on the recorded physiological parameters.

The expected deliverables include empirical data on the physiological and psychological effects of a multisensory relaxation program in automotive environments, with a focus on assessing their impact on occupant comfort and stress levels.

Appendix I

Personal Project Brief - IDE Master Graduation Project

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	3 Mar 2025
Mid-term evaluation	28 Apr 2025
Green light meeting	23 Jun 2025
Graduation ceremony	21 Jul 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

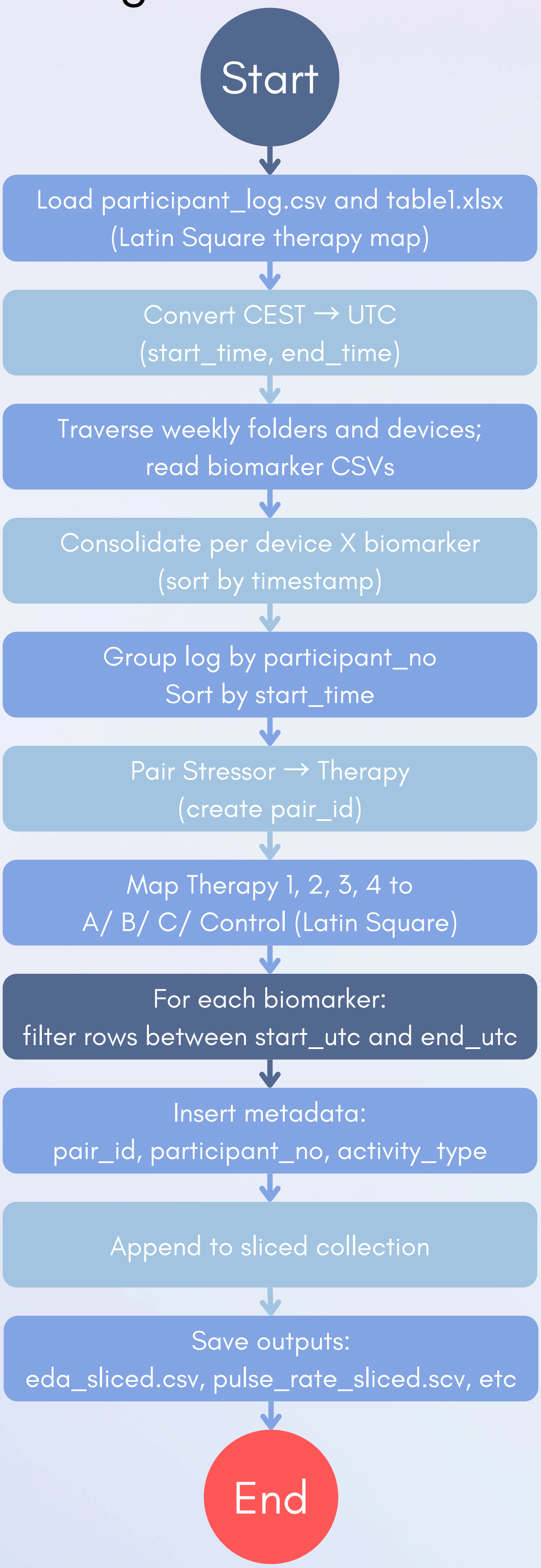
My main motivation for pursuing this topic for my graduation project stems from my fascination with, and relative familiarity with, the automotive industry. With a technical background in mechanical engineering, I felt that this research would allow me to utilise both my prior skill set and the human-centered approach to problem-solving that I have developed throughout this master's program.

This project also offers a valuable opportunity to gain insight into current trends within the automotive sector, helping me reorient myself to better align with its evolving direction. More specifically, research on automotive interiors particularly caught my attention due to the apparent lack of occupant-oriented developments in recent years. I believe that empirical analysis conducted by someone genuinely passionate about the evolution of this area could resonate more meaningfully with both industry and academia.

As for my learning ambitions, I aim to:
1. Develop a deeper understanding of how automotive research is conducted
2. Gain proficiency in statistical modelling and support my findings with data
3. To translate my design visions into solutions that can be empirically validated

Appendix J

Python - Data Slicing



Appendix J

Python - Data Analysis