

Designing and Evaluating Haptic Avatar Biosignals for Social Virtual Reality

Industrial Design Master Thesis
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Designing and Evaluating Haptic Avatar Biosignals for Social Virtual Reality.

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Preface

This graduation project marks the end of my Industrial Design journey at the Eindhoven University of Technology after completing both the Bachelor and the Master. This report contains the outcome of my Final Master Project (FMP), a semester-length project on which I worked with great joy. Through collaborating with the Distributed and Interactive Systems (DIS) group I was able to work on this project in an inspirational atmosphere where a lot of interesting research is performed. For me, this project was very meaningful in developing towards the virtual reality domain which has sparked my attention for quite some time already.

Please enjoy reading through my FMP journey and hopefully it can bring inspiration as well.

Acknowledgments

I would like to name some people here who have supported me in completing this FMP over the past semester. I would have not been able to do it without them.

First of all, my mentoring team Minha and Abdo. Thank you both for the continuous support in the forms of praise as well as asking critical questions throughout the process. Especially a great thank you to Abdo for the daily supervision at CWI, the elaborate amount of coaching support and time spent on sharing thoughts have been very helpful.

Also thanks to Jack and Tom for helping out with questions regarding the technology. Whenever I got stuck you were able to provide me with fresh ideas on how to tackle the problem at hand. In specific a thank you to Tom for letting me use his previously created ESP32 circuit to control the Peltier element and his advise throughout when getting stuck on something with the Peltier.

Thanks furthermore to all of the study participants who gave me their time and provided me with the data to gain insights from.

Last but not least, thank you to all family, friends, and my boyfriend for the continuous faith in me completing this quite extensive project that I took upon myself.

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1. Introduction

This is a TU/e Industrial Design Master thesis, titled ‘Designing and Evaluating Haptic Avatar Biosignals for Social Virtual Reality’. Throughout the thesis period there has been a strong collaboration with the Distributed and Interactive Systems (DIS) group at the Centrum Wiskunde en Informatica (CWI).

The context in which this thesis project finds itself is the design and evaluation of the interaction between people (as avatars) in the virtual reality (VR) environment. Physical nonverbal communication cues, such as facial, vocal and postural expressions, touch, interpersonal space and gaze [19], are lacking in this VR interaction. Since this causes a decrease of feeling socially connected to others in the virtual world [51], this thesis project aims to explore a new nonverbal communication cue: sharing biosignals.

In this exploration the double diamond design process model [7] was used to guide the workflow throughout the project. The discover stage is marked by evaluating the outcomes from previous work by the author and diverging thought by diving into existing literature. Then, in the define stage, the focus of the project was determined and the research question finalized. The develop stage encompasses the largest part of the project, namely the iterative prototyping process in which the design of the research prototype is established. Finally, in the deliver stage, the study with the prototype is performed and conclusions are made.

2. Background

2.1 Social Virtual Reality

In contrast to what would be expected by many, virtual reality will most likely develop towards a medium for social interaction rather than solely a place for gamers [42]. A social virtual reality (VR) environment is a space, perceived through a head-mounted display (HMD), in which we can interact remotely with other people. Examples of such spaces are Meta Horizon, Bigscreen, AlcoveVR, VRChat, and AltspaceVR [2]. As VR technology is continuously innovating, these spaces are constantly evolving with the newest available technology. Though, a question that keeps arising is 'how can we experience the sensations (or subjective perceptions) of other people [44]'. Due to VR spaces being far from a finalized, there are still many research opportunities on how to design these sensations.

2.2 Avatar Representation

In social VR spaces people are represented as avatars, although it differs greatly between platforms how these avatars are stylized and which parts of the body are included, as can be seen in Fig. 1. For someone to feel present in the virtual space, and also feel co-present with others, the realism of the avatars plays an important role [23]. Within these spaces people also adjust their actions based on the cues they get from other avatars [16]. However, the cues are currently limited in comparison to physical interactions with people. Whereas cues like facial, vocal, and postural expressions and gaze can be replicated quite literally to someone's virtual avatar, a cue like touch requires further exploration on how to be integrated in the virtual space. Regarding interpersonal space, personal space is shown to be equivalent to a real-world setting [33, 53, 55], which creates the possibility to use interpersonal space between avatars as a measure.



Figure 1. Several social VR platforms.

1. Meta Horizon (Image source: Meta, accessed via <https://techcrunch.com/2022/06/10/meta-horizon-home-quest-2/>)

2. Bigscreen (Image source: Bigscreen, accessed via <https://www.bigscreenvr.com/>)

3. AlcoveVR (Image source: AlcoveVR, accessed via <https://alcovevr.com/>)

4. VRChat (Image source: VRChat Inc., accessed via <https://store.steampowered.com/app/438100/VRChat/>)

5. AltspaceVR (Image source: Microsoft, accessed via <https://learn.microsoft.com/nl-nl/windows/mixed-reality/altspace-vr/overview>)

2.3 Biosignals

In addition to existing nonverbal cues, an upcoming field of research explores the use of biosignals as a communication cue. These biosignals are for example heart rate, skin conductance, respiration, body temperature, and diverse brain signals. Unlike the usual nonverbal cues, they do not convey explicit interpretable information as they are not visible from outside the body [5], but when externalized people still manage to give meaning to them by coupling them to states of being or emotions [14, 29]. According to Feijt et al.'s systematic review on sharing biosignals [14], biosignals as a nonverbal cue can augment feelings of connectedness, empathy, intimacy, affective interdependence, and sharing of an experience between people. However, they state to be critical on when to use biosignal sharing so its implementation adds value rather than it being there solely because it is technically possible.

For this work, heart rate and body temperature are considered for designing the avatar biosignal cues. These signals lend themselves well as they have a sense of familiarity to them that makes them easier to comprehend, as opposed to more complex signals like skin conductance and brain signals.

2.3.1 Sharing heart rate information

Heart rate (HR) information has been employed in various ways in research to foster social connection between people. For example, sharing HR between romantic partners via smartwatch animations [30, 32] or a pulsating ring [54] to form a new type of communication while being away from each other. More work on sharing HR between two people uses vibration signals on the wrist. Empatalk [25] incorporates this in a video chat system and conclude that the vibrotactile HR enhances engagement in the conversation and increases the feeling of co-presence. WearBEAT [38] shares the HR with the other person located in the same room and shows in a preliminary study to create physical connectedness, although the existing relation with the other person is marked to be important for fostering this connectedness. Other studies have also looked into displaying HR in objects like a cycling helmet [52], a scarf garment [18], a hat for gameplay [12], and a body pillow [41] to make pairs aware of each others state. Morris et al. developed EmbER [39], a system to improve social connection with a pre-recorded narrator on a screen through haptic HR pulses on the wrist and auditory breathing patterns. No significance was found for the haptic HR pulses by themselves, this is possibly due to the placement or the created sensation not being interpreted as a natural HR. Other work by Liu et al. [31] found someone's HR being shown as a graph instead of plain text to improve the relationship with that person, thus they encourage to provide the HR in different forms. Work by Kuling et al. [24] also found that hearing someone's HR increases the interpersonal distance that is kept, they explain this finding as a compensation strategy for the increased feeling of intimacy.

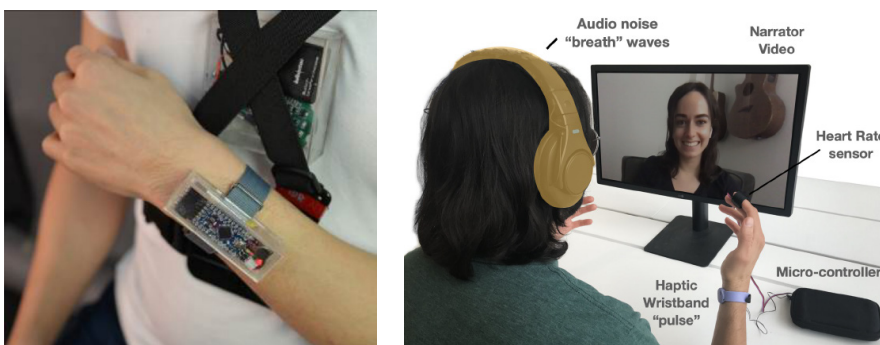


Figure 2. Related work providing heart rate vibration pulses as a nonverbal cue. Left: WearBeat's wristband [38] Right: EmbER's wristband [39]

2.3.2 Heart rate usage in VR

In contrast to previously mentioned work, this work aims to provide HR feedback in a VR environment rather than the real world environment. Chen et al. compared visual, auditory, and haptic forms of HR feedback [6] to become more self-aware. They found audio and haptic (as vibrations in the VR controllers) to be preferable as this is more natural to humans, making it more comprehensive than a visual representation. More recent work of Moullec et al. [40] also explored the relationship between the user and their avatar by providing HR feedback both as a haptic vibration wristband as well as a visualization on the screen. For future work they recommend to explore haptic-only HR feedback as visual-only did not significantly improve the experience and a combination was perceived as disturbing by participants. Other studies focus on providing HR feedback in collaborative VR environments. In 2010, Janssen et al. [22] studied auditory HR feedback as a nonverbal cue. Similar to Kuling et al. [24] their findings show that people increase their kept interpersonal distance when hearing the other person's HR, making HR in its effects on experience and behavior equivalent to other nonverbal cues like gaze. In 2017, Dey et al. [10] tested the effects of visually showing a collaborator's HR. From the lack of significance in their findings they recommend to avoid making the HR feedback too subtle as the engagement factor of VR overrules it. In follow-up work by Dey et al. [9] audio-haptic HR feedback similar to Chen et al.'s [6] results in more promising findings like an increased feeling of presence of the collaborator and a better understanding of their emotional state. More recent work of Lee et al. [26] has explored visual HR representations for avatars in VR that are not actually other humans. They conclude that the use of biosignal feedback could be useful to better understand the avatar's emotion and the atmosphere of the space.

To contribute to this existing body of knowledge, this work will focus on haptic HR feedback as nonverbal cue in VR. From the above mentioned findings, audio-haptic as combination [6, 9] and audio by itself [22] demonstrated to be successful approaches, but haptic HR by itself remains understudied in the VR context. Although haptic feedback from someone's own HR has been studied [40], getting someone else's HR has shown to cause different effects (in comparison to one's own) when presented in audio form [8].



Figure 3. Related work using heart rate visualization to convey one's own heart rate (top) or that of another avatar (bottom). Top left: Chen et al.'s visuals [6], top right: Moullec et al.'s visuals [40], bottom: Lee et al.'s visuals [26].

2.3.3 Body temperature

In comparison to HR, much less studies have aimed at using body temperature as a social nonverbal cue. The Baroesque Barometric Skirt [3] aims to facilitate conversation by using the environment temperature and its wearers body temperature to change RGB colored strips that are woven into the fabric. The HeatCraft system [27] is an ingestible sensor that increases the user's awareness of the body by heating up pads on the waist based on the temperature measured by the ingested sensor. AMIA [12], an augmented version of the dice game Mia, portrays the change in body temperature as a colored icon on a hat only visible for the other players. In the context of playing a game the colors rarely changed which made the element less meaningful, however it could be more meaningful when using the temperature itself instead of the rate of change.

In addition to studying HR in haptic vibration form, the body temperature will be studied in this work in thermal form. From the above mentioned work, displaying body temperature as a thermal stimuli shows to be a successful approach for being aware of one's own body [27]. This work will explore whether this also applies for being aware of someone else's body when feeling their body temperature.

Previous work on augmenting voice messages with temperature by Eli Ali et al. [13] give some insights on the effects of thermal stimuli. Positive messages rate higher in valence when a warm stimuli is applied, for negative messages no effect shows when adding the warm stimuli. Earlier work also found the feeling of social proximity to someone to be larger when holding a hot beverage than when holding a cold beverage [21]. In general, warm temperatures are perceived as positive when applied in isolation [45, 46, 56]. However, work of Yoo et al. [57] contradicts this by finding a lower valence rating for warm than for cold stimuli. Their participants associated the warmth with heat from a cell phone, a hot summer, or ignition, which might culturally be more relevant hazards than for the participants of the other studies.

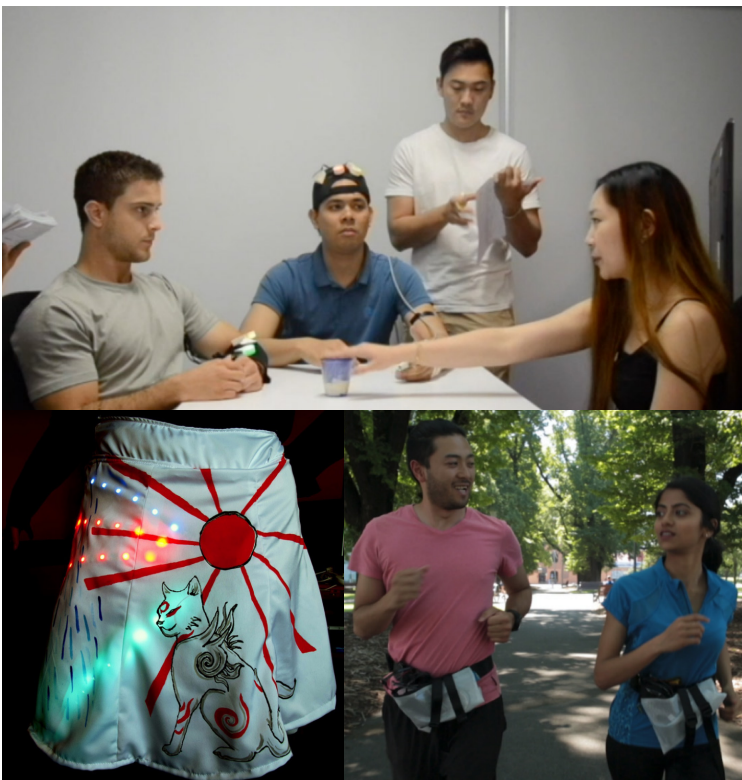


Figure 4. Related work using body temperature as nonverbal cue.
Top: displayed as a color changing icon on a hat in the AMIA game [12].
Bottom left: using light strips in the Baroesque Barometric Skirt [3].
Bottom right: HeatCraft system displaying internal body temperature as a thermal display on the waist [27].

2.4 Project Direction

Problem definition

In current social VR interaction a lot of the usually available nonverbal communication cues are missing. Therefore, a sensation of someone else being there in the virtual space with you is lacking. For social VR platforms to allow for more social connection between people, new nonverbal cues must be explored.

Project objective

The aim of this work is to explore haptic biosignals, in the form of vibrotactile heart rate and thermal body temperature, as a nonverbal cue in social VR. To keep the scope of the project manageable, this will be done in a VR environment in which the participant will interact with a fictitious avatar rather than with a real other person. The objective of the work then contains two parts: 1) Exploring how to design these biosignals properly so they feel natural to the participants, and 2) Studying how haptic biosignals could be of added value on the interaction with an avatar in VR.

Research questions

As an overarching research question this work is interested in **'How can haptic biosignals, in the form of vibrotactile heart rate and thermal body temperature, contribute to the interaction between a VR user and a virtual avatar?'** As previous work found effects on the kept interpersonal distance when providing heart rate information, a sub question is **'How does adding vibrotactile heart rate and/or thermal body temperature feedback of another avatar influence the kept interpersonal distance by a user?'**

3. Method

In this section, the design process for both the virtual environment as well as the haptic stimuli is presented.

3.1 Designing the virtual space

3.1.1 The technology

The platform used to create the VR environment is Unity (version 2021.3.11f1) [50]. Some key aspects that were used in the setup of the project (all are included in Unity's own registry of packages):

- » **The Universal Render Pipeline.** This scriptable render pipeline ensures high quality graphics while keeping performance cost manageable. Also, it supports a wide range of platforms to export a project to. [28]
- » **The OpenXR Plugin.** A plugin that makes VR development simpler and adds the possibility to target a wide range of devices.
- » **The XR Interaction Toolkit package.** This package forms the base for interactions with the VR environment, for example by clicking a button on the controller to translate to a specific action in VR.
- » **The TextMeshPro package.** This package uses more advanced text rendering than Unity's built-in UI text which makes text clearer to read in VR.
- » **The Animation Rigging package.** This package makes it possible to make a rig (equivalent of a skeleton) of a body which can afterwards be animated to behave however you would like.
- » **The Visual Code Editor package.** This package sets Visual Studio as the core code editor and optimizes the intellisense functionality which aids mainly in code-completion help while writing code.

The head-mounted display (HMD) used to display the VR environment is a Meta Quest 2 (formerly named Oculus Quest 2) paired with the third iteration of the Oculus Touch controllers. As the Quest 2 can be used standalone, it was preferred over other devices that would rely on the computing power of the attached computer. However, the available laptop (TU/e's standard laptop for students, a HP ZBook Studio G4) is not capable of providing enough computing power.



Figure 5. A participant wearing the Meta Quest 2 HMD combined with the Touch controllers in either hand.

3.1.2 Outlining the environment design

Following Marcolin et al.'s [35] philosophy on designing a VR environment, the first step is to choose a direction. For this work, an experience in the present time surrounding the encounter with another avatar is the main idea. Second, decide the emotional space. To let the experience be about the encounter with the avatar, the rest of the environment must not be distracting, thus a neutral valence with low arousal and high dominance space is preferred. Third, determining the design space elements. An encounter with another avatar during daytime feels like a safer experience than during evening- or nighttime, thus bright colors, daytime sunlight, and positive nature sounds would be fitting. Fourth, defining the narrative of the experience leads to an encounter with the avatar in a quiet nature space, for example a forest clearing. Lastly, the output technology chosen is the Quest 2 HMD which works well for a nature environment as spatial audio is available for the internal speakers.

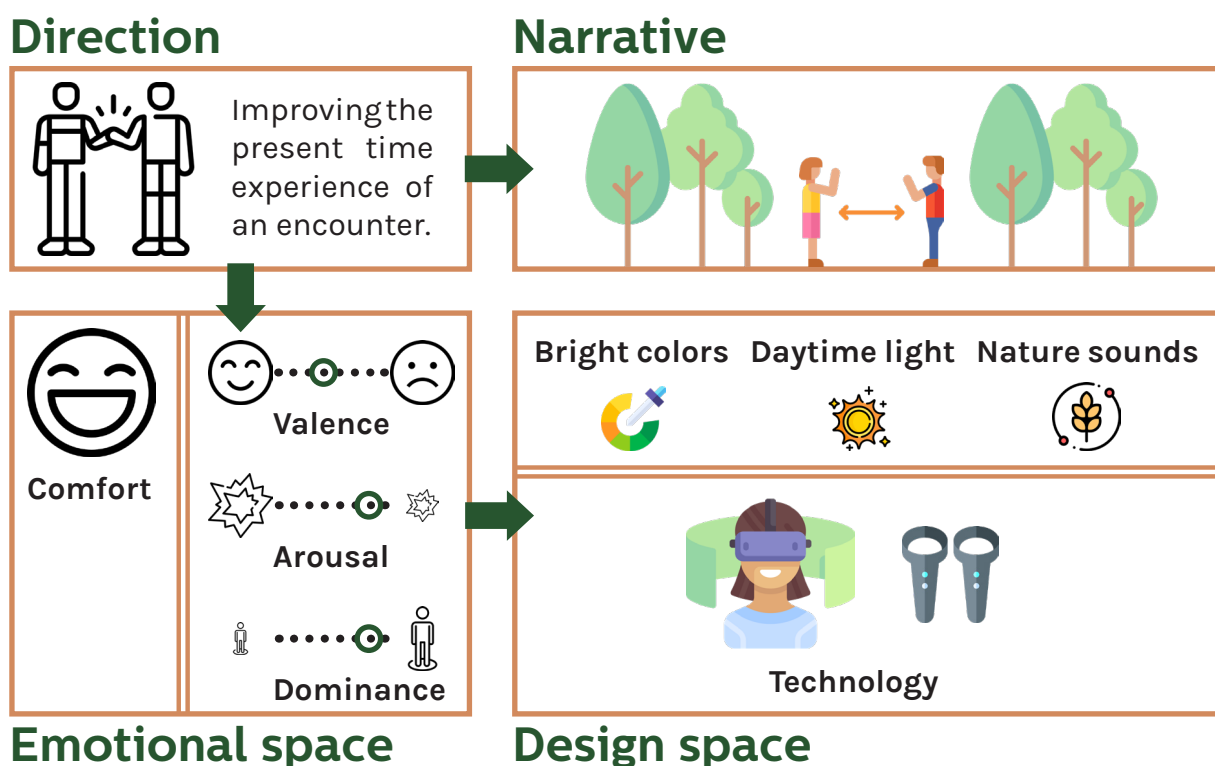


Figure 6. Outlining the design of the VR environment using Marcolin et al.'s [35] philosophy on how to design impacting artificial VR experiences. The icons used were created by Freepik on Flaticon.com.

3.1.3 The design process

With the narrative of the VR environment established, encountering an avatar in a forest clearing, the design development can begin.

The basic skill set

As this is my first time designing for VR, the Unity starter course 'Unity Essentials' and the more elaborate 'VR development' course were very helpful in acquiring the proper skills to use the software. From this course the basic knowledge like making objects from 3D shapes, using teleportation areas or mats, coupling fictitious hands to the controllers, and making menu windows were the most applicable. In my first VR scene I created a simple area containing some plants constructed from separate shapes, a table with some grabbable objects on top of it, a teleportation mat, simple hands, and a first

version of the explanation menu for interaction features. These interaction features of the controllers are: 1) Touching the thumbstick to enable the interaction ray, 2) Pressing the trigger to click the element the ray is pointing at (a button or for teleportation), 3) Pressing the upper button to move to the next scene.

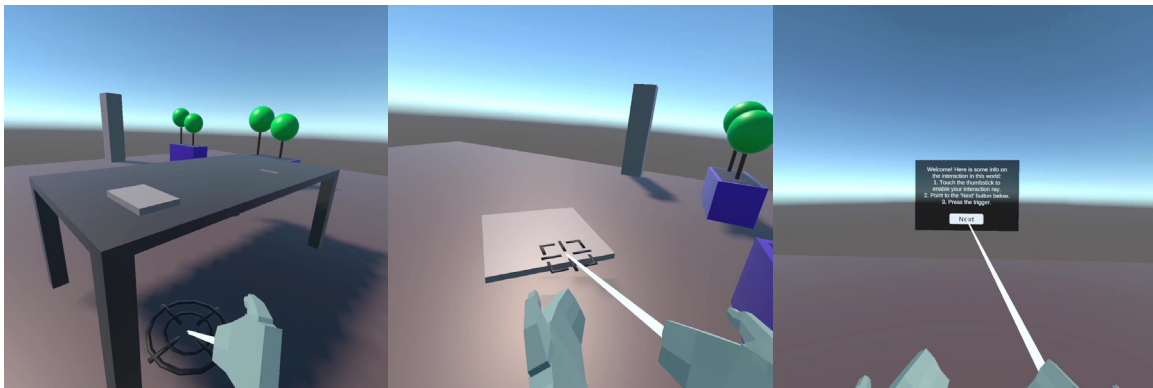


Figure 7. Learning the basic skills to get acquainted with Unity.

First forest iteration

The designed narrative is relatively simple, the user is spawned on the edge of a forest clearing in the mountains as if having come from a path leading up there. Entering the area on an edge rather than in the middle allows the user to acclimate before exploring the environment and encountering the avatar [36]. The path leading up to the clearing serves the purpose of replicating a familiar context of having discovered a new piece of nature while on a walk, encouraging the behavior of the user to explore the clearing [36]. Besides, natural elements like a bright sky with sunlight, grass², and trees³ represent the nature as a positive and safe environment [11]. To bring the environment to life bird sounds⁴ were added, adding to the relaxing atmosphere [1].

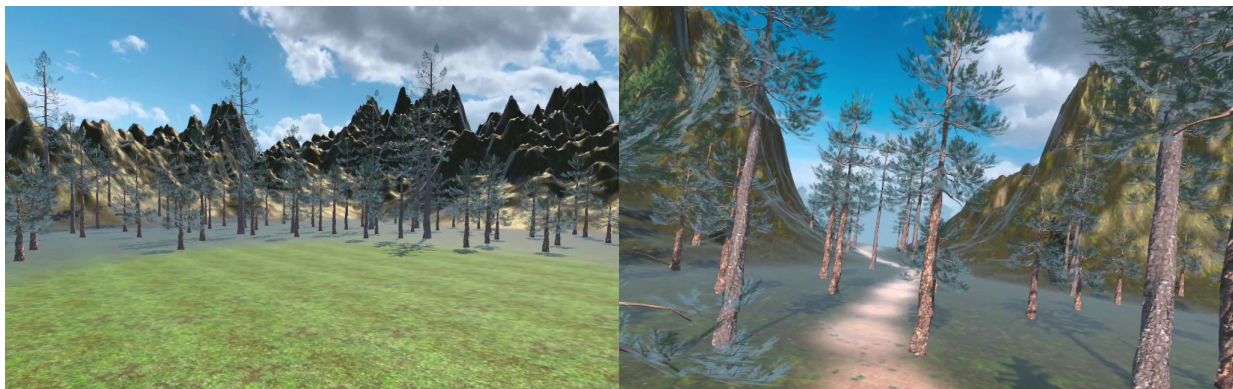


Figure 8. The first iteration of the forest design.

First avatar iteration

As the realism of the avatar plays an important role to enhance the feeling of co-presence [23], it was decided to search for external sources to retrieve high quality avatars, rather than trying to design them myself from scratch. The first iteration includes Sunbox Games' avatars⁵ that are customizable in the Unity inspector window. Although their appearance is nice, some issues show when trying to implement behavior. For example, they lack proper mouth muscles so when animating a talking mouth they either show minimal movement or a weird external mouth. Another element employed in this iteration is the ability of an avatar to turn towards the user. Although it took some effort to get this right, e.g. avatars rotating into the ground, the result allows for a more natural way of interaction as the avatar looks at the user while talking.

¹ Material used: 'Yughues Free Ground Materials' by 'Nobias / Yughues'

² Material used: 'VIS - PBR Grass Textures' by 'VIS Games'

³ Package used: 'Realistic Pine Tree Pack' by 'Hipern'

⁴ Package used: '44.1 General Library (Free Sample Pack)' by 'InspectorJ Sound Effects'

⁵ Package used: 'Stylized Customizable Avatars FREE' by 'Sunbox Games'



Figure 9. The first iteration of the avatar design. F.l.t.r. the avatar, the weird external mouth, rotation gone wrong, correct rotation.

Second forest iteration

The forest environment was upgraded with other trees⁶ that were a bit more full in leaves to make the effect of the clearing more evident. Also, the sky was altered to a plain blue sky to more clearly show the sun. For moving around the clearing several teleportation mats were added to enable a combination of teleportation for larger distances and real user walking for smaller distances. As taught in Unity's VR development course, a black fade is shown on teleportation to minimize the feeling of vection (a mismatch of the body's real location and what is perceived by the brain).

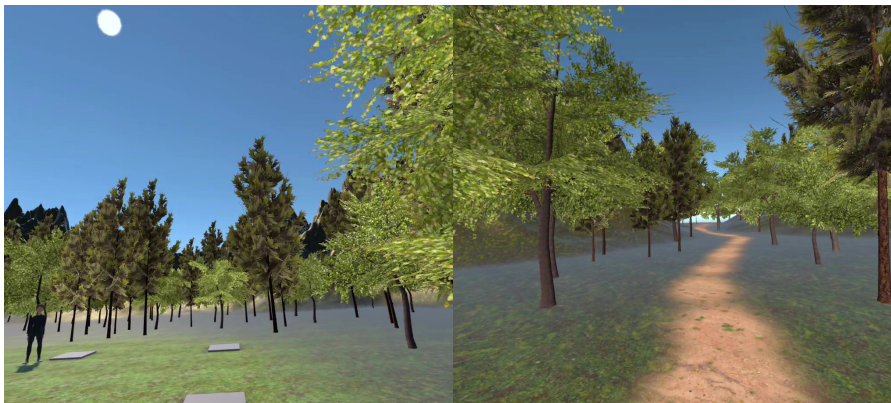


Figure 10. The second iteration of the forest design. A clear sun, teleportation mats, and nicer trees have been added.

Second avatar iteration

Regarding the limitations of the avatars of the first iteration, the search for more suitable ones continued. Popular social VR platforms make use of the Ready Player Me (RPM) [37] avatar platform where users can design their own avatars. Through an Unity SDK integration it was possible to create custom avatars on the RPM platform and subsequently import them in the Unity project. In comparison to many other available avatars, these avatars can blink and move their body (including their mouth) to a very advanced level. To avoid gender bias in the study, similar looking male and female avatars were created and randomly selected for each trial [53].

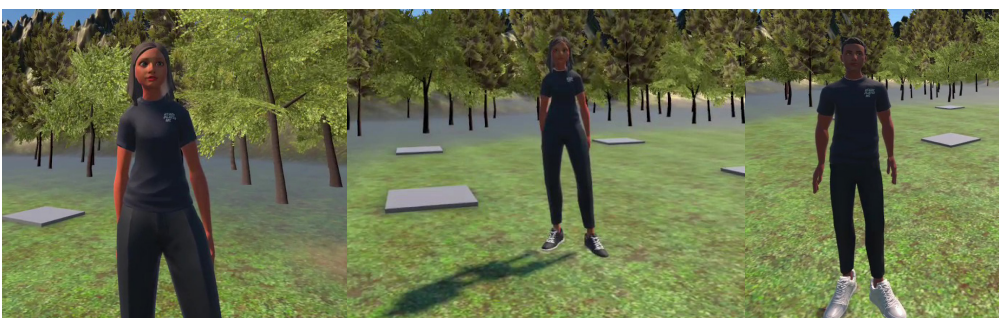


Figure 11. The second iteration of the avatar design, using the Ready Player Me avatar platform to design custom neutral looking avatars.

⁶ Package used: 'Mobile Tree Package' by 'Laxer'

Avatar animation

To make the avatars more lively, animations were added to their appearance. This short animation⁷ of moving the arms while talking is repeated throughout the trial scene. Also, stories to tell were produced by means of AI-generated texts which were then converted to speech also using AI-voices, more details on this process can be found in appendix A.

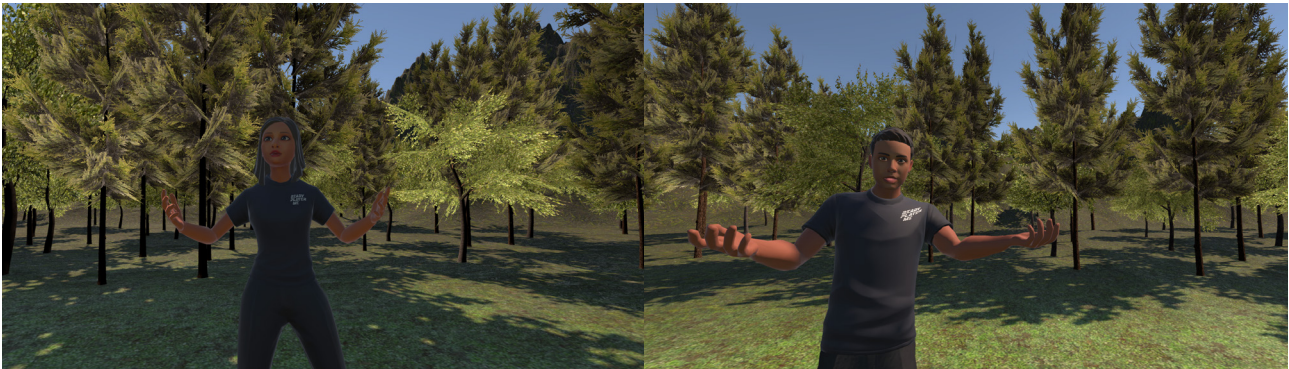


Figure 12. Avatar animation implemented. The avatars now move their body, especially their arms, while telling their stories.

First VR questionnaire iteration

In order to avoid systematic bias and enhance the feeling of presence in the VR environment it is important to respond to questionnaires within VR instead of transitioning to the physical world [43]. Using a simple black canvas with white text, the interaction flow was implemented. By pushing the upper button on the controller, the user indicates to be done with the current trial. When confirming, the trial is deactivated by letting the avatar disappear. Then several question canvases appear one by one until the last one is completed. Then, the next trial is activated by re-spawning the user to the edge of the clearing and a new avatar appears.

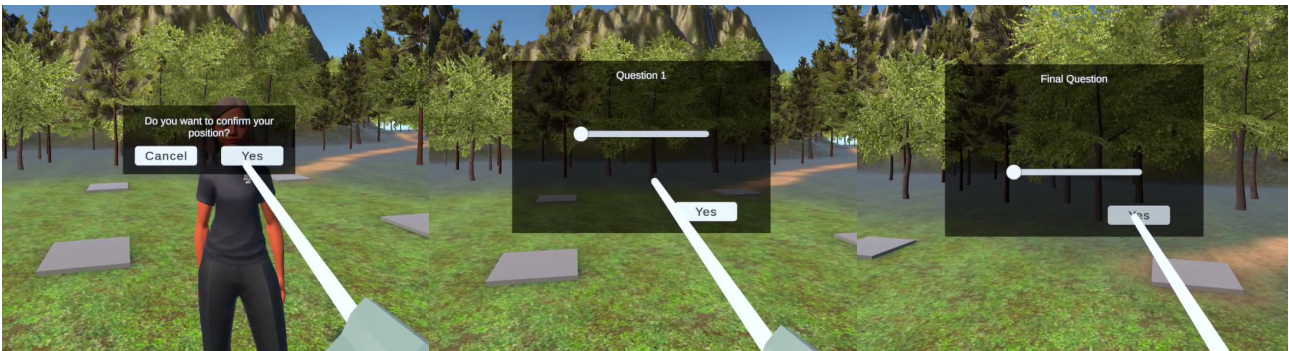


Figure 13. First VR questionnaire interaction flow implementation.

Second VR questionnaire iteration

To measure the experience after each trial, 7 Point Likert Scales questions were asked:

- » **I wanted to maintain a sense of distance between us.** (strongly disagree - strongly agree)
- » **I found the sensation of haptic stimulation (thermal, vibration feedback) to be comfortable.** (very uncomfortable - very comfortable) + a No Answer option in case no sensation was felt.
- » **I felt excited during this last interaction.** (very calm - very excited)

Also, the igroup presence questionnaire (IPQ) [20] was added after each set of trials to measure the sense of presence experienced in the VR environment.

⁷ Animation used: 'Talking' from Mixamo.com

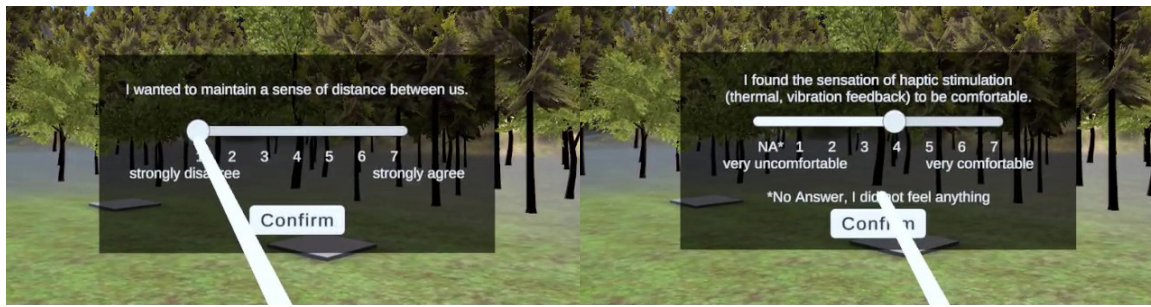


Figure 14. Second VR questionnaire iteration. The empty question boxes have been replaced by Likert Scale questions with a slider.

Finalizing for study purposes

The last step in designing the VR environment is implementing the aspects needed for running a study with the developed environment. For example, the initial start scene created was transformed to a training area for participants to learn the controls and become acquainted with being in VR if it is their first time. Besides, small extra canvases were added to remind a participant to round up a trial after the trial time has passed and at the end of the study to prepare the participant that the app will be closing. Also, more tiles were added to the environment to make the space between tiles match with the amount of walking space available for participants in the real world (2.5 meters). Lastly, a self-avatar replaced the fake blue hands, of which the participant can see only the arms as they move the controllers and the rest of the body when looking down.



Figure 15. The training area was added to teach the participant how to use the controls.



Figure 16. Elements added for study purposes: a time reminder and a closing warning. Also a self-avatar was added to have more of a body presence than just the fake blue hands.

3.2 Designing the biosignals

3.2.1 The technology

Heart rate as vibration stimuli

Initially the idea was to use a previously used high quality vibration motor, a Lofelt L5 actuator. However, as participants of that study indicated the strength of the vibrations not to be strong enough to be noticeable while being immersed in watching videos, it would for sure not be strong enough to withstand the immersion level of VR. As the Oculus Quest Touch Controllers contain a vibration motor as well, the choice was made to dive into learning to write code for them. From Oculus' documentation⁸ can be found that the motor elements that can be controlled are the frequency (set to 1 to enable haptics) and the amplitude (set value between 0 and 1) of the vibration.

Body temperature as thermal stimuli

Approximately the same hardware setup has been utilized as for my M2.1 project. This setup revolves around a Peltier element being controlled by an ESP32. As the ESP32 must receive 3.3 voltage while the Peltier requires 7.5 voltage, a motor driver is located in between to provide each element with the voltage that they need, more details can be found in appendix B. The Peltier can be controlled in two ways:

- » **By providing a 'power' value.** Values larger than zero heat up the element, smaller than zero cool it down. A power value of zero shuts off the element.
- » **By providing a 'temperature' value.** Through PID⁹ calculation the element either heats up or cools down to try and achieve the set temperature.

Instead of serial port communication, as in the M2.1 project between the Processing and Arduino programs, wifi communication is implemented for the ESP32 as the VR HMD must be able to communicate values to the board.

3.2.2 The heart rate design

Setting complex vibration values on the Touch controllers

The first main hurdle to overcome was discovering how to communicate more complex vibrations to the controllers. The documentation only explains setting a frequency and amplitude to the 'SetControllerVibration' function, this will just set a simple constant vibration. The first exploration aimed to set an audio file as vibration, as this worked well for the L5 actuator before. However, no successes were booked with this method as setting an audio file as input for the vibration function turned out to be an impossible task. In the search for alternative methods the function 'SendHapticImpulse' from the XR Interaction Toolkit was found, which allows to set an amplitude as well as a duration of that amplitude. Although this seems like a small difference, it makes it possible to communicate a series of amplitudes that together form a more complex vibration.

```
// starts vibration on the right Touch controller  
OVRInput.SetControllerVibration(1, 1, OVRInput.Controller.RTouch)
```

```
public bool SendHapticImpulse(float amplitude, float duration)
```

Figure 17. Top: the basic vibration function with frequency and amplitude set to 1, result is a basic vibrations. Bottom: the functionality making it possible to send more complex vibration patterns to the Touch controllers.

⁸ Documentation can be found at: <https://developer.oculus.com/documentation/unity/unity-haptics/>

⁹ Documentation can be found at: <https://playground.arduino.cc/Code/PIDLibrary/>

Heart rate as a series of amplitudes

The next challenge was to come up with a way to make a series of amplitudes feel as close to a heart rate as possible. At first the function was explored further by figuring how to send different separate amplitudes to either both or one of the two controllers¹⁰. Afterwards, a search for best practices online led to the use of an Animation Curve¹¹ to communicate the curve's amplitude values to the Touch controller. Next, shapes were explored to replicate a heart rate feeling in the Touch controller:

1. A simple rumble vibration to explore what the difference in amplitude feels like on the controller.
2. Adapted from the Neurokit2 simulation of a complex cardiac activity (ECG) graph¹².
3. After further studying what an ECG graph represents and which parts we usually feel on our body.

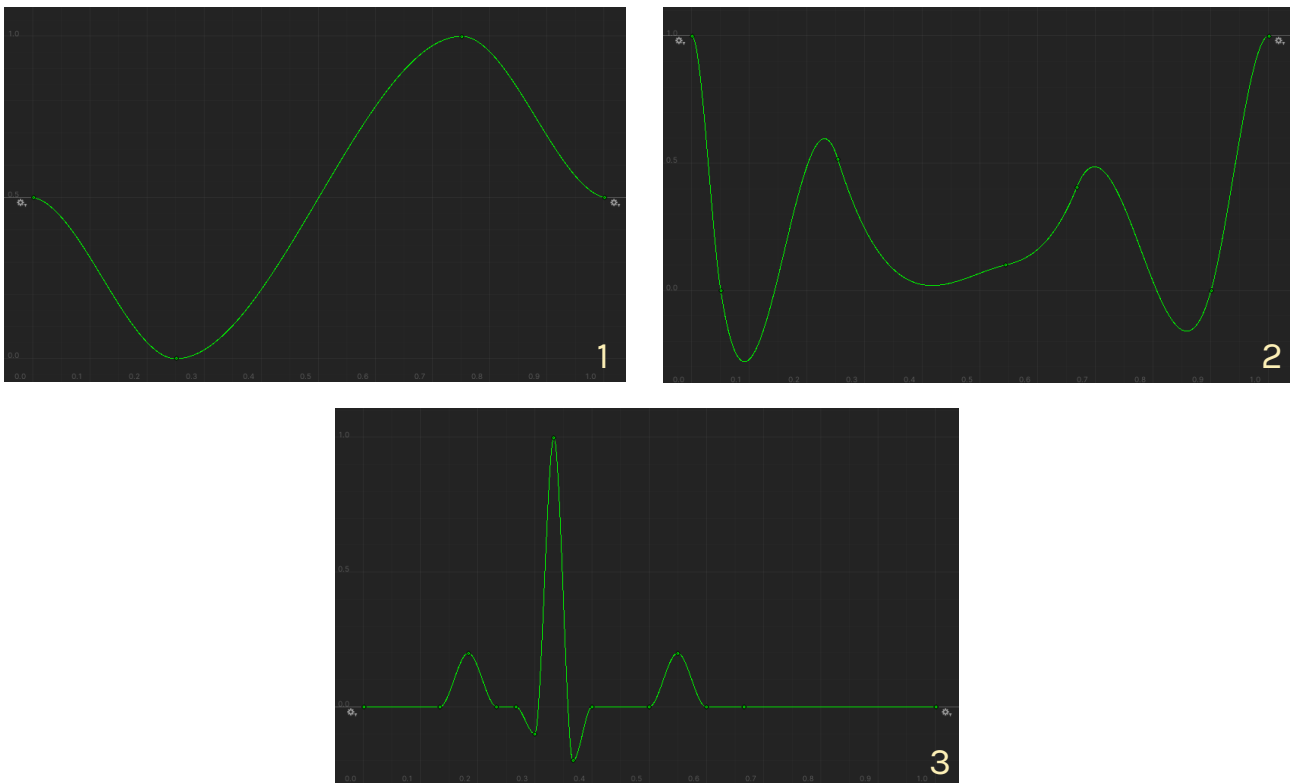


Figure 18. The exploration of different animation curves to represent heart rate vibration.

Implementation into the VR environment

As the aim is to let the heart rate belong to the avatar that the user is encountering, a varied intensity based on distance was applied. The closer the user approaches towards the avatar, the more intense the heart rate vibration can be experienced in the Touch controller. When further than five meters away, no vibration will be felt at all. This distance was chosen as the vibration will then at around 3.70 meters be at an intensity level that is well noticeable, which is according to the study of proxemics [17] the switching point between a public and a social distance.

¹⁰ The script with this exploration can still be found as 'HapticController' in the Unity project file.

¹¹ Documentation can be found at: <https://docs.unity3d.com/Manual/animeditor-AnimationCurves.html>

¹² The respective information used: https://neuropsychology.github.io/NeuroKit/examples/signal_simulation/signal_simulation.html

3.2.3 The body temperature design

Determining the temperatures

Iterating on the M2.1 design, where a linear heating or cooling effect was designed, this design requires variable heating. To represent the body temperature of the encountered avatar, the temperature must vary based on the distance between the user and the avatar. Just like the design of the heart rate feedback proxemics seems a strong theory to base the feedback upon. According to proxemics literature by Hall [17] there are four zones of interpersonal distance:

- » The public zone, distances larger than 3.70 meters and is usually used for public speaking.
- » The social zone, distances between 1.22 and 3.70 meters and is usually used for interactions among acquaintances.
- » The personal zone, distances between 0.46 and 1.22 meters and is usually used for interactions among good friends or family.
- » The intimate zone, distances smaller than 0.46 meters and is usually used for interactions with romantic partners.

As location of the temperature probe, the inside of the forearm was chosen as this is suitable for local warm stimuli [34] while also being an acceptable area for social touch for relationships like acquaintances and strangers [49]. The local skin temperature on the forearm is at room temperature around 34 °C [48]. The temperature for the public zone was therefore set to 36 °C to only be slightly noticeable and representing actual body temperature. When entering the social zone, the temperature increases to 40 °C to clearly differentiate in stimuli between the zones. This change of 4 °C is regarded as dominant but pleasant still, whereas an increase of 6 °C would be regarded as unpleasant [46]. When entering the personal and intimate zones the temperature will again increase by 2 °C per zone, respectively to 42 °C and 44 °C to avoid the maximum temperature becoming too hot. A thin piece of fabric in between the skin and the Peltier element protects the skin from becoming uncomfortably warm. Although this might increase the detection time of the stimuli, this would mainly be a problem if the trials were very brief [13].

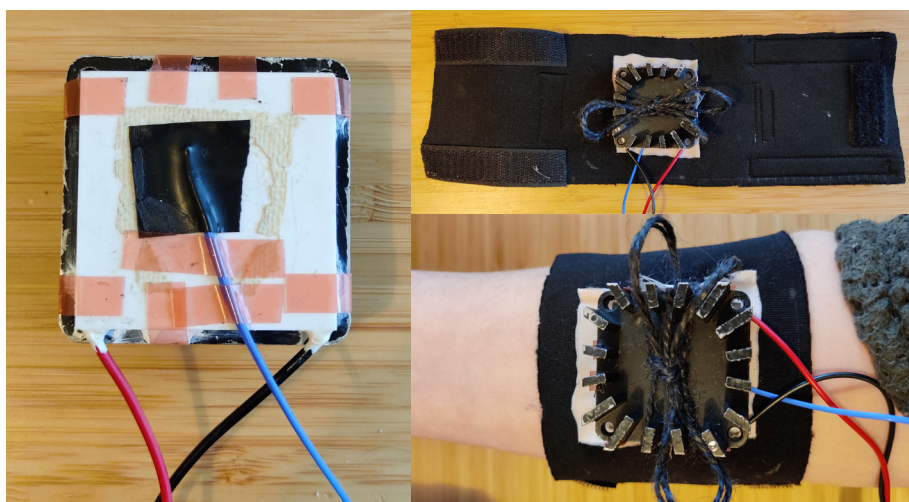


Figure 19. The Peltier element. Left: without the armband, right: attached to the armband and adjustable with velcro around the arm, with a thin pink piece of fabric to protect the skin.

Controlling the Peltier's temperature

Between the two methods to control the Peltier's behavior, providing a temperature value seems the most convenient for the aim of the study. However, in order to make this method properly work the PID calculation must be done correctly by the Peltier. This happens through tuning the Kp, Ki, and Kd parameters of the algorithm. Unfortunately, trying out a broad range of values for each of these parameters did not result in finding a desirable behavior of the Peltier to be at the set temperatures based on the distance between the user and the avatar. Alternatively, the method of sending power values to the Peltier seemed to be more reliable, although it required hard coding the behavior into a Unity script. After a trial-and-error process the following behavior was found to be the most accurate in achieving the correct temperatures at the right time:

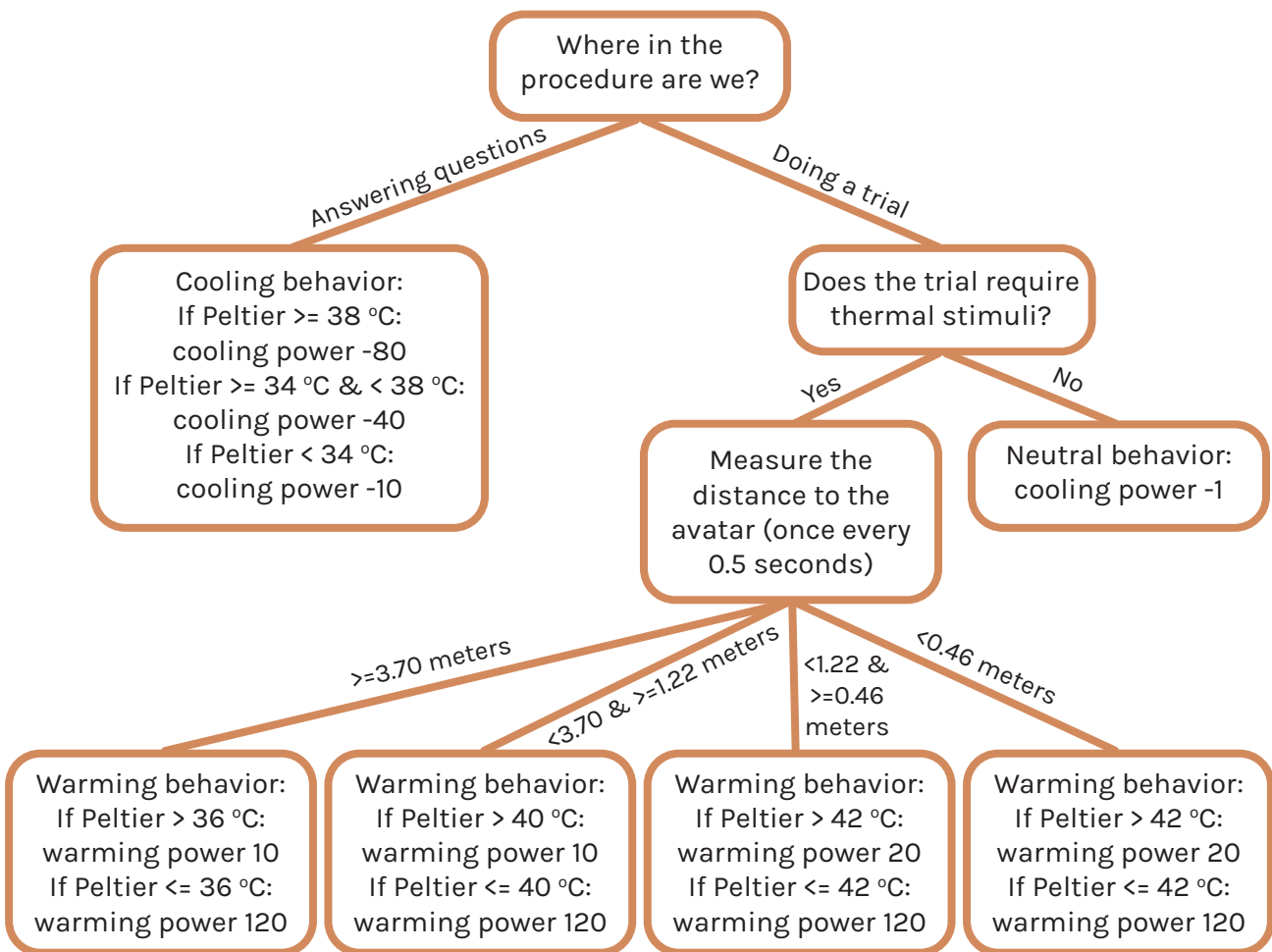


Figure 20. Peltier behavior controlled from the Unity script 'ThermalCommunication'

3.3 The final prototype

The final prototype that was used for the study looks as follows when being worn by participants.

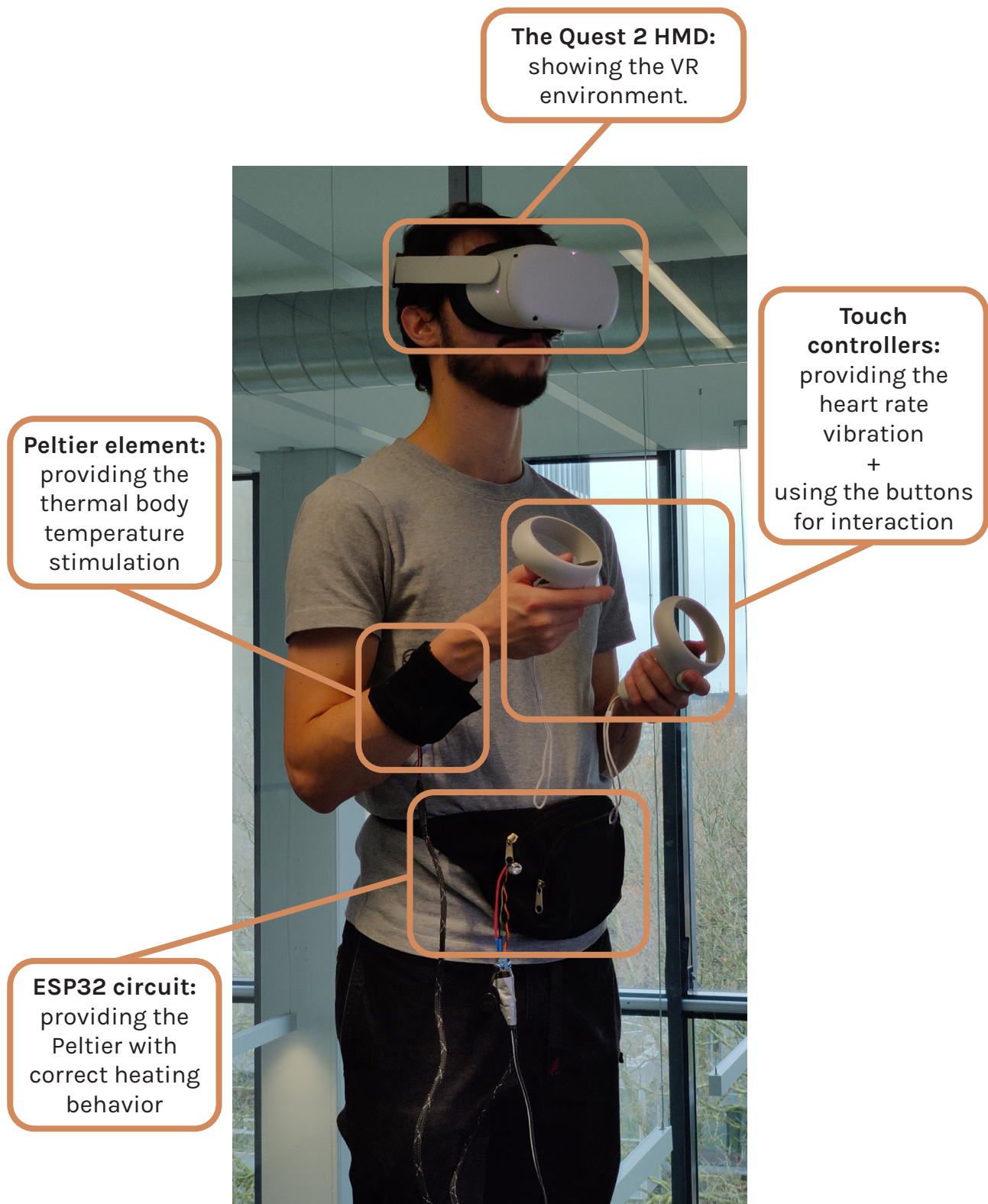


Figure 21. All the parts that belong to the final prototype setup.

3.4 Study setup

For consistency between participants, the study takes place in a room of ± 22 °C in which a 2.5 by 2.5 meters square is set as play area when being in the VR environment. The total study length is designed to last between 50 and 60 minutes. Participants were recruited through an invitation message that was posted in Whatsapp and Slack channels. In total, including the pilot, 12 participants were recruited; 3 Female, 9 Male; 6 aged 18-24, 5 aged 25-34, 1 aged 45-54; 1 owning a Quest 2, 11 not owning any VR headset; 1 using VR daily, 2 using VR 1-2 times per month, 6 using VR 1-2 times last year, 3 never used VR.

Pre-study

Participants were first given a form containing information about the procedure of the study. Then, they were asked to fill in a consent form, a participant information form, and a pre-study simulator sickness questionnaire, all forms can be found in appendix C. After completing the forms, the participant received an explanation by the researcher on the prototype they were going to be wearing. This explanation did mention that the Touch controller would vibrate and the Peltier element on the arm would warm up, however, it did not mention what these stimuli were meant to be representing the biosignals of the avatar they would encounter in VR. Furthermore, the participant was told that their task in each trial was to find a comfortable position relative to the avatar they encountered.

Study

The participant first put on all the parts of the prototype with help of the researcher. Then they were able to do the entire study by themselves as all the explanation they needed was presented to them in the VR environment. First, they learned how to use all the interaction features in the training environment. Once fully trained and comfortable with using these features they proceeded to the actual study environment. The study includes 24 trials divided in 4 blocks of which one block does not include any additional stimuli, one contains both vibration and thermal stimuli, and the other two contain either of the two. Per block this means there are six trials in which the avatar will always be at a random location and will tell two negative, two neutral, and two positive stories in a random order. While the participant is performing the study, data on their behavior during the study and their answers to the questions are being logged. Also, as elements like block order, trial order within a block, gender of the avatar per trial, story to tell per trial, and location of the avatar per trial are randomized quite some scripts have been added in the background of the Unity scene. The flow of logging data and scripts performing actions in the background can be seen in figure 22. Additionally, a video showing the run-through of the study from the participant's view can be viewed [here](#).

Post-study

After completing the study, participants were asked to fill in a post-study simulator sickness questionnaire and some comfort rating scales about wearing the prototype. Then, a semi-structured interview was conducted to gain more insights on how the participant experienced the study. Questions were aimed at their perception of the environment in total, the biosignal vibration and thermal feedback, the avatars and their stories, and how the stimuli could further be developed for other VR scenarios.

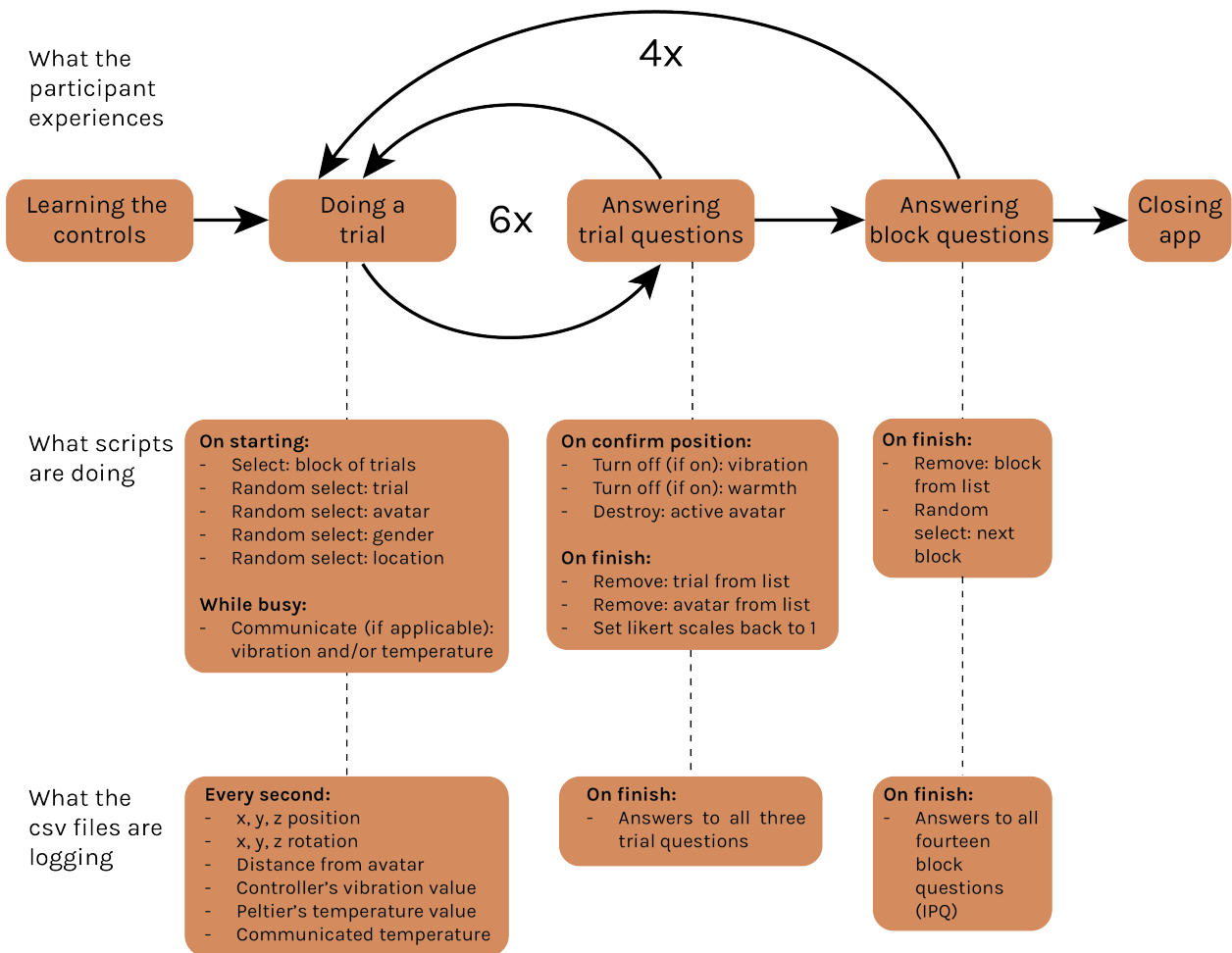


Figure 22. The procedure of the study including information on what scripts are doing in the background to make the procedure possible and information on what data is being logged for analysis purposes.

4. Results

4.1 Quantitative results

This section presents the quantitative results from the question data after each trial and the actual distance kept from the avatar. All data analysis has been performed using the ILLMO¹³ software.

4.1.1 Post-trial questions

Q1: I wanted to maintain a sense of distance between us.

	No extra stimuli	Thermal body heat	Heart rate vibration	Both thermal + vibration
Average answer value	3.05098	3.01898	4.2907	3.99753
Standard deviation	1.24014	1.23726	1.27451	1.2767

Performing T-tests gave the following results. The significance was also tested through creating receiver operator curves and these confirmed the results of the T-tests.

	No stimuli vs. Thermal	No stimuli vs. Vibration	No stimuli vs. Both	Thermal vs. Vibration	Thermal vs. Both	Vibration vs. Both
Difference between averages	-0.0757576	-1.18033	-0.984848	-1.10457	-0.909091	0.195479
Effect size (Cohen's d)	0.055454 (tiny size effect)	0.853579 (medium size effect)	0.780498 (medium size effect)	0.775428 (medium size effect)	0.696287 (small size effect)	0.148022 (tiny size effect)
T value	-0.3186 (<1.9788 thus not significant)	-4.8059 (>=1.9796 thus significant)	-4.4836 (>=1.9788 thus significant)	-4.3659 (>=1.9796 thus significant)	-3.9999 (>=1.9788 thus significant)	0.8334 (<1.9796 thus not significant)
Confidence interval	-0.546348 to 0.394833 (incl. 0 thus not significant)	-1.66652 to -0.694135 (excl. 0 thus significant)	-1.41951 to -0.55019 (excl. 0 thus significant)	-1.60541 to -0.603727 (excl. 0 thus significant)	-1.35884 to -0.459343 (excl. 0 thus significant)	-0.26885 to 0.659807 (incl. 0 thus not significant)

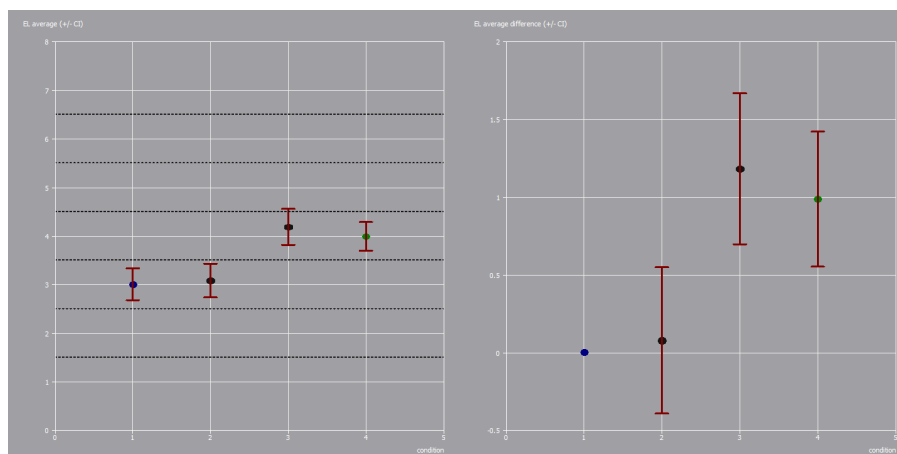


Figure 23. Data collected from post-trial question 'I wanted to maintain a sense of distance between us' (1 = strongly disagree, 7 = strongly agree). The x-axis presents the data per condition: 1 = no extra stimuli, 2 = thermal body heat, 3 = vibration heart rate, 4 = both thermal + vibration. Left: a histogram plot of the data. Right: T-test output plot of the data

¹³ ILLMO documentation can be found at: <https://illmoproject.wordpress.com/>

Q2: I found the sensation of haptic stimulation (thermal, vibration feedback) to be comfortable.

	No extra stimuli	Thermal body heat	Heart rate vibration	Both thermal + vibration
Average answer value	4.04034	4.55438	3.33457	3.21208
Standard deviation	0.953534	0.947553	0.937889	0.936327

Performing T-tests gave the following results. The significance was also tested through creating receiver operator curves and these confirmed the results of the T-tests. Comparisons to the 'no stimuli' condition have been left out as this was mostly answered with 'No Answer'

	Thermal vs. Vibration	Thermal vs. Both	Vibration vs. Both
Difference between averages	1.1564	1.3226	0.166196
Effect size (Cohen's d)	1.138784 (large size effect)	1.251321 (large size effect)	0.148836 (tiny size effect)
T value	4.9486 (>= 1.9878 thus significant)	5.4817 (>= 1.9867 thus significant)	0.8115 (< 1.9811 thus not significant)
Confidence interval	0.691888 to 1.62092 (excl. 0 thus significant)	0.843251 to 1.80195 (excl. 0 thus significant)	-0.239506 to 0.571897 (incl. 0 thus not significant)

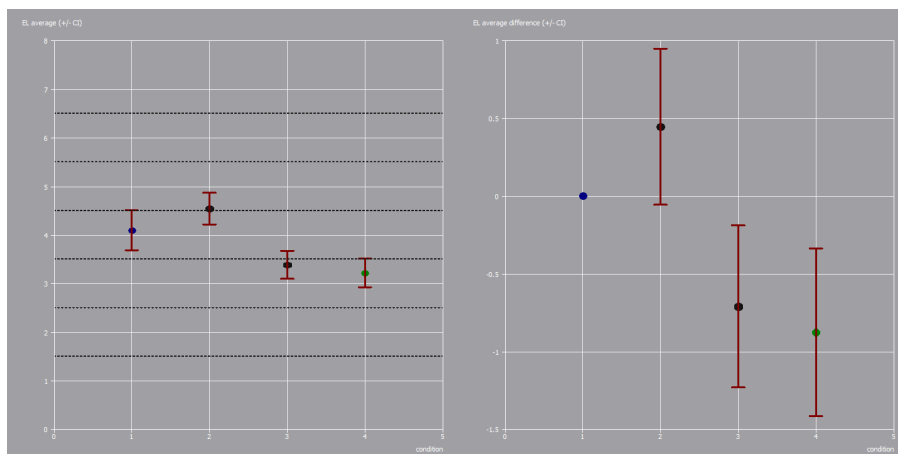


Figure 24. Data collected from post-trial question 'I found the sensation of haptic stimulation (thermal, vibration feedback) to be comfortable' (1 = very uncomfortable, 7 = very comfortable). The x-axis presents the data per condition: 1 = no extra stimuli, 2 = thermal body heat, 3 = vibration heart rate, 4 = both thermal + vibration.
Left: a histogram plot of the data. Right: T-test output plot of the data

Q3: I felt excited during this last interaction.

	No extra stimuli	Thermal body heat	Heart rate vibration	Both thermal + vibration
Average answer value	2.49111	2.62836	3.14396	3.41152
Standard deviation	1.15765	1.18082	1.23335	1.24151

Performing T-tests gave the following results. The significance was also tested through creating receiver operator curves and these confirmed the results of the T-tests.

	No stimuli vs. Thermal	No stimuli vs. Vibration	No stimuli vs. Both	Thermal vs. Vibration	Thermal vs. Both	Vibration vs. Both
Difference between averages	-0.151515	-0.700447	-0.893939	-0.548932	-0.742424	-0.193492
Effect size (Cohen's d)	0.117462 (tiny size effect)	0.565650 (small size effect)	0.730608 (medium size effect)	0.434784 (small size effect)	0.595301 (small size effect)	0.162344 (tiny size effect)
T value	-0.6748 (<1.9788 thus not significant)	-3.1848 (>=1.9796 thus significant)	-4.1970 (>=1.9788 thus significant)	-2.4480 (>=1.9796 thus significant)	-3.4197 (>=1.9788 thus significant)	-0.9141 (<1.9796 thus not significant)
Confidence interval	-0.595849 to 0.292819 (incl. 0 thus not significant)	-1.13584 to -0.265058 (excl. 0 thus significant)	-1.31542 to -0.472463 (excl. 0 thus significant)	-0.992842 to -0.105022 (excl. 0 thus significant)	-1.17203 to -0.312823 (excl. 0 thus significant)	-0.612554 to 0.22557 (incl. 0 thus not significant)

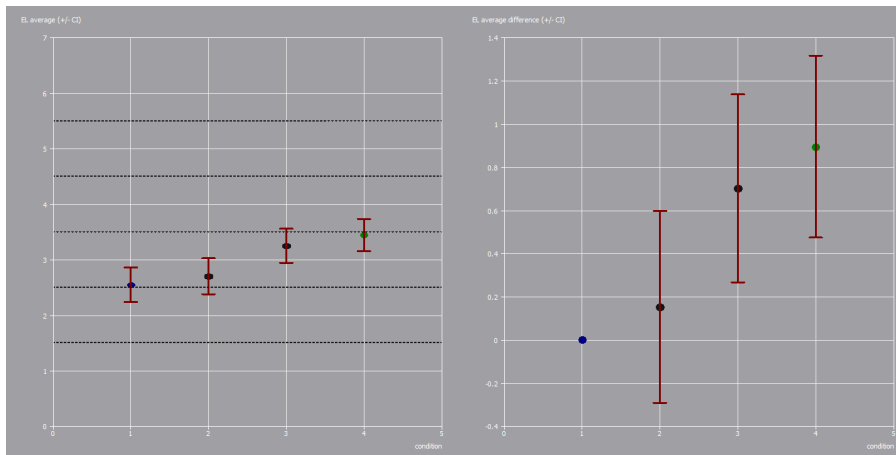


Figure 25. Data collected from post-trial question 'I felt excited during this last interaction' (1 = very calm, 7 = very excited). The x-axis presents the data per condition: 1 = no extra stimuli, 2 = thermal body heat, 3 = vibration heart rate, 4 = both thermal + vibration. Left: a histogram plot of the data. Right: T-test output plot of the data

4.1.2 Distance to avatar

Interpersonal distance when confirming position at the end of a trial

	No extra stimuli	Thermal body heat	Heart rate vibration	Both thermal + vibration
Average distance (m)	1.97242	1.92076	2.91659	2.61096
Standard deviation	0.652247	0.760229	1.19903	1.46385

Performing T-tests gave the following results. The significance was also tested through creating receiver operator curves and these confirmed the results of the T-tests.

	No stimuli vs. Thermal	No stimuli vs. Vibration	No stimuli vs. Both	Thermal vs. Vibration	Thermal vs. Both	Vibration vs. Both
Difference between average distance (m)	0.0516642	-0.944168	-0.638537	-0.995832	-0.690201	0.305631
Effect size (Cohen's d)	0.072941 (tiny size effect)	0.986788 (medium size effect)	0.563482 (small size effect)	0.998750 (medium size effect)	0.591755 (small size effect)	0.227712 (tiny size effect)
T value	-0.4190 (<1.9788 thus not significant)	-5.5794 (>=1.9795 thus significant)	-3.2370 (>=1.9788 thus significant)	-5.6470 (>=1.9795 thus significant)	-3.3994 (>=1.9788 thus significant)	1.2875 (<1.9795 thus not significant)
Confidence interval	-0.192323 to 0.295651 (incl. 0 thus not significant)	-1.27914 to -0.609195 (excl. 0 thus significant)	-1.02889 to -0.248185 (excl. 0 thus significant)	-1.3449 to -0.646761 (excl. 0 thus significant)	-1.09198 to -0.288425 (excl. 0 thus significant)	-0.16426 to 0.775522 (incl. 0 thus not significant)

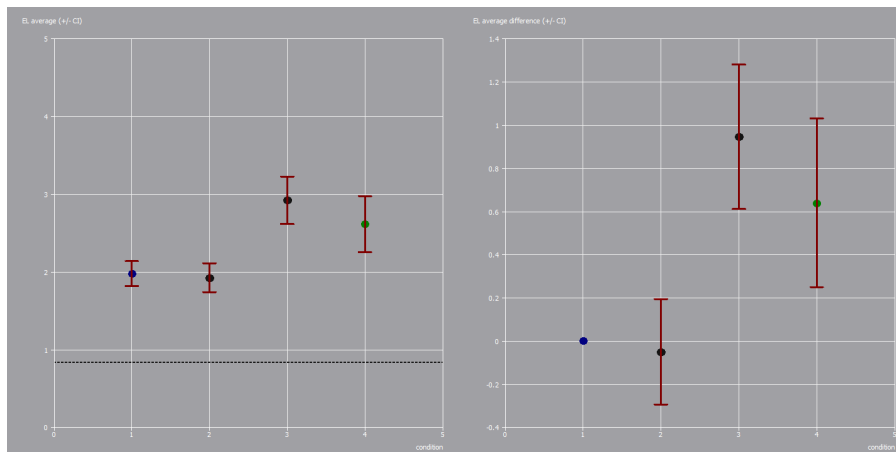


Figure 26. Data collected on the interpersonal distance kept by participants for the different conditions. The x-axis presents the data per condition: 1 = no extra stimuli, 2 = thermal body heat, 3 = vibration heart rate, 4 = both thermal + vibration. Left: a histogram plot of the data. Right: T-test output plot of the data

4.2 Qualitative results

This section presents the qualitative results obtained from the semi-structured interviews held post-study.

4.2.1 Design of the environment

Regarding the design of the environment and its immersion factor for the participants, there were two types of participants. On the one hand people felt very amazed:

P1: "It really felt like being somewhere different and that was very interesting."

P2: "I was really not used to VR as a whole, so I was at first very surprised. Like, whoa, there's a totally different world and it's nice."

P6: "It felt very real. I was really amazed by how the development of this kind of technology has evolved. Very realistic environment. Also, very calm atmosphere that was created so that's nice."

On the other hand there were people who were more actively pointing out details of the quality of the environment:

P3: "The surroundings was a bit clearer that it was virtual in the graphics fidelity and the way it looked. That's something you notice in the beginning, because you kind of look around and then you get to the task of teleporting. And it doesn't bother me that much. I would say immersion wise, if I would compare this to a triple A game that's on a super computer, it is going to create different levels of immersion. But at the same time. I was there with a task to do and it didn't distract me from it."

P4: "How it looked reminded me of a medium old video game. Like a simple 3D game, it was semi-stylized to me. It did feel different to me than when you're playing a regular game or looking at your screen."

P10: "I kind of liked that it was still, like it resembled of course real life, but with the kind of assets you always still knew it was a digital space and I kind of like that so it didn't distract me too much from what was happening and on the task itself."

Especially the ability to teleport made it for P2 less of a natural environment:

P2: "The environment itself was OK I guess, so it was nice that you could move around. It did not feel that natural, like you could click with your laser to point and just fade to that same point."

Some design decision were specifically picked up positively by participants as well:

P2: "I really like the path that ended up in the far distance."

P7: "Not the environment I was expecting. It was in the forest, I was expecting something with a city. But the forest gave me some calming, that's why I could focus more on the senses."

4.2.2 Design of the avatars

The design of the avatars sparked different opinions within the participant group. Some people experienced them as being quite realistic humans:

P5: "The people. They felt quite real. I think it really helped for me, also for the realness of the environment, that the sounds and the stimuli changed based on your distance and that you could hear them where they were located and for the rest just how they behave and how they talked it were human like voices."

P7: "Well, I know it's quite difficult to make a realistic representation of a real human, but I think these came quite near and the way they talked was for me quite nice, the tone."

P11: "They seem pretty real, especially because the surround sound changes very much depending on your distance towards the subject. That's what felt most real to me."

But the fact that the avatars were not made to be too much human-like was also appreciated:

P1: "I really like that they are a little bit cartoonish and they really reminded me of the Sims for some reason and that has something very endearing, right. So, it's really you kind of recognize that it should be a person."

P3: "I thought the characters were decently convincing, especially because they weren't trying to be perfect humans."

P8: "They felt quite as real persons to me in a sense because they were not too detailed and not too real. They gave a good impression to me and they seemed to be happy most of the time."

And then some participants were not very much impressed by the design of the avatars:

P4: "They looked like humans to me. But not too much, I didn't get the feeling that I was talking to a real person."

P6: "I don't find the avatars very interesting. Even though they did their best in making the noise, making the sound of their voice louder when you approached and stuff like that. I did find that their faces were a bit fake and I also thought the way they moved were a bit unrealistic. I did hear that they sometimes had a very optimistic story and sometimes it was a bit sad or a bit dark, but I would not pay much attention."

Whereas most participants did not listen that carefully to the stories of the avatars:

P7: "Of course, the things they said were always the same. So, in the end I could almost repeat what they said."

P8: "I was often thinking, about the stories about the woods and everything, there was like OK, now I heard enough about woods, let's continue."

P2 did listen well to them and coupled the different trial stories as if it really was the same person telling them things:

P2: "They were just two of the same people. But they told different stories. One time where he more or less told about the forest attacking him, that was the point of I don't trust this guy anymore because he's just crazy. But then he told another story about his traumas in the woods or something like that. And I was like, OK, but you're still the guy who thought he was attacked by a tree."

Regarding the body the participants were given themselves, not many of them actively acknowledged it. Although they liked there being something rather than nothing representing them:

P10: "I think it would be nice to, just if you look down, there is something there that it's not just a nothing."

P11: "It felt more like an indication of where my pointer pointers are. Just a little bit of added value, but yeah so. Some feedback."

4.2.3 Design of the vibration heart rate

Although there were hesitations for some participants, quite some of them managed to pick up the heart rate rhythm:

P1: "I had a feeling it was, you know, kind of rhythm, like maybe like waves, or like a heart rhythm."

P3: "It felt quite natural that when I approached someone else I have this vibration and my assumption is that it needs to represent the heartbeat of that other person."

P7: "I noticed that at some point I was standing in a position, and it represented a bit of a pattern, close to a heart rhythm."

Also, one participant was concerned about the heart rate of the avatar:

P2: "I felt 'chill a bit' like the heartbeat was very fast. I would like the vibrations if it would be a bit slower ... it didn't feel as part of the person."

In contrast, another participant ignored the vibrations:

P6: "I just neglected it. And sometimes I even hardly felt that it happened."

The fact that they were perceiving a heart rate that was not their own sparked some thoughts for the participants as well. Ranging from aversive feelings to it making sense to feel it:

P2: "Usually, I also don't feel other people's heartbeats whenever I stand next to them."

P3: "Rationally is not very natural. Because if I talk to someone I don't feel their heartbeat, that would be kind of strange. But, it also kind of worked in a way. It didn't distract me and it gave another sort of stimuli to knowing like I'm close to this character, which I'm interacting with, which made sense in the experience."

P5: "It's a little bit weird to feel it, like normally you would also not feel it, so it's really kind of messing with your mind what you are feeling."

4.2.4 Design of the thermal body temperature

Opposite to the vibration, the temperature stimuli was perceived as less present:

P2: "I couldn't pinpoint the point where it was on or not."

P5: "I found it very hard to feel if it was warm or not. I think in the beginning I felt it and then I didn't really feel any changes."

Explanations for this lack of perception ranged from not being focused on it to temperature just not being a stimuli with a clear switching on and off point like the vibrations did have:

P1: "I just tried to get to the avatar, to feel close, or to have a comfortable conversation, that I didn't really focus on the temperature. It wasn't really prominent."

P10: "I think it was quite comfortable because I didn't really notice it so much, or at least I wasn't focused on it, which would also be a good thing because it didn't distract me at all from the experience."

P11: "Yeah, that was quite comfortable. It was not really too hot or anything. I couldn't really detect when it was turning on or engaging so there wasn't really a switch point, but at one point I thought about it and it was warm."

In combination with the vibration stimuli, which P8 perceived as annoying, the warmth did balance the experience:

P8: "I find the thermal a bit hard to quantify because it was way more subtle than the vibration. I had the feeling when the vibration was going I was less annoyed by the vibration. Maybe that was because the heat was on, but it was much more subconscious. It was easier to rule out the vibration of the controller, it balanced it or something."

At least, the design aim of not making the Peltier element become uncomfortably warm did succeed:

P9: "The warmth was more comfortable for me."

P7: "It was probably a bit heating up or having the same temperature as my arm, but that was not annoying or something. I enjoyed the warmth."

None of the participants by themselves mentioned that the temperature could be representing the body heat of the avatar. For example, P11 explained they see warmth more as an ambiance indicator:

P11: "I really associated it more with the actual environment, so makes sense if it would be sunny or a bit more frosty or anything, or I guess it would be better to convey some ambiance from the actual environment."

4.2.5 Factors influencing the kept distance

The task of the participants was to find a comfortable distance to the avatar. In the interview afterwards they explained elaborately which factors they felt most influenced their choice of distance.

First, although the stories told by the avatars was mentioned by participants not to be constantly influencing their kept distance, they had some vivid memories of encounters with negative stories:

P1: "The person was kind of like depressed or something or was talking about kind of down things, negative things, and I noticed that I really wanted to keep my distance."

P3: "I remember there was one that was more of a negative story. Something like I often feel alone or something and it happened right when I teleported right in their face and then I was just like, oh hold up this is this is a bit much now."

P8: "Sometimes I also felt a bit discomfort about the people. At once the guy was talking about how he felt watched in the woods, that was discomforting for me. I wanted to maintain distance because I really didn't like that person at that moment and also felt a bit watched almost."

Besides, the neutral stories sometimes made the interaction feel more like the avatar was giving a lecture:

P1: "Well, there was a I thought like there was some very scientific talk about like uranium and it was kind of a lecture thing that was I was like, OK I'm OK with getting a little bit of distance from this because I can like still listen to it and not involve myself."

P10: "I think for the factual, it really felt more like a lecture or like a group guide where you just stand at a distance."

Second, the fact that the avatar was not a familiar person to them caused participants to stay further away throughout the entire study:

P9: "So, with a stranger, which this case would be, I guess. I think I'd be more likely to stay away. Just because boundaries. If it will be a friend or a family, I'd be more inclined to be closer because I trust them and I'd expect them to trust me."

P10: "I did notice for myself at least, was that I do stand a little bit further than how I would normally stand with friends. You don't stand really close to a stranger you don't know because that's weird."

Third, the heart rate vibrations impacted the perceived kept distance for almost all participants. They explained to want to stay further away from the avatar because they either find the stimuli itself to be too much when being very near:

P1: "I felt I wanted to go closer to the avatar to feel it at a certain distance. But then the vibrations became that prominent, when I transported to the square that I was like expecting to want to be in then the vibrations were like very 'there' and I didn't really like it. And then when it was like on the background and low then it was kind of soothing."

P10: "The ones that were like a bit lower intensity, those were quite comfortable. The higher intensity kind of took me out of the experience a bit more. I wouldn't have that in natural life to just vibrate my hands so that took me out a bit."

P11: "I tried to look at what distance the feedback wasn't there, but I felt like that was still pretty far away from the avatar to really follow the story they were saying. Ultimately, I stepped closer. And so I could follow the story a bit better and just accepted that it was not really comfortable."

Or they kept distance based on how the added heart rate made them feel about the avatar:

P7: "I noticed that at some point I was standing in a position ... and then I was like all right. I'm going to go further away. When it was not dominant it was OK for me."

P8: "I felt that I was more triggered, and I was more annoyed by the person. So, with the vibration I was even more thinking, could you please shut up? Whenever I felt annoyed, I didn't want to get as close to the person as I would like if I was not annoyed. It was more like 'I can go away more quickly' or something. If there was a vibration, I didn't want to start the conversation with that person."

P9: "It felt to me like it pushed me away from the person that the harder the vibration was the further away I wanted to be from that person. It wasn't necessarily uncomfortable. I don't know why, it was just a feeling that I had."

Fourth, the body heat thermal stimuli was only mentioned by a few of the participants. P3 actively interacted with it even, using it as a gameplay element for the avatar to be able to indicate to stay out of its intimate zone:

P3: "I noticed that I was purposely getting a bit closer for it to get warm and then drew myself back again to get the sensation. I would say especially getting like super up close, like comically close, where I can't even see their face. That's the point where I was also getting warm and it kind of deterred me from it. The point where I was like, oh, this is a bit too much, but it was also kind of a funny way of the character being like hey, back off. So, in a way it was more of this like gameplay element where I'm playing with it more than natural feedback."

Also, P9 indicated the heart rate vibration to be a factor of staying further away, but when the warmth was added at the same time this drew them in slightly:

P9: "I was more likely to be closer to the person as the warmth got warmer. The effect of the vibrations were stronger than the warmth, so I was more likely to stay further away than that the warmth drew me in."

4.2.6 Applicability for use on social VR platforms

In conversation about whether adding biosignals to social VR platforms would be something the participants want, the opinions how they would use it differ. For instance, the implementation of using them to signal how someone is doing was suggested:

P1: "I do really imagine that it would be very nice to go into a chat room and talk to a person and then have some sensation of how the person is and how the person is doing because you don't really see them, like the avatar is not complete."

P7: "People need their space, also in the Metaverse. So, in that sense I think these kind of things can help with controlling the distance and also noticing how other people experience their space. Because in real life we do that all the time and you really notice quite quickly when somebody feels uncomfortable."

Additionally, the suggestion was made to be able to signal vibrations to other to maintain your preferred distance to others:

P5: "Well, I wouldn't personally like the vibrations. Except if you want to create a barrier then that could be interesting."

P7: "When you are feeling 'I want my space here'. Then you maybe could send off more vibrating kind of signal and then a lot of people will say, oh wait, I don't want to be close to this person, but then you get your space."

Also, some ethical remarks were made about the heart rate giving away emotional state and thermal being more of a subconscious stimuli, and therefore being able to influence someone without them knowing:

P2: "From an ethical point of view, I don't know if I want to disclose my heartbeat at all times. Of course if I'm tired it's fine, you can know I'm tired, but if I'm nervous you don't really need to know I'm nervous, so I would like to have the option to put it on or off."

P8: "If everybody is able to like influence me in this way or something then I have the feeling that I cannot myself like think about. Is this a good person? This is an annoying person or is this even a person?"

Lastly, people commented on the risk for over-stimulation if they would get biosignal stimuli from everyone they encounter on a social VR platform:

P3: "In VR chat, it's like immensely chaotic, and that's kind of the draw of the of the environment. I could also see how this is like totally going to overstimulate you. But, that might be part of the experience."

P10: "Especially if there are loads of avatars it could become overwhelming and if, for example, somebody just walks past you or like there are people that walk into your space without your control, suddenly you have different feedbacks from them. Maybe you would be able to like select that person that you're talking to or interacting with, from which you can feel it."

5. Discussion & Conclusion

Current social VR interaction lacks a lot of the nonverbal cues that are available when talking to people in the real world. Therefore, this work aimed to explore the biosignals heart rate and body temperature as potential new forms of nonverbal communication cues. The objective was two-fold: 1) Exploring how to design these biosignals properly so they feel natural to the participants, and 2) Studying how haptic biosignals could be of added value on the interaction with an avatar in VR.

5.1 Discussion on the design of haptic biosignal stimuli and future work

For the first objective, the feedback of the participants is very valuable for evaluating which design decisions were successful and what could be designed differently. Within this work, design choices were mainly made based on previous work and the technical possibilities within the time frame of the project. Intermediate testing by myself and a pilot participant were indicators on whether the biosignal design was conveyed well by the prototype.

5.1.1 Make the heart rate more recognizable

The heart rate vibrations provided by the Touch controllers were not always recognized as such. This had two causes: 1) The vibrations were too evident and therefore distracting, 2) The vibrations were ambiguous by themselves.

As a design alteration to tackle the first cause, a personal comfort level of intensity could be set beforehand. This could then be the level of intensity on the verge of entering the social zone from the public zone at 3.70 meters. Whereas previous work found visual heart rate to be easily overruled by the level of immersion of VR [10, 40], vibrations show to be more capable of doing this. Future work could focus on finding the optimal level of intensity where the vibration is perceived but not overruling in the experience.

The second cause was explained by participants as it not being a familiar experience to feel someone else's heart rate when being on a distance. When used in combination with auditory stimuli, as done by Chen et al. [6], this lack of recognition did not arise. Providing the heart rate in a multi-sensory way may therefore lead to a more correctly perceived representation. Another imaginable explanation is the quality of the vibration motors in the Touch controllers and the way they vibrate. As explained in section 3.2.2, the motors are not optimal to convey complex vibrations. Unfortunately, the Meta Quest Touch Pro controllers were not yet available when doing this design. For future work these might be used to set PCM (Pulse Code Modulation) vibration to have more control over the output and to make use of the multiple vibration actuators per controller.

5.1.2 Increase intensity of thermal body temperature

In this study, the thermal stimuli was provided by a Peltier element. Instead of presenting the participant with actual body temperature feedback, as this would be too subtle [12], the feedback would increase in temperature when coming closer to the avatar. In accordance with previous work on providing thermal feedback, the change in temperature per step was set to a maximum of four degrees Celsius [46]. From the study it can be concluded that this still was too subtle as the moments of change were not detected clearly. This could be explained by the study being in VR, causing a higher level of immersion into that

environment, so neglecting more subtle cues from outside. Especially when presented at the same time as the heart rate vibration, the thermal stimuli would be overruled. This is a similar effect as was found with vibration and auditory stimuli in earlier work [15]. Recommendations for future design of thermal body temperature would be to either make the temperature differences much larger to be able to detect them clearly, or make it an ambient stimuli by for example changing room temperature.

5.2 Conclusions on the research questions

For the second objective, a study implementing the designed haptic biosignals was performed. In this section the research question belonging to the objective: 'How can haptic biosignals, in the form of vibrotactile heart rate and thermal body temperature, contribute to the interaction between a VR user and a virtual avatar?' together with the sub question: 'How does adding vibrotactile heart rate and/or thermal body temperature feedback of another avatar influence the kept interpersonal distance by a user?' will be answered per biosignal.

5.2.1 Heart rate vibration enlarging interpersonal distance

Heart rate vibrations contributed to the interaction by enlarging the kept interpersonal distance. Whereas interactions without the heart rate vibration made people stand in the close phase of the social zone (between 1.22 and 2.10 meters), interactions with the heart rate stimuli pushed people to the far phase of the social zone (between 2.10 and 3.70 meters). Besides, the post-trial question about the feeling of wanting to maintain at a distance was also answered more strongly. Like previous work in which participants are hesitant about sharing their heart rate with others, especially with people they do not know well [38, 47], receiving the heart rate of the avatar (a stranger) induced mixed feelings. For example, P3 explained their mixed feelings as follows:

"Rationally is not very natural. Because if I talk to someone I don't feel their heartbeat, that would be kind of strange. But, it also kind of worked in a way. It didn't distract me and it gave another sort of stimuli to knowing like I'm close to this character, which I'm interacting with, which made sense in the experience."

P2 also highlighted their concern about the well-being of the avatar "I felt 'chill a bit' like the heartbeat was very fast.", which was found as well in earlier work when a biosignal is perceived as being too high or low [30, 52].

The heart rate vibration was not for everyone as recognizable. However, this ambiguity might not be much of a problem in an environment in which more cues are available, a hint might be enough [12]. As P9 indicated:

"It felt to me like it pushed me away from the person that the harder the vibration was the further away I wanted to be from that person. It wasn't necessarily uncomfortable. I don't know why, it was just a feeling that I had."

In earlier work this need to keep more distance when hearing someone's heart rate both outside of VR [24] and within VR [22] was also found. Although P9 was not able to explain exactly why they wanted to maintain a larger distance when feeling the heart rate vibration, the behavior is the same as someone who did recognize the vibrations as heart rate.

In conversation about implementation on social VR platforms, increasing the interpersonal distance through heart rate vibration was seen as useful. For example, to create a barrier between your-self and strangers by sending out vibrations when you want more space to yourself. By using the heart rate in this way, it becomes a very apparent nonverbal cue for people to stay away. Besides using the heart rate to signal themselves, it was also picked up that this signal could be used to gain more information on other people. For instance, to know better how someone is doing and how they experience their personal

space. So, although it was novel to participants to experience a vibration heart rate they saw potential to use it in a social VR environment when tweaked to their preferences on intensity.

5.2.2 Translating body temperature to ambient emotional states

Providing body temperature stimuli when being close to the avatar did not contribute significantly to the experience when examining the quantitative data. However, a slight decrease of interpersonal distance could be seen and was mentioned during the interviews. For example, P8 and P9 mentioned the warmth compensating for the increased distance they wanted to keep due to the heart rate vibrations. In the current design the actual (and amplified when standing very close by) body temperature was conveyed which, by always being warm, was interpreted as comfortable and therefore the avatars always being happy. In this form, the body temperature is then not a very useful nonverbal cue as it only conveys positive information.

For thermal stimuli to be able to represent body temperature states more accurately, presenting an emotional state interpretation might be better. For instance, the comfortable warm temperature could then be applied when the body temperature of someone matches a happy state of being. In this way, the ambiguous body temperature becomes more interpretable as we have strong emotional associations with certain temperatures [4]. By providing a wider range of temperatures, it could be studied whether cool temperatures enlarge the kept interpersonal distance in VR interaction just like warmth decreases it, like found by Ijzerman et al. [21] in a real-world scenario by giving people either a cold or hot drink to hold.

So, the current contribution of thermal body temperature stimuli to the interaction with the avatar is minimal. The study's insights hint at body temperature being a factor to decrease the interpersonal distance in VR. But, further research on how to make body temperature a more comprehensible thermal feedback might shed light on how to make it more meaningful for nonverbal interaction.

5.3 Limitations

The limitations of this work are primarily technical and time related. The technical aspects include the level of development of the vibration motors within the Touch controllers and the limitations of using a Peltier element to provide heat. Although it was possible, after many ways of trying, to convey a more complex vibration with the Touch controllers it still remained a medium quality motor providing the vibrations. The main limitation this gives is that vibrations never stop at once, they fade out as the motor is turned off, and this causes vibrations to overlap each other slightly. Furthermore, the Peltier element gives great prototyping possibilities to heat up a local spot to a certain extent. However, it must be noted that this could not be used for long periods of time or for much higher temperatures than used in this study, the Peltier would simply not be capable of providing that without internally overheating. Time limitations relate mainly to the testing phase, as Oculus broke the developer mode with a software update just before the testing was planned. This meant that uploading the VR environment made with Unity to the Quest 2 was not possible. When this bug was fixed the only remaining time to perform the study was around Christmas time and early in the new year, resulting in a participant group of just 12 people that is only partially counterbalanced. The counterbalancing here means that the starting block was differentiated among the participants.

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Appendices

A. Avatar stories

Step 1: AI-generated texts were created using the Copy.AI tool online, an example is shown below.

Mode 'Description'

Description: Monologue about being in the forest

Tone: Happy

1. "It's peaceful and quiet. No noise, no people. Just me and the forest."
2. "Yes, of course. I love to explore the woods. The trees are so tall and the air is fresh. If you ask me what my favorite part of the forest is, I would have to answer that it's when I spot a pretty bird flying overhead. I wonder if they can tell just how far they've flown or even how far they will fly? Sometimes, I get so carried away with imagining that sometimes, it makes my heart pound as fast as any drumbeats in heaven. To think that perhaps they feel everything just as we do..."
3. "I'm sitting by a forest, looking through the canopy, watching squirrels chase each other. I've been studying tree rings and they say there was a period of time where this species of squirrel got smaller. I wonder why? I look at that and think about 20,000 years ago humans were just starting to move into Europe for the first time. It must have been way harder than it is now because it took us thousands of years to get here yet these squirrels are probably newbies here too. They're trying different things out, testing out their boundaries and that is anything but boring to watch!"
4. "It was a nice night, outside, with the sound of crickets and distant traffic. I couldn't remember having felt so relaxed in years. There was something about being out there in nature that just makes you feel good. I took my shoes off and walked around for awhile, watching the forest as it closed and opened around me as if guided by an unseen hand. Soon I found myself standing beneath a large tree that had been struck by lightning years before and stood alone in the woods surrounded by dusk-shrouded trees. Wind rustled through the leaves above, creating delicate sounds that seemed to come from all directions at once, like gentle finger tips tapping on glass. Then suddenly it came to me; this is what peace feels like!"
5. "The forest is a living thing. It moves with the wind, it breathes in and out with the rhythm of its own life, and it stirs around us as we walk on its ground. In the forest, you can see the world differently. You may hear the birds singing their beautiful songs while they fly through the air, or you may feel their wings brushing against you as they pass by. You will smell all of these things around you—the earthy scent of plants that grow deep underground and make their way to sunlight each day; or maybe something else entirely—something you cannot explain until you've experienced it firsthand. In the forest, there are no words to describe what happens when you are there—when everything is so alive and vibrant and full of color. You cannot look at anything without seeing something new or different than what was before your eyes moments ago. The forest is where I go to escape from reality for a little bit every day—where I can walk for miles without having any idea where I'm going or what's happening around me, because everything is just so beautiful and soothing when I'm out there somewhere in its depths"

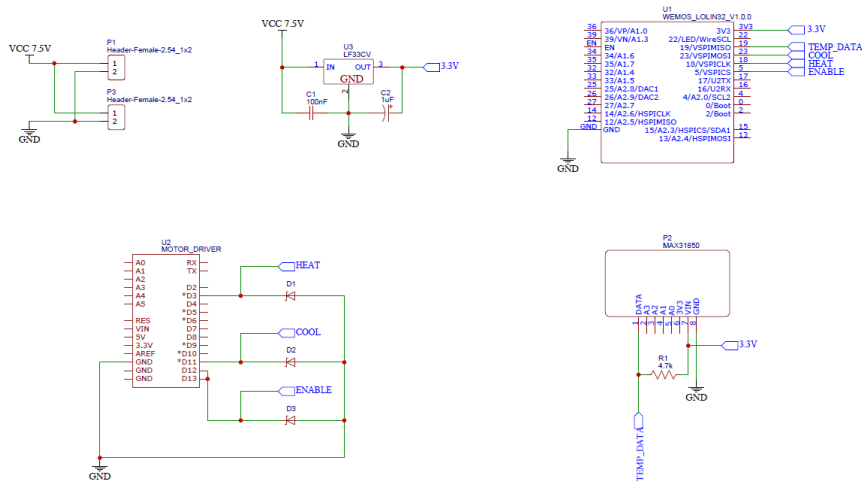
Step 2: A database of the different stories was created. This database can be viewed [here](#). Also, the created stories were checked with the sentiment analysis tool of Hugging Face.

Step 3: The stories were converted using Google's Text-to-Speech functionality using AI-voices.

B. Prototype technical details

The Unity project can be viewed in a Github repository that can be viewed [here](#). A repository containing the first steps of the process can be viewed [here](#), the newer repository was created because the old one lacked the implementation of Large File Support. The scripts can be found through Assets --> Scripts.

The Peltier's ESP32 circuit as well as the code loaded onto it can be seen below.



```
#include <DallasTemperature.h>
#include <OneWire.h>
#include <PID_v1.h>
#include <analogWrite.h>
#include <WiFi.h>
#include <ESPmDNS.h>
#include <ESPAsyncWebServer.h>

/**
 * Constants for driver mode. MODE_DIRECT means any received value for the
 * TARGET characteristic is interpreted as power level for the Peltier element
 * in the range of -128 to +127, with negative values being interpreted as
 * cooling, positive values interpreted as heating and 0 being interpreted as
 * turning the element off. MODE_PID on the other hand means that the value of
 * the TARGET characteristic is interpreted as target temperature that the PID
 * algorithm will try to approach.
 */
#define MODE_DIRECT 0
#define MODE_PID 1

// Pin definitions for temperature probe and the board's builtin LED
#define TEMP_PROBE 19
#define LED_BUILTIN 22

// Pin definitions for the wire connections responsible to heating, cooling and
// enabling the driver
#define DRIVER_COOL 23
#define DRIVER_WARM 18
#define DRIVER_ENABLE 5

// Acceptable maximum and minimum temperature for the Peltier element
#define MAX_TEMP 45
#define MIN_TEMP 0

// PID constants
#define KP 4
#define KI 0.2
#define KD 1
```



```

// WiFi credentials and hostname
const char* ssid = "TP-Link_E2DC"; //Pampus
const char* password = "41742670"; //Pampus@CW
const char* hostname = "thermalwear";

// Initialise web server
AsyncWebServer server(80);

// Initialise OneWire protocol with pin for temperature probe
OneWire oneWire(TEMP_PROBE);
DallasTemperature temperatureSensors(&oneWire);

// Variables for keeping track of last main loop update and last temperature
// update.
unsigned long lastUpdate = millis();
unsigned long tempLastUpdate = millis();

// Initialise variables holding temperature PID setpoint and current PID output
// level.
double temperature = 0, setpoint = 32, pidOutput = 0;
// Initialise target to 0 and driver mode to DIRECT mode
int8_t target = 0;
int driverMode = MODE_DIRECT;

// Initialise PID with given variables and constants
PID pid(&temperature, &pidOutput, &setpoint, KP, KI, KD, DIRECT);

/**
 * Flashes the board's internal LED. This is useful for getting feedback on
 * connection and write status. The optional parameter `repeat` repeats the
 * flashing the specified number of times.
 *
 * @param repeat Repeat the flashing n times. Defaults to 1
 */
void flashLED(uint8_t repeat = 1) {
  for (uint8_t i=0; i<repeat; i++) {
    // Get current status of LED
    int status = digitalRead(LED_BUILTIN);

    // If LED is on
    if (status == LOW) {
      // Turn LED off
      digitalWrite(LED_BUILTIN, HIGH);
      // Wait 200ms
      delay(200);
      // Turn LED on
      digitalWrite(LED_BUILTIN, LOW);
    } else {
      // Turn LED off
      digitalWrite(LED_BUILTIN, LOW);
      // Wait 200ms
      delay(200);
      // Turn LED on
      digitalWrite(LED_BUILTIN, HIGH);
    }

    // Wait 200ms
    delay(200);
  }
}

/**
 * Requests the current temperature of the Peltier element from the temperature
 * probe and stores the retrieved value in the variable `temperature`. The
 * value is refreshed at most every 100ms. Calling the function more often than
 * that will simply drop any extraneous requests.
 *
 * @returns True if the value was refreshed, false otherwise
 */
bool requestTemperature() {
  // Make sure the value is only read at most every 100ms
  if (millis() > tempLastUpdate + 100) {
    // Request temperature from temperature probe
    temperatureSensors.requestTemperatures();
    // Write temperature to variable `temperature`
    temperature = temperatureSensors.getTempCByIndex(0);
  }
}

```

```

    // Update refresh timestamp
    tempLastUpdate = millis();
    return true;
}

// Return false if value was not refreshed
return false;
}

/**
 * Sets the Peltier element to warming mode by writing the given value to the
 * DRIVER_WARM pin and pulling the DRIVER_ENABLE pin HIGH.
 *
 * @param value Power level at which the Peltier element should be heating
 */
void warm(uint32_t value) {
    // Write value to pin for warming and set cooling pin to 0
    analogWrite(DRIVER_WARM, value);
    analogWrite(DRIVER_COOL, 0);

    // Enable driver
    digitalWrite(DRIVER_ENABLE, HIGH);
}

/**
 * Sets the Peltier element to cooling mode by writing the given value to the
 * DRIVER_COOL pin and pulling the DRIVER_ENABLE pin HIGH.
 *
 * @param value Power level at which the Peltier element should be cooling
 */
void cool(uint32_t value) {
    // Write value to pin for cooling and set warming pin to 0
    analogWrite(DRIVER_WARM, 0);
    analogWrite(DRIVER_COOL, value);

    // Enable driver
    digitalWrite(DRIVER_ENABLE, HIGH);
}

/**
 * Disables the heating element altogether by writing 0 to both, the heating
 * and the warming pin, as well as pulling the DRIVER_ENABLE pin to LOW.
 */
void shutoff() {
    // Disable driver
    digitalWrite(DRIVER_ENABLE, LOW);

    // Write 0 to pin for cooling and pin for warming
    analogWrite(DRIVER_WARM, 0);
    analogWrite(DRIVER_COOL, 0);
}

/**
 * Sets up the routes for the HTTP server and starts the server on port 80.
 */
void setupHTTPServer() {
    // Root path returns empty 200 response
    server.on("/", HTTP_GET, [](AsyncWebServerRequest *req) {
        req->send(200, "application/json", "{\"status\": \"OK\"}");
    });

    // Return current temperature
    server.on("/temperature", HTTP_GET, [&](AsyncWebServerRequest *req) {
        AsyncResponseStream *res = req->beginResponseStream("application/json");
        res->printf("{\"temperature\": %f}\n", temperature);

        req->send(res);
    });

    // Return current status
    server.on("/status", HTTP_GET, [&](AsyncWebServerRequest *req) {
        AsyncResponseStream *res = req->beginResponseStream("application/json");

        if (driverMode == MODE_DIRECT) {
            res->printf("{\"mode\": \"DIRECT\", \"temperature\": %f, \"output\": %d }\n", temperature, target);
        }
    });
}

```

```

} else {
    res->printf("{ \"mode\": \"PID\", \"temperature\": %f, \"output\": %f}\n", temperature, pidOutput);
}

req->send(res);
});

// Return current driver mode
server.on("/mode", HTTP_GET, [&](AsyncWebServerRequest *req) {
    AsyncResponseStream *res = req->beginResponseStream("application/json");

    if (driverMode == MODE_PID) {
        res->println("{ \"mode\": \"PID\" }");
    } else {
        res->println("{ \"mode\": \"DIRECT\" }");
    }

    req->send(res);
});

// Set driver mode to DIRECT
server.on("/mode/direct", HTTP_POST, [&](AsyncWebServerRequest *req) {
    driverMode = MODE_DIRECT;
    req->send(200, "application/json", "{ \"status\": \"OK\" }");
});

// Set driver mode to PID
server.on("/mode/pid", HTTP_POST, [&](AsyncWebServerRequest *req) {
    driverMode = MODE_PID;
    req->send(200, "application/json", "{ \"status\": \"OK\" }");
});

// Disable the driver
server.on("/shutoff", HTTP_POST, [&](AsyncWebServerRequest *req) {
    // Switch to DIRECT mode and set target to 0 to disable the driver
    driverMode = MODE_DIRECT;
    target = 0;

    req->send(200, "application/json", "{ \"status\": \"OK\" }");
});

// Set the device to the given target temperature
server.on("/temperature", HTTP_POST, [&](AsyncWebServerRequest *req) {
    // Make sure the request contains the param 'target'
    if (req->hasParam("target", true)) {
        auto p = req->getParam("target", true);
        int value = p->value().toInt();

        if (value >= MIN_TEMP && value <= MAX_TEMP) {
            // Set driver mode to PID and set target temperature
            driverMode = MODE_PID;
            target = value;

            req->send(200, "application/json", "{ \"status\": \"OK\" }");
        } else {
            req->send(400, "application/json", "{ \"status\": \"ERR\", \"message\": \"Target temperature not in valid range\" }");
        }
    } else {
        req->send(400, "application/json", "{ \"status\": \"ERR\", \"message\": \"Target temperature not specified\" }");
    }
});

// Set the device to the given target output level
server.on("/power", HTTP_POST, [&](AsyncWebServerRequest *req) {
    // Make sure the request contains the param 'target'
    if (req->hasParam("target", true)) {
        auto p = req->getParam("target", true);
        int value = p->value().toInt();

        if (value >= -125 && value <= 125) {
            // Set driver mode to DIRECT and set target output level
            driverMode = MODE_DIRECT;
            target = value;

            req->send(200, "application/json", "{ \"status\": \"OK\" }");
        } else {

```

```

    req->send(400, "application/json", "{ \"status\": \"ERR\", \"message\": \"Target output value must by within range [-125, 125]\" }");
  }
} else {
  req->send(400, "application/json", "{ \"status\": \"ERR\", \"message\": \"Target output value not specified\" }");
}
});

server.begin();
}

/**
 * Setup function called by the Arduino runtime on boot. Initialises the serial
 * link to 115200 baud for debugging, sets pin modes, initialises temperature
 * sensor, PID, WiFi and HTTP server.
 */
void setup() {
  // Begin serial connection
  Serial.begin(115200, SERIAL_8N1, 26, 25);
  Serial.println("Setting up device...");

  // Initialise pins
  pinMode(DRIVER_ENABLE, OUTPUT);
  pinMode(LED_BUILTIN, OUTPUT);
  // Turn on builtin LED (pin is active low)
  digitalWrite(LED_BUILTIN, LOW);

  WiFi.config(INADDR_NONE, INADDR_NONE, INADDR_NONE, INADDR_NONE);
  WiFi.setHostname(hostname);
  WiFi.begin(ssid, password);

  while (WiFi.status() != WL_CONNECTED) {
    Serial.print(".");
    delay(100);
  }

  Serial.println("WiFi connected");

  // Start mDNS service
  if (MDNS.begin(hostname)) {
    Serial.println("mDNS service started");
  }

  // Initialise temperature sensor and request current temperature
  temperatureSensors.begin();
  while (!requestTemperature()) {}

  // Initialise PID
  pid.SetOutputLimits(-255, 255);
  pid.SetMode(AUTOMATIC);

  // Set up HTTP server routes
  setupHTTPServer();
  Serial.println("HTTP server started");

  flashLED(3);
}

/**
 * Setup function called by the Arduino runtime continuously. Reads temperature
 * and incoming data every 100ms, prints debugging output and is responsible
 * for interacting with the Peltier element driver.
 */
void loop() {
  // Update temperature value
  requestTemperature();

  // Ensure code is run at most every 100ms
  if (millis() > lastUpdate + 100) {
    // Print debugging output to serial link
    Serial.print("TEMP: ");
    Serial.print(temperature);
    Serial.print(" MODE: ");
    Serial.print(driverMode);
    Serial.print(" VALUE: ");
    Serial.print(target);
    Serial.print(" OUT: ");
  }
}

```

```

// If we're in direct driver mode
if (driverMode == MODE_DIRECT) {
  // Map value of target value from [-128, 127] to [-255, 255]
  uint32_t output = abs(map(target, -128, 127, -255, 255));

  // Check target value
  if (target == 0) {
    // Turn element off if target value is 0
    shutoff();
    //cool(0);
  } else if (target > 0) {
    // Turn heating on if value is bigger than 0
    warm(output);
  } else if (target < 0) {
    // Turn cooling on if value is smaller than 0
    cool(output);
  }

  // Print output value
  Serial.println(output);
} else if (driverMode == MODE_PID) {
  // If target temperature is outside of acceptable range
  if (target > MAX_TEMP || target < MIN_TEMP) {
    // Set setpoint to current temperature, i.e. maintain current status
    setpoint = temperature;
  } else {
    // Otherwise set PID setpoint to target temperature
    setpoint = target;
  }

  // Compute new PID value
  pid.Compute();

  // Check computed PID output value
  if (pidOutput > 0) {
    // Warm if it is bigger than 0
    warm(pidOutput);
  } else if (pidOutput < 0) {
    // Cool if it is smaller than 0
    cool(abs(pidOutput));
  } else if (pidOutput == 0) {
    // Turn element off if it is equal to 0
    //shutoff();
    cool(0);
  }

  // Print output value
  Serial.println(pidOutput);
} else {
  // If driver mode has any other value, turn element off
  shutoff();
  Serial.println("OFF");
}

// If temperature rises above 60 degrees, turn element off for safety
if (temperature > 60) {
  driverMode = MODE_DIRECT;
  target = 0;
  shutoff();
}

// Update refresh timestamp
lastUpdate = millis();
}
}

```

C. Study forms



Background information

All the information will be kept confidential and can only be accessed by the researchers in the DIS group of CWI.

1. Participant ID: _____

2. Gender:

- Male
- Female
- Non-binary
- Prefer not to disclose
- Other

3. How old are you?

- <18
- 18-24
- 25-34
- 35-44
- 45-54
- >54

4. What is your occupation? _____

5. Do you own a Virtual Reality (VR) device/headset?

- Yes, I own a _____
- No

6. Whether you own a VR headset or not, how frequently have you used a VR device?

- Always (daily)
- Often (every week)
- Sometimes (1-2 times a month)
- Few times (1-2 times in the last year)
- Never

7. Which social VR platform(s) have you used? (multiple choices possible)

- Altspace
- VRChat
- Mozilla Hubs
- Rec Room
- NeosVR
- Other: _____
- None

8. Do you have any visual impairment?

- No
- Yes, I have problems with _____

9. Do you wear lenses or glasses to the experiment session to correct your vision?

- No
- Yes

10. Do you have any hearing impairment?

- No
- Yes, I have problems with _____

11. Do you have any motor impairment?

- No
- Yes, I have problems with _____

12. In general, how sensitive is your skin (forearm) typically to hot temperatures (E.g., holding a hot cup of coffee)?

- Not at all
- Slightly sensitive
- Moderately sensitive
- Very sensitive
- Extremely sensitive

13. In general, how sensitive is your skin (forearm) typically to cold temperatures (e.g., holding a cold glass of ice tea)?

- Not at all
- Slightly sensitive
- Moderately sensitive
- Very sensitive
- Extremely sensitive

14. Can you write down the six numbers you see in the following picture:

Three numbers on the **first row**: ___ ___ ___ Three numbers on the **second row**: ___ ___ ___



1

Informed consent form

This document gives you information about a study that is part of a TU/e Industrial Design master project of Simone Ooms (the researcher) performed within the DIS group at CWI Amsterdam. Before we begin, it is important that you learn about the procedure followed throughout the study and that you give your informed consent for voluntary participation. Please read this document carefully.

The aim of this study is to test adding vibration (within one of the VR controllers) and temperature (on the forearm) stimuli to a virtual reality environment. During the study you will experience 24 trials in which you will meet an avatar. These trials are split in 4 groups, in each group the stimuli will be different, note that there will not always be stimuli. After each trial you will see a question screen appear, these can be answered by dragging the slider with your controller ray. After finishing the questions, the next trial will start. After finishing a group of trials, another question screen will appear. Also, after answering these questions a next group of trials will start. After all trials have been completed a small interview will be conducted with the researcher.

Your participation is completely voluntary. You can refuse to participate without giving any reasons and you can stop your participation at any time during the user study. Such decisions will have no negative consequences whatsoever.

The user study does not involve any risks or detrimental side effects.

The study will last approximately 45 minutes.

2 Confidentiality & Data collected

We will not be sharing personal information about you to anyone outside of the research team. The information that we will disseminate from this study will be used for our research purposes only. It will be completely anonymous, and it cannot be traced back to you. Only the researchers will know your identity. Photos and videos of the study will be made but all will be anonymized by blurring faces.

The data that will be collected during the study are the answers given to the questions after each trial and group of trials, the continuous temperature of the thermal feedback element, photos and videos of the study (if you agree to), an audio recording of the interview (will be transcribed and de-identified before it will be stored). All data will be stored on the server of the DIS group of CWI.

3 Research team

The main researcher of this study is TU/e master student Simone Ooms (s.c.ooms@student.tue.nl).

The TU/e mentor of the researcher is Minha Lee (m.lee@tue.nl).

The CWI supervisor of the researcher is Abdallah El Ali (abdallah.el.ali@cw.nl).

4 Certificate of Consent

- I **do** give permission, to publicly publish* photos and videos of me (your face will be blurred). Next to this, my data may also be used for the purpose of this research. I understand that this data will be processed anonymously.

- I **do not** give permission, to publicly publish* photos and videos, I will thus not be seen in any of the photos or videos. However, I **do** give permission for my data to be used for the purpose of this research. I understand that this data will be processed anonymously.

*In a report, paper, presentation, or portfolio of the research team.



I, (NAME)..... have read and understood this consent form and have been given the opportunity to ask questions. I agree to voluntary participate in this research study.

Participant's Signature

Date

Simulator Sickness Questionnaire

Kennedy, Lane, Berbaum, Lilienthal (1993)***

Date: _____ - _____ - _____ Participant ID: _____

Pre-study

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
2. Fatigue	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
3. Headache	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
4. Eye strain	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
5. Difficulty focusing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
6. Salivation increasing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
7. Sweating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
8. Nausea	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
9. Difficulty concentrating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
10. 《 Fullness of the head 》	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
11. Blurred vision	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
12. Dizziness with eyes open	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
13. Dizziness with eyes closed	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
14. * Vertigo	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
15. ** Stomach awareness	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
16. Burping	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>

* Vertigo is experienced as loss of orientation with respect to vertical upright

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

*** Original version: Kennedy, R.S., Lane, N.E., Berbaum, K.s., & Lilienthal, MG(1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3),203-220

Participant ID:

Please give your ratings by marking on the spaces.

Emotion

I am worried about how I look when I use this device. I feel tense or on edge because I am using the device. *2.5/5*



Attachment

I can feel the device on my body. I can feel the device moving.



Harm

The device is causing me some harm. The device is painful to use. *2.5/5*



Perceived change

Using the device makes me feel physically different. I feel strange using the device.



Movement

The device affects the way I move. The device inhibits or restricts my movement. *2.5/5*



Anxiety

I do not feel secure using the device.

