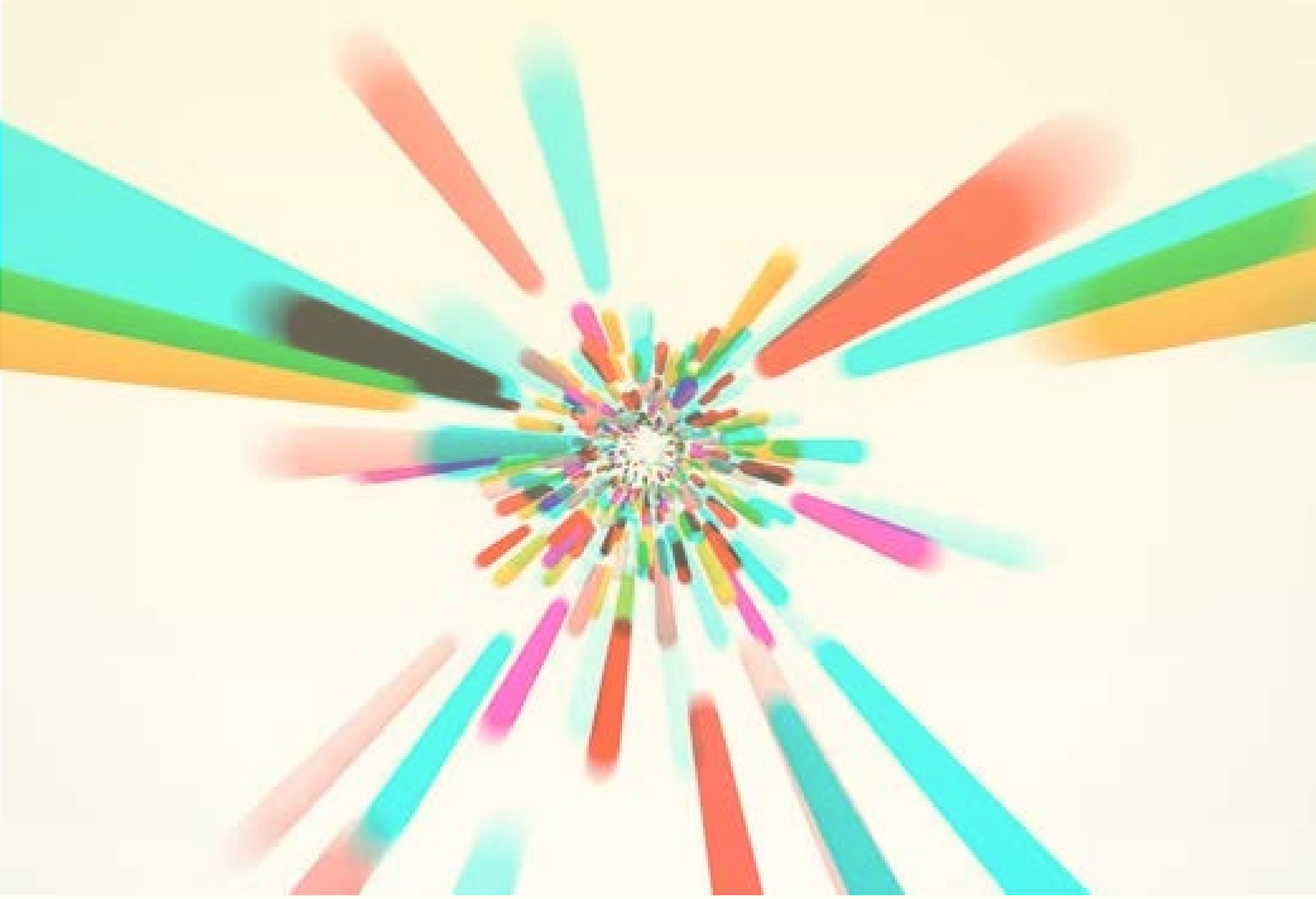
How it feels:

The value and application of physical sensation in XR

Explore Somatosensory experience's possibility in future XR trends.



Master Thesis | Integrated Product Design

Xiangyu Li

11th July 2023

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The value and application of physical sensation in XR

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Master Thesis | Integrated Product Design

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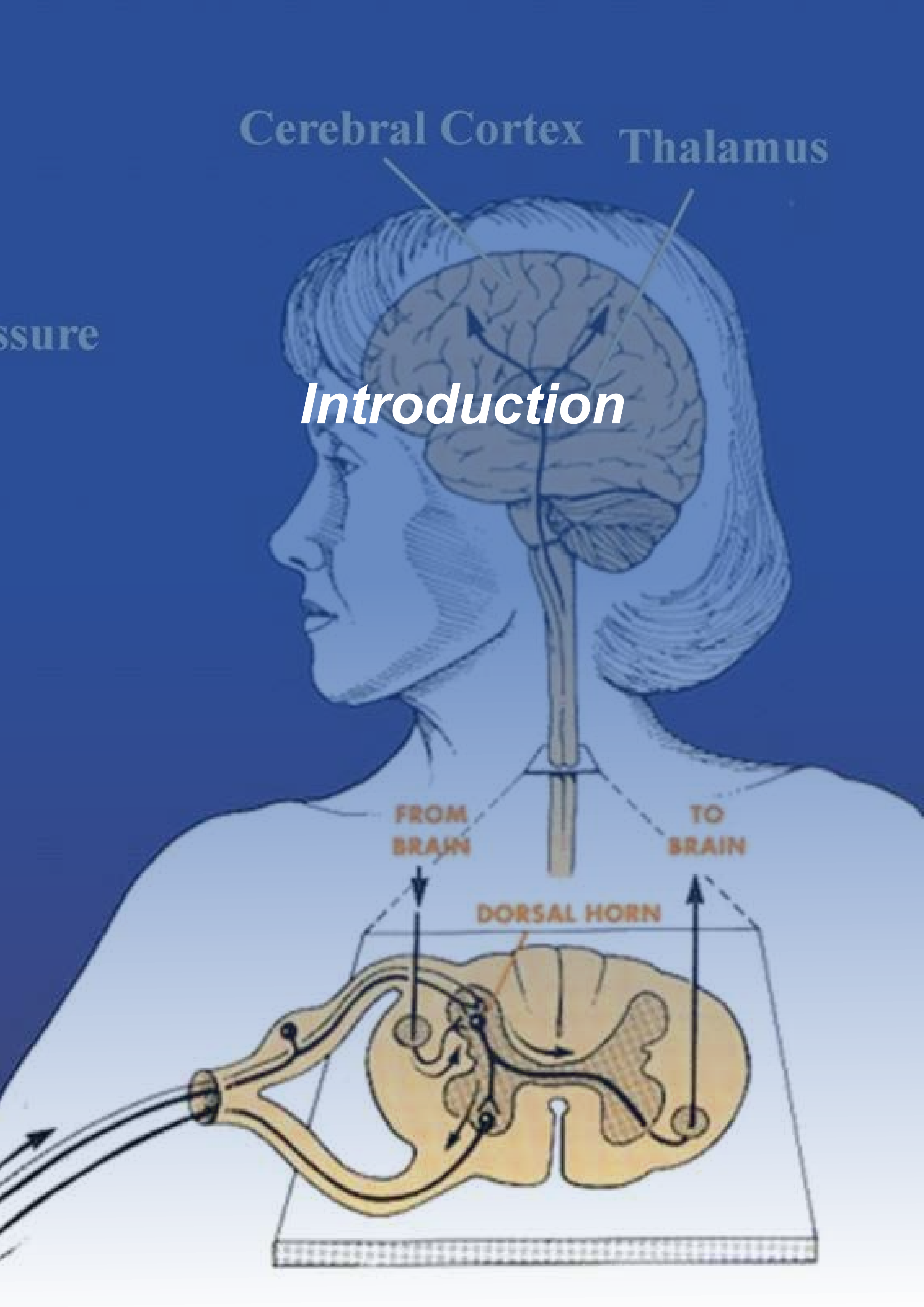
Introduction



Introduction

From virtual reality to extended reality

Immersive technologies have transformed the way we experience and interact with digital environments. The evolution of immersive technologies has progressed from the development of Virtual Reality (VR) to the advent of Augmented Reality (AR) and now to the realm of Extended Reality (XR). In a nutshell, immersive technologies create or extend reality by merging the physical world with digital or simulated reality. It takes the human-to-PC interface and modifies it, either by immersing the user in a completely digital environment (VR), adding to or augmenting the user's surroundings (AR), or both (MR). These technologies have a rich history that dates back several decades. The origins of VR can be traced back to the mid-1960s when Ivan Sutherland sought to conceptualize VR as a 'window into a virtual world.' This world would be perceived by users as authentic in its visual, auditory, and interactive aspects (Sutherland, 1965). Contemporary research has distilled the essence of VR into three core characteristics: immersion, environmental perception, and interaction with the environment. (Cipresso et al., 2018). Following VR, the concept of AR was first proposed by Milgram and Kishino (1994). AR emerged as a significant technological progression. AR is an enhanced system that superimposes virtual objects into the real world in real-time, enriching the user's experience.

XR has generated considerable interest across diverse disciplines, including medicine, engineering, architecture, and education. Since its inception, XR's potential has been recognized, and its applications widely explored (Xanthidou et al., 2022). Use cases span a broad spectrum, encompassing virtual surgeries for medical training, realistic simulations for engineering design, virtual walkthroughs for architectural projects, and interactive learning experiences for educational purposes. Furthermore, XR technology has also found significant utility in design. It enhances the immersion of the virtual world and simulates it in the real world, thus enabling designers to gain a more comprehensive understanding of their designs in a real-world environment (Mütterlein, 2018). The benefits of XR in design extend beyond visualization and prototyping, thus facilitating previously unimaginable visualization and interaction with designs, leading to more innovative and practical design outcomes. XR has thus evolved into a valuable tool in the design process by transforming how designers conceptualize, create, and present their designs.

In traditional XR experiences, the focus has primarily been on visual and auditory aspects, using headsets or displays to provide virtual sounds and visuals. However, recent advancements in technology have allowed for the incorporation of additional sensory feedback, enabling users to interact with virtual objects and physical environments through touch, vibration, and even scent (Rakkolainen et al., 2021).

Sense of “Presence” in XR

Figure 1. Remote instruction via Hololens

In the XR field, “Presence” refers to a complex psychological state of “immersion.” This state encompasses feelings of physical existence within a digital environment and the potential for interaction and response, similar to experiences within the real world (Botella, 2005). Enhancing this sense of presence could blur the distinction between the virtual and real-world, amplifying the user’s immersive experience in XR environments. Achieving the sense of presence in XR is significantly enhanced by the provision of multisensory stimuli to users. Studies have demonstrated that the more authentic the virtual stimulus interaction, the more realistic the user’s behavior becomes (Baños et al., 2000, 2009). If these multisensory stimuli can successfully mimic real-world experiences, the expectations of XR users will correspondingly align with those experienced in reality, thereby enriching their overall XR experience.

Current research on taste, smell, and tactile experiences in the XR domain has begun to yield results. For example, studies by Ehrlichman and others have found that smells can alter emotional states by influencing emotions, evoking intense pleasure or discomfort, creating alertness or relaxation, and reviving long-forgotten emotional memories (Ehrlichman, Bastone, 1992). Somatosensory and haptic devices can provide continuous feedback to users, enhancing their experiences through force-feedback components, such as tactile sensations and the physical weight of virtual objects. Erika Kerruish (2019) highlighted the significance of digital taste and smell in the cultural dimensions of bodily perception in XR devices. Integrating multisensory experiences into XR technologies is crucial for enhancing presence and creating a realistic user experience. However, given the current state of technology and its applications, improving XR’s sense of presence seems more feasible and valuable with somatosensory than taste and smell, especially regarding users’ insight into spatial perception. Haptics offers immediate and continuous feedback, which is vital for maintaining a sense of presence and engagement in a virtual environment. For instance, feeling the weight of virtual objects or resistance from virtual surfaces can significantly enhance the sense of realism. Conversely, taste and smell are more passive senses; they can contribute to the overall atmosphere of the experience but may not significantly affect a user’s ability to interact with the virtual environment.

The Value and Insufficiency of Somatosensory in XR

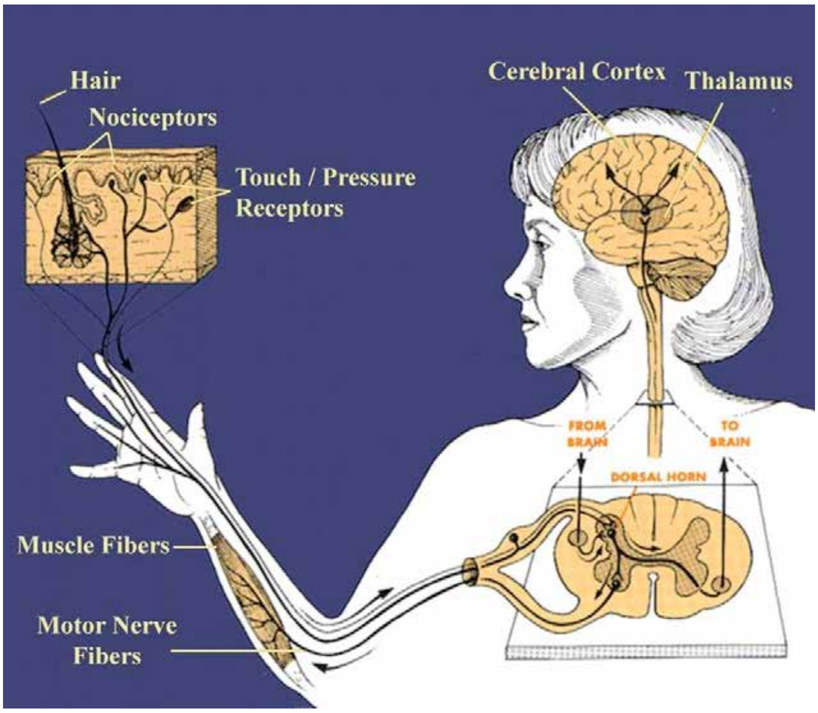


Figure 2. The Somatosensory System: Interphase between body and environment.

Figure 2 shows the somatosensory system, encompassing various sensory abilities, comprises cutaneous or skin-related sensations, such as pressure (tactile response), pain (nociception), vibration, and temperature. Moreover, proprioception (positional sense) and kinesthesis (sense of bodily movement) are integral components of this system. (Daly et al., 2012) The skin is in fact the largest sensory organ in the body, providing a plethora of information that enables the detection of different textures and pressures, as evidenced by Braille readers. Though most somatosensory feedback operates subconsciously, it is integral to numerous motor activities (Prescott, Ratté, 2017). XR technologies have advanced rapidly, improving the multisensory experiences in user experience. The multisensory experiences simulate our perception of the surrounding environment, encompassing direction, sound, touch, visual effects, etc. In XR devices, these experiences are primarily achieved by integrating optical, acoustic, and haptic feedback technologies. However, the accuracy of these mechanisms, specifically in terms of spatial distance recognition, is currently under scrutiny.

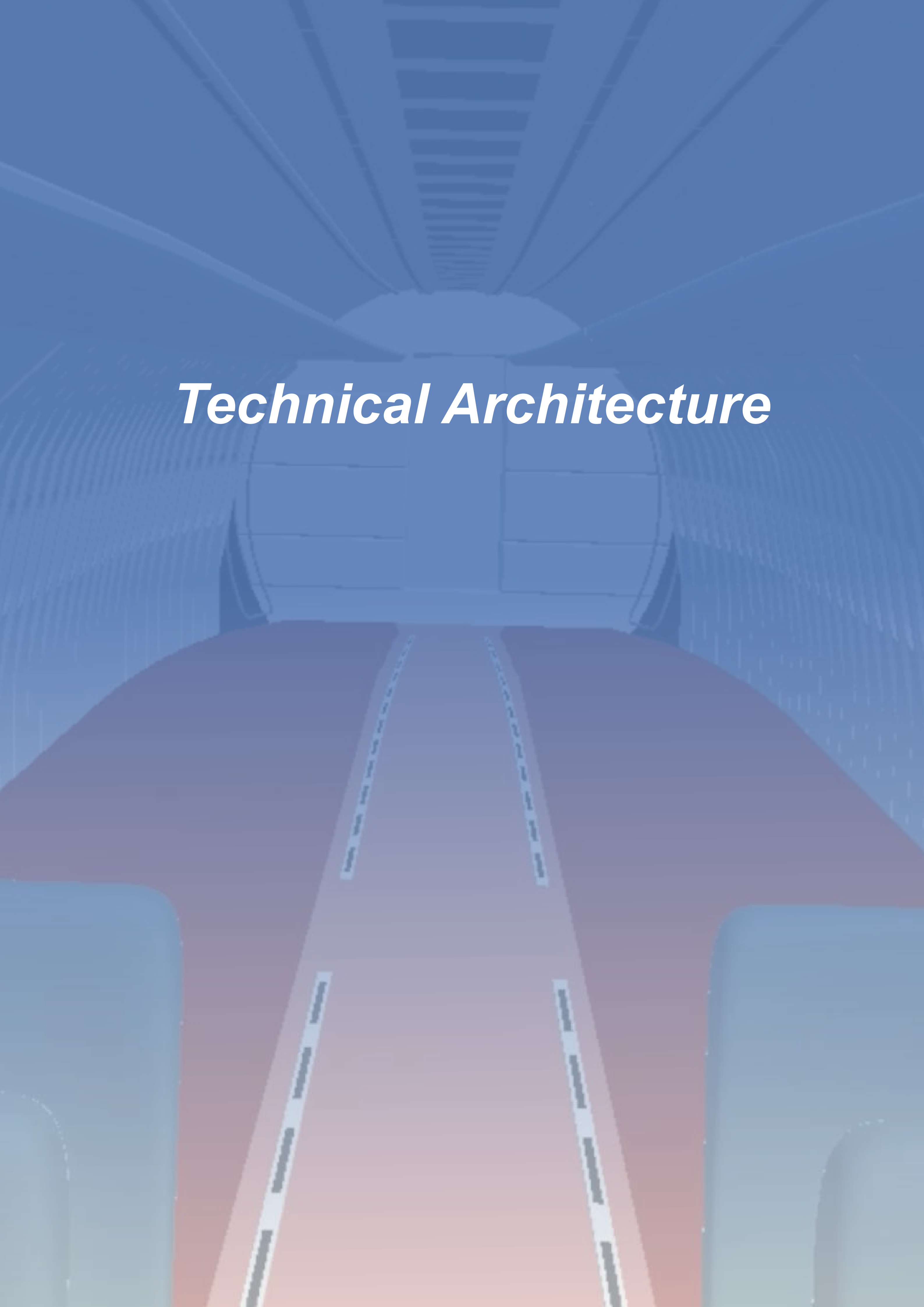
Empirical data indicate that individuals are proficient in estimating distances up to 20 meters in actual environments, yet they consistently underestimate these distances in virtual environments (Thompson et al., 2004). This observation suggests an inherent inability of cognitive processes related to distance perception to be effectively transposed to digital domains. The study conducted by Grechkin et al. (2010) corroborates this perceptual incongruity within Augmented Reality (AR) conditions, with participants exhibiting significant underestimation of distances. This pervasive trend underscores a fundamental limitation in current VR/AR technologies — the lack of precise spatial distance recognition.

Potential remediation for this challenge may involve incorporating the somatosensory system within XR technologies. By furnishing tactile feedback that aligns with visual inputs, it may enhance the user's sense of presence and augment their capacity to accurately gauge distances and their relative position within the XR setting. Additionally, providing realistic proprioceptive feedback, such as movement or body position sensations, could substantially enhance the precision of spatial recognition, leading to a more immersive and authentic XR experience.

Research Objective

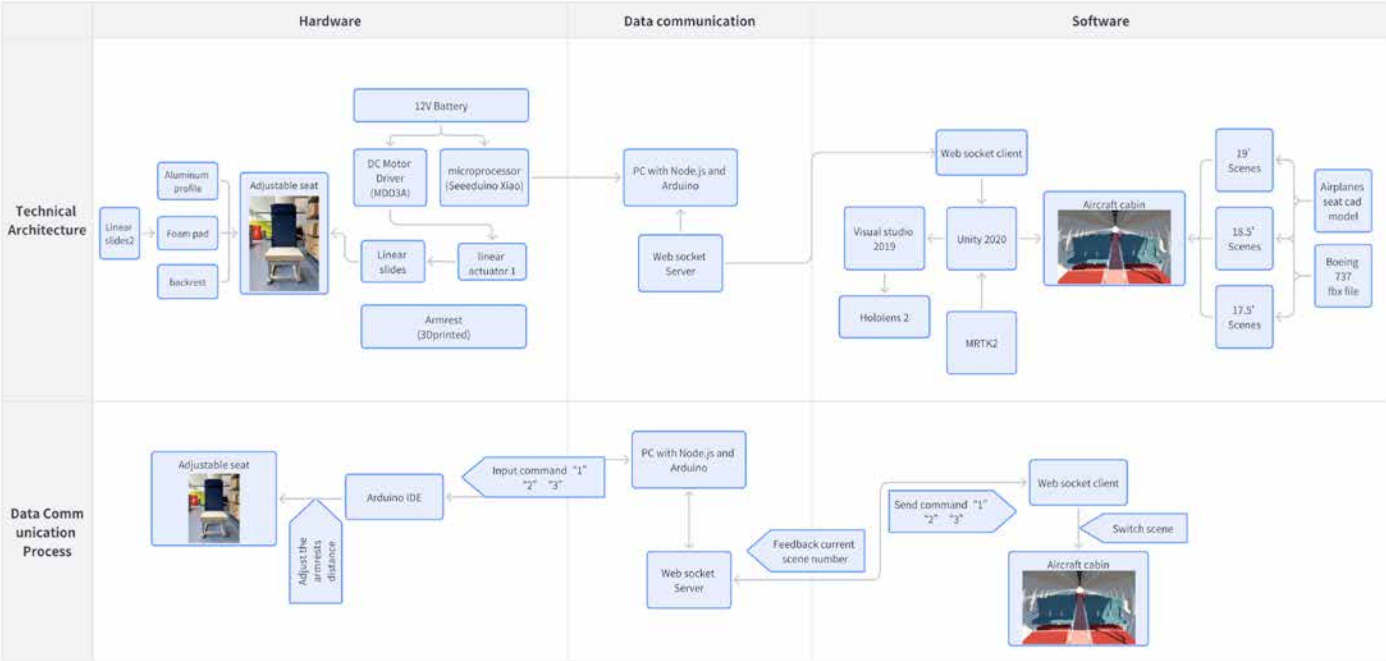
Various projects at TU Delft have investigated aircraft seats' seating comfort/discomfort experience. Precise user feedback during the design phase is a pivotal guiding element. However, spatial-based limitations often present significant challenges to the effectiveness of the iterative process. Accordingly, researchers have proposed using Extended Reality (XR) devices as supplementary tools within the testing protocols. This study intends to contribute to the body of knowledge in two primary areas: the role of the somatosensory system in improving spatial recognition and the application of XR in design procedures, specifically within the aviation sector. Most contemporary discussions on XR technologies focus predominantly on visual and auditory interactions, with limited emphasis on somatosensory.

This research advocates for exploring the somatosensory system and its incorporation within XR systems, particularly in spatial recognition. This paradigm shift could introduce novel methodologies in XR design that perceive the body as a recipient of sensory stimuli and as an active participant in sensory perception. This could redefine our understanding of somatosensory in XR and contribute to a more holistic approach to multisensory design. Additionally, this study aims to examine the deployment of XR in the evaluation of aircraft interior design. The successful integration of XR technologies could potentially revolutionize the design process by presenting a more immersive and authentic user testing environment. In light of the present deficiency in precise spatial recognition within XR applications, this research could offer fresh insights into optimizing XR use in design, thereby improving spatial perception accuracy and enhancing ergonomics and user experience in real-world applications, such as aircraft interior design.



Technical Architecture

System Architecture



Figrue 3. The System Architecture

The system involves an intricate integration of hardware, software, and data communication elements as showing in the Figure 3. It measures the effect of somatosensory on participants' spatial recognition accuracy and sense of presence within a virtual aircraft cabin environment. The envisioned application of this system is centered around the aircraft cabin setting. To provide users with a more immersive experience, we have utilized the Unity platform to construct a virtual Boeing 737 cabin environment, complete with two rows of typical 3x3 seating arrangement, bisected by an aisle and complemented by standard overhead luggage compartments. Seat widths are represented in three variations: 17.5 inches, 18.5 inches, and 19 inches. This range has been selected following SeatGuru, a reputable online source for aviation seating and other flight-related information, which collates the prevailing seat width dimensions for mainstream airlines' economy class (SeatGuru, 2023). Concurrently, within the physical environment, the system necessitates a device that furnishes somatosensory feedback to synchronize with the virtual space, thereby providing participants with a somatosensory experience within the XR setting. To accomplish this objective, the following functionalities are essential in this prototype:

1. Virtual environment: Use HoloLens to provide users with an immersive virtual aircraft cabin with an adjustable seat.
2. Tactile experience: Provide a physically adjustable aircraft seat with the exact dimensions as the virtual cabin seat, and the spacing of the armrests can be adjusted in sync with the virtual environment.
3. Data connection: Connect the HoloLens, physical seat, and PC to achieve control, status detection, data collection, and other functions.

Hardware Part:

Figure 4. The Adjustable Chair

Figure 5. The Transmission Structure

The hardware mainly consists of an adjustable seat crafted from existing airplane seats. As show in Figure 4, the main frame is made of aluminum profiles. The cushion part uses foam pads from the NEVEON® and is covered with mesh fabric to reduce surface friction. The backrest comprises wooden boards, PVC pipes, and elastic mesh fabric. The seat's armrest spacing ranges from 17.5 to 19 inches; the angle between the seatback and the cushion is 103°; the seat depth is 15.5 inches.

A linear actuator adjusts the width of the armrest spacing of the seat, the armrest and the base are fixed on a linear slide rail, and the linear slide rail is connected to the linear actuator through two aluminum alloy connecting rods as shown in Figure X. When the linear actuator moves upward, the connecting rod pushes the linear slide rail outward, increasing the spacing between the armrests.

Hardware Part:

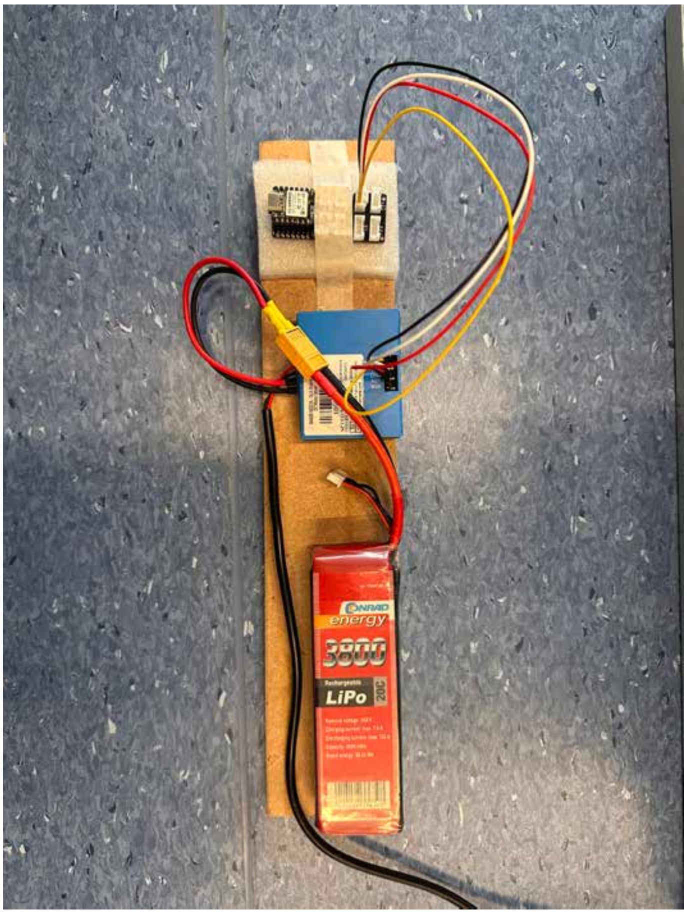


Figure 6. The Linear Actuator Control System

Figure 7. The Anthropometry Measuring Chair

The movement of the linear actuator is driven by a control system composed of Seeedunio Xiao, a DC motor driver, a 12V power supply, and a linear actuator as showing in Figure 6. Seeeduino Xiao is programmed with Arduino and can realize movements at different distances through keyboard input. The primary purpose of designing this adjustable seat is to provide users with a physical location in the virtual environment and a somatosensory in the elbow area through the armrest.

We used a lightweight Anthropometry measuring chair showing in Figure 7 to measure the participants' anthropometric data. This device was made by Yayu Ping, a graduate student from TU Delft.

Software Part:

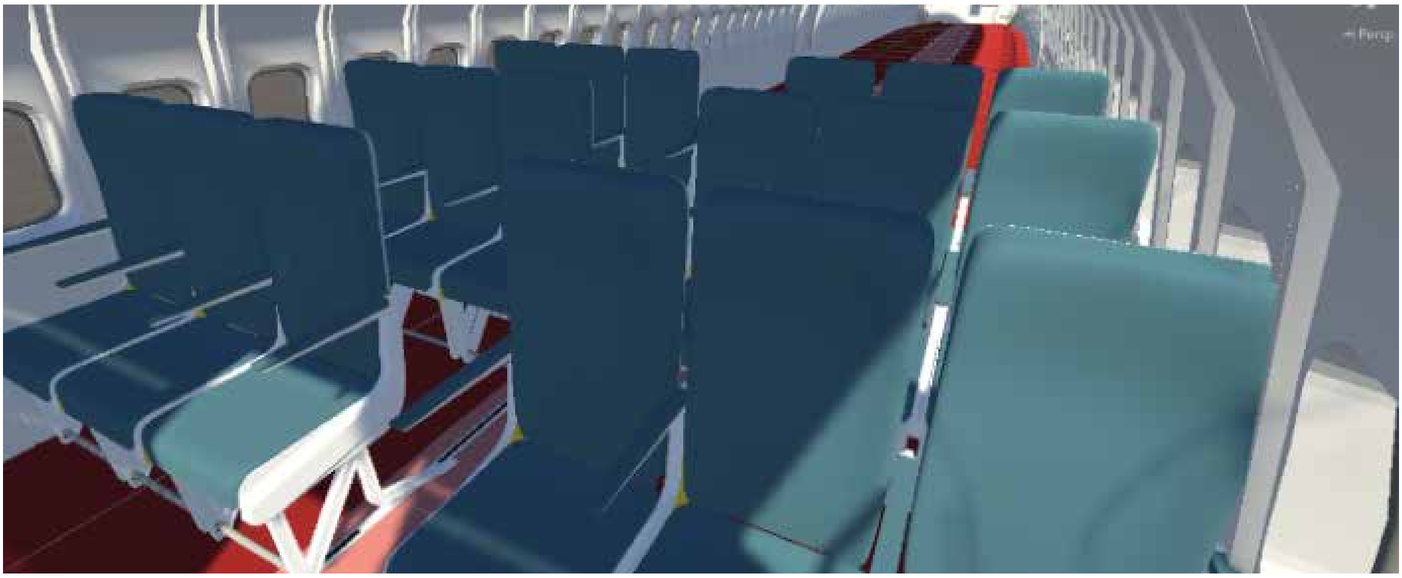


Figure 8. The Virtual Boeing 737 Cabin

The main goal of the software part is to provide users with a virtual scene that can interact with the real world. The device that presents this virtual scene in this design is Microsoft HoloLens2. HoloLens2 is an augmented reality device with more accurate spatial positioning, gesture tracking, and eye-tracking functions. Also, compared with VR devices, it can observe the status of the real world through transparent lenses. Unity builds the virtual scene. There are two reasons for choosing the Unity platform. First, Unity is a powerful general game-making platform that can realize various functions by writing C# code. Second, the Unity platform has better software support for HoloLens and can use Microsoft's MRTK plugin to set up the scene requirements that HoloLens needs quickly. After determining the software and hardware platform for the virtual scene, we start designing scene details and animation effects as show in Figure 8.

Figure 9. How to Align the Seats

As show in Figure 9, we align the three different seat sizes based on each row's middle seat to reduce the unrealistic feeling caused by the model position change when the scene is switched. For the convenience of control, these three sizes of seats are placed in three scenes, each scene only differs in seat size, and an external PC controls the scene to switch scenes.

Data Communication:

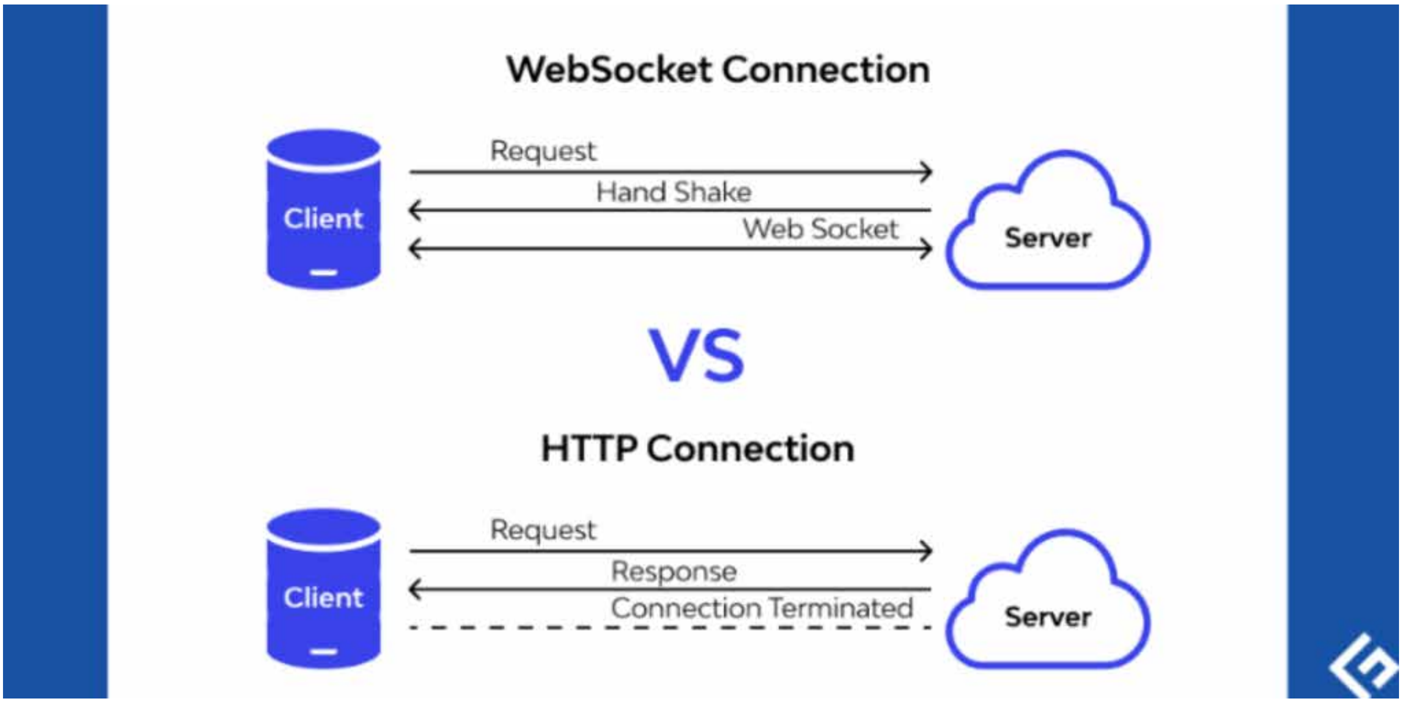


Figure 10. The Websocket Connection System

As this system involves different devices and includes multiple software, a program is needed to achieve data transmission and control between various parts. This system uses WebSocket for communication. WebSocket is a network transmission protocol that can simplify data exchange between clients and servers, allowing the server to push data to the client actively. In the WebSocket API, browsers and servers only need to complete a handshake and a persistent connection can be created between the two for two-way data transmission. In this system, the WebSocket server will run on the PC for control by the organizer during the test, and the WebSocket client will be built into the Unity application. When the Unity client receives the server's instruction, it will switch the scene in the virtual space and change the armrest spacing of the seat.

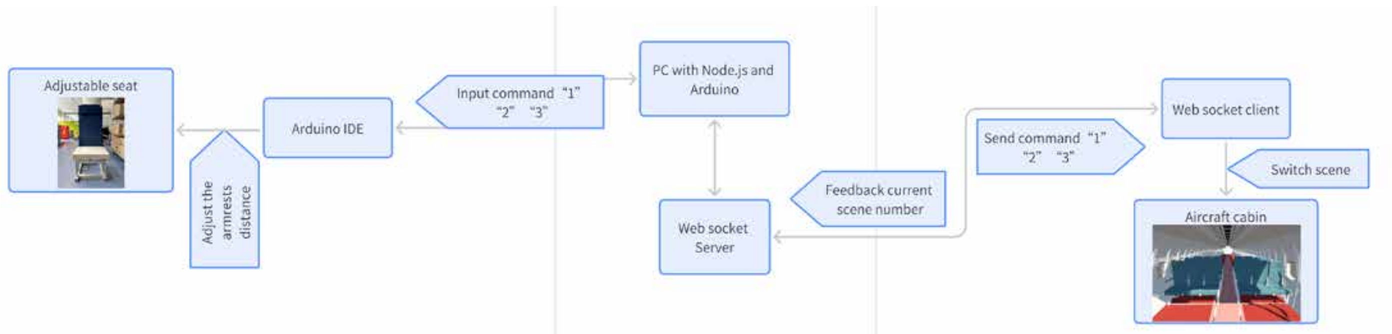


Figure 11. The Data Communication System

It is also feasible to add a WebSocket client to Arduino. However, because the operating speed of the linear actuator is much smaller than the speed of scene switching and to reduce the possibility of packet loss when the server sends information to multiple clients, this experiment did not include Seeeduino in the WebSocket communication network. Instead, the organizer directly controls it on the Arduino IDE port. The specific operation logic is shown in the Appendix A.

Materials and Methods

Test Setup

Figure 12. The Test Environment

We conducted experiments in a specially designed space to examine the influence of somatosensory on users' distance perception in virtual spaces. This experiment was set up in the dimly lit 3*6 m Delft University of Technology classroom, housing the adjustable aircraft seat prototype. The seat features adjustable armrests (17.5in-19in range) controlled by a linear actuators.

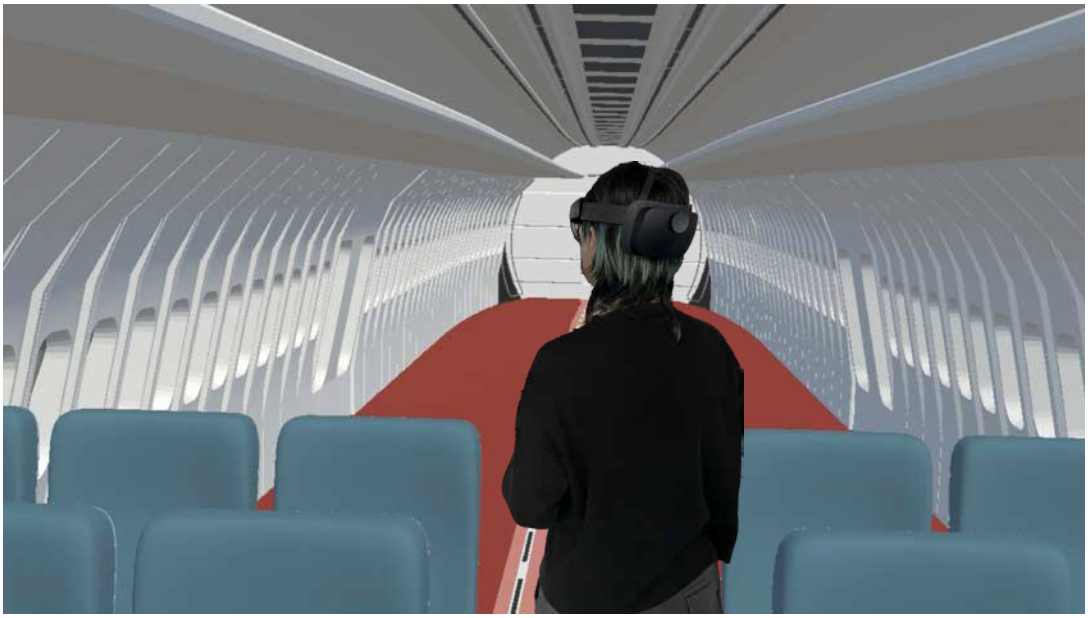


Figure 13. The Scene Observed by the Participants

During the test, participants will wear HoloLens2 running a Unity application, simulating a Boeing 737-800 aircraft cabin with three rows of adjustable seats. These adjustments, controlled via an external computer, include armrest spacing (17.5', 18.5', 19').

Figure 14. Adujest the Armrest

Figure 15. How to Estimate the Armrest Distance

The prototype in the testing space mirrors these adjustable parameters, providing a tangible counterpart to the virtual seat in the Unity application. Participants will experience these three seat sizes with and without the addition of somatosensory, with seat sizes remotely adjusted by the organizer via an external computer.

Participants will be notified and asked to estimate the distance between the armrest whenever the scenes switch. The order of experience will be randomly assigned. After examination and data collection, participants will complete a questionnaire to evaluate their device-using experience.

Primary goal

1. Explore the role of somatosensory in enhancing spatial recognition in XR systems: This research investigates the potential of somatosensory and its integration within XR systems. The goal is to develop new methods and interfaces in XR design that account for the body as an active participant in sensory perception, redefining our understanding and utilization of touch in XR.
2. Investigate the application of XR in aircraft interior design evaluation: By harnessing XR technologies, this study aims to offer a more immersive and authentic user testing environment. It seeks to identify new strategies for enhancing the fidelity of spatial perception in XR applications, leading to improvements in ergonomics and user experience in real-world design scenarios.

Secondary goal

1. Enrich the current knowledge on multisensory experiences within XR systems: By shifting the focus to somatosensory, this research hopes to contribute to a more comprehensive approach to multisensory design in XR.
2. Offer innovative insights into the use of XR in design evaluation: By addressing the existing gap in spatial recognition accuracy, this study could provide innovative insights into optimizing XR use in design, potentially revolutionizing design processes in various industries.

Hypothesis

The somatosensory can enhance users' perception of changes in virtual space and improve their ability to estimate distances between people/virtual objects and other virtual objects.

Time Schedule

Figure 16. The Time schedule

Ethics

The Human Research Ethical Committee (HREC) of the Delft University of Technology approved the experiment setup and protocol under file number 3233.

Recruitment Requirements:

For this test, we aim to recruit 24 participants of varying genders (12 males and 12 females) below 65 years of age. Our primary recruitment area will be within TU Delft, prioritizing individuals with prior experience in flying and VR/AR usage.

Anonymization, Storage, and Access to Data:

The collected data will be anonymized in such a way that the names and addresses of the participants can no longer be identified.
The data will be stored on a secure server at TU Delft, which the researchers can only access. The data will be managed according to the data management plan (attached). The data will NOT be shared and reused by default. However, participants can voluntarily donate their data to the research team at TU Delft to be anonymously used in future research.

Data Measurement

The data measurement in this experiment primarily falls into two categories. The subjective measurement includes a 10-point Likert scale on the igroup presence questionnaire (IPQ) and the NASA task load index (NASA-TLX). The objective measurement is armrest distance estimations of participants with and without the inclusion of somatosensory.

IPQ form

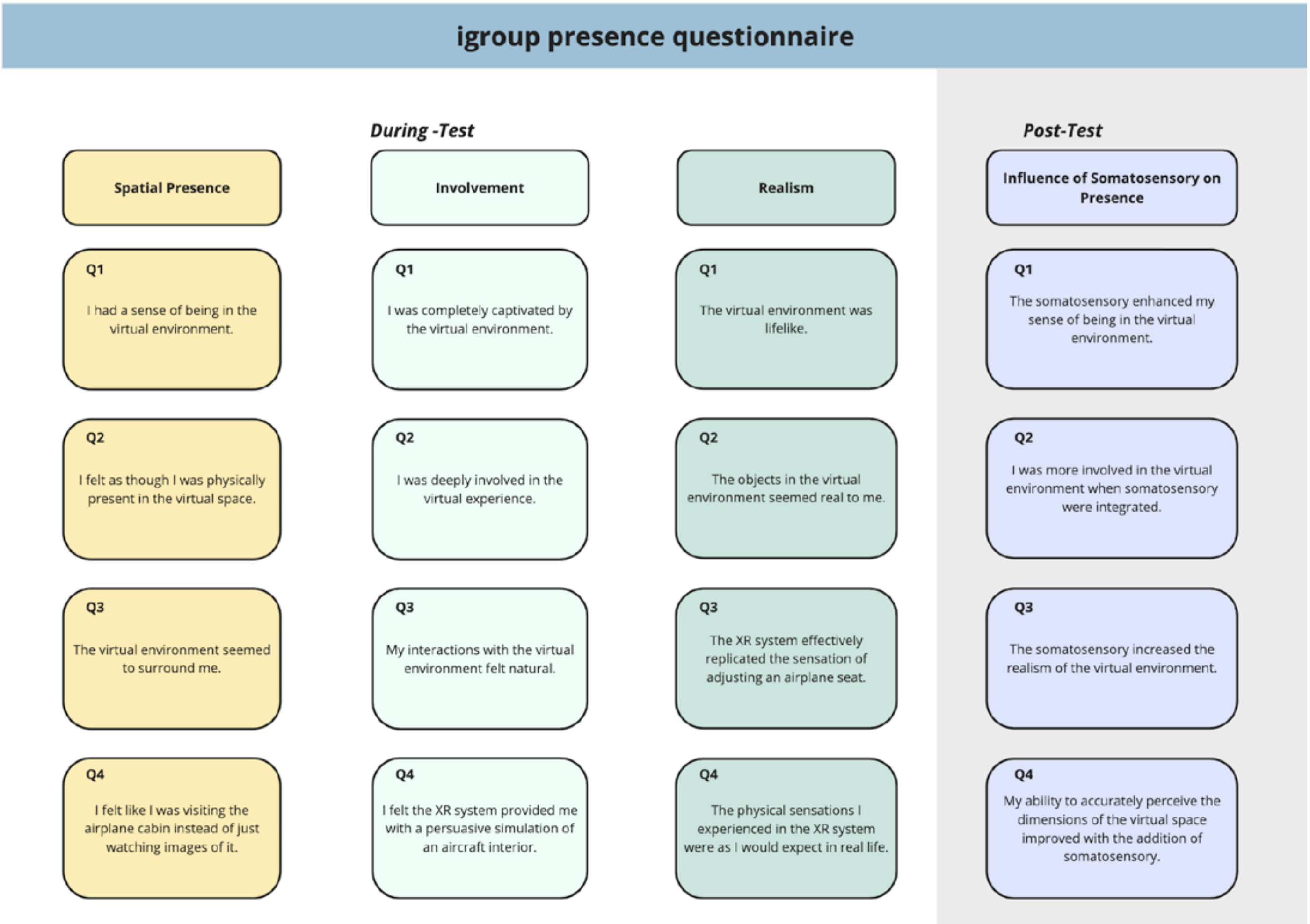
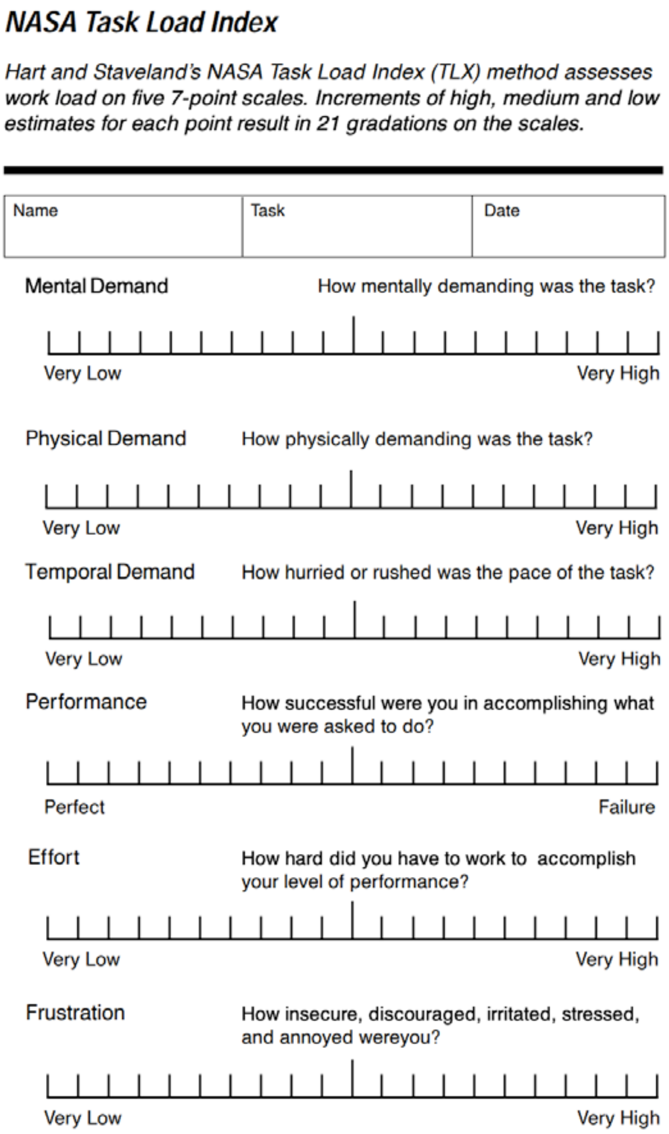


Figure 17. The ipq Questionnaire

This questionnaire will be distributed to participants before and after the experiment, the fourth section applicable only post-experiment. Participant responses will shed light on the influence of somatosensory on the sense of presence within an XR environment. We have formulated a questionnaire to examine participants' sense of presence before and after integrating somatosensory within the XR system. This questionnaire has been modeled upon the igroup Presence Questionnaire (IPQ), a standardized tool widely used in Human-Computer Interaction to measure a user's sense of presence within a virtual environment.

The rationale behind using the IPQ is its robust, multi-dimensional approach to gauging presence. This makes it highly suitable for investigating the complexities of XR interactions, especially those enhanced by somatosensory. However, given the unique nature of our study, we have made certain modifications to the original questionnaire to measure the influence of somatosensory within XR environments more precisely. The questionnaire will consist of a series of statements that participants must rate on a scale of agreement. These statements will be designed to gather participant impressions on the overall sense of being there (spatial presence), the extent to which the virtual environment is perceived as the predominant reality (involvement), and the sense of being physically present in the virtual environment (realism).

NASA-TLX



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

We also incorporated the NASA Task Load Index (NASA-TLX) to evaluate the usability of the XR system implemented in this study. The NASA-TLX is a widely used subjective, multidimensional assessment tool that measures perceived workload to assess a participant's interactions with a system.

Figure 18. The NASA Task Load Index

The NASA-TLX employs six subscales: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. Each subscale captures a unique facet of the perceived workload, allowing for a comprehensive user experience assessment. Mental Demand measures the cognitive load and complexity of the task, Physical Demand evaluates the physical exertion required, and Temporal Demand quantifies the perceived time pressure. The Performance subscale assesses the individual's perception of their performance, Effort measures the perceived investment of resources to accomplish the task, and Frustration assesses the individual's emotional response to the task

Participants will rate their experience on these subscales post-interaction with the XR system. By comparing the workload scores across different experimental conditions, we aim to evaluate how adding somatosensory impacts the perceived workload and, consequently, the usability of the XR system.

The combined use of IPQ and NASA-TLX provides a comprehensive system evaluation from both presence and workload perspectives. This dual-method approach enables a more holistic understanding of user experience within XR environments enhanced with somatosensory, providing invaluable insights for future design improvements.

Armrest distance

We have also included objective measures to ascertain the accuracy of participants' spatial perception within the XR environment. Specifically, we have measured the distances between armrests that participants estimated with and without the inclusion of somatosensory.

Figure 19. How to measure distance estimated by participants

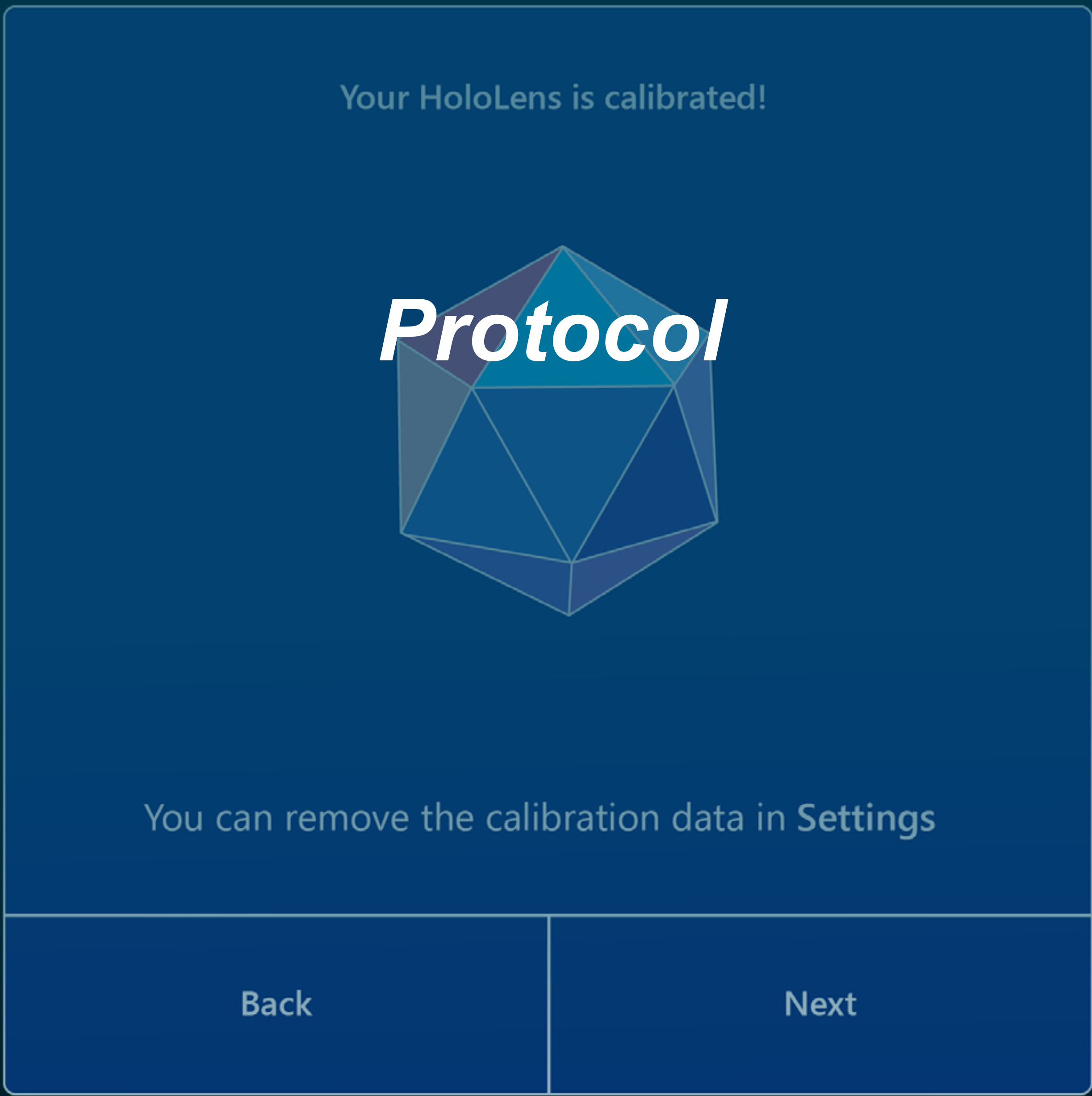
Each participant, while experiencing different simulated seat conditions, was tasked with estimating the distance between the armrests of the virtual aircraft seat. These estimations were subsequently compared with the actual, pre-determined distances, objectively measuring the participant's spatial perception accuracy.

Participant NO.	Original data (in 44.45 mm)	**Arm width**	17W	17WO	18W	18WO	19W	19WO
1 WO / W								
2 W / WO								
3 WO / W								
4 W / WO								
5 WO / W								
6 W / WO								
7 WO / W								
8 W / WO								

Figure 20. The Objective Measurement Record Sheet

By comparing the estimated and actual distances across different seat configurations and tactile conditions, we aim to understand the potential of somatosensory in improving spatial perception within XR systems. This objective measure, in tandem with the subjective evaluations obtained from IPQ and NASA-TLX, provides a holistic perspective on the impact of integrating somatosensory in XR systems.

Protocol


Your HoloLens is calibrated!
You can remove the calibration data in **Settings**
Back
Next

Materials required:

1. Virtual airplane interior modeling built by Unity in Win 10 laptop
2. An adjustable airplane seat
3. HoloLens 2
4. A laptop that can run Python and Javascript
5. Seeeduino Xiao
6. Liner actuator
7. Tape measure
8. IPQ questionnaire and NASA-TLX table
9. Objective Measurement Record Sheet

Data Collection

The research process commences with participants providing informed consent to conduct a methodical and ethically sound data collection. This step ensures that all participants understand the research purpose, the nature of their involvement, and their rights as participants. The approved inform consent will show in Appendix X

Following this, participants are requested to complete a pre-experiment questionnaire to capture basic demographic data and any relevant background information that could influence their interaction with the XR system or their perception of space.

Subsequently, participants undertake the first round of tasks, during which their estimations of the armrest distances are systematically recorded. After completing these tasks, participants are asked to complete the first set of IPQ and NASA-TLX questionnaires. These tools will gauge the initial sense of presence the participants experience within the XR environment and evaluate the usability of the XR system, respectively.

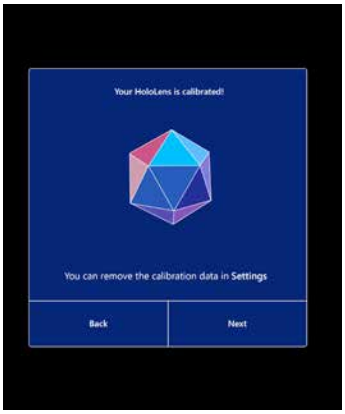
A second round of tasks is conducted post a five-minute rest period, following the same sequence of task execution and questionnaire completion as in the first round. This rest period and the repetition of the procedure allow for the collection of comparative data to examine any changes in perception or system usability.

Upon the culmination of the two task rounds, participants must complete the remaining elements of the IPQ questionnaire. This final step enables the research to investigate changes in the participants' sense of presence within the XR environment pre- and post-incorporation of somatosensory.

Test plan

Participants will be randomly divided into two groups and given a participant number; one group will be tested in Seat with armrest first, and the other group will be tested in Seat without remrest first.

Participants sit on a chair with an armrest distance of 17.5’ and use their hands to estimate the distance between the armrests.



Participants wear the HoloLens and perform calibration while the organizer explains the basic operations.

Participants survey the airplane interior with the organizer’s guidance.

Participants sit on assigned chairs, guided by the organizer, and observe their seat surroundings.

Participants estimate the distance between the armrest and signal to complete when they are done.

Participants fill out the questionnaire when the first round of tasks is over

Organizer change settings, and participants estimate the distance between the armrest and signal to complete when they are done.

The organizer measures the necessary anthropometric data of the participants

Analysis Methods

The objective measurement results, the distances between handrails estimated by participants under various conditions, will be processed using statistical methods. After the test is completed, the collected data is first processed to obtain the error between the distance estimated by the participants and the actual distance.

The processing method involves subtracting the actual distance of 17.5inch (44.45 cm) from the data measured when the participant is not wearing the HoloLens at an estimated 17.5 inches (44.45 cm) to obtain the arm width (Aw) of each participant. Then use the actual distance (17.5 inches, 18.5 inches, and 19 inches) minus the Aw and the six sets of data measured after wearing the HoloLen to get the error between the measured data and the actual data of the participants in six situations. The obtained error data is divided into two groups: with somatosensory (W) and without somatosensory (WO) for paired sample t-test to determine whether there is a significant difference in the participants' ability to estimate distance with and without the addition of somatosensory. This statistical analysis will help verify the impact of somatosensory on the accuracy of spatial perception within XR systems.

The responses to the IPQ questionnaire and NASA-TLX table will first undergo data normalization to reduce the error caused by participants' personal biases. The normalized data will undergo ANOVA repeated measures to verify whether there is a significant difference in the users' sense of presence and workload in the two situations. The responses to the IPQ questionnaire will provide insights into the perception of presence in the XR environment. In contrast, the NASA-TLX table will provide information on the overall usability and workload associated with the XR system.

We will analyze the quantitative and qualitative data separately and then integrate the results to understand comprehensively. For example, a high correlation between participants' spatial estimation accuracy and their subjective sense of presence (as reported in the IPQ) might indicate a strong link between these factors. Similarly, any correlation between usability scores (from NASA-TLX) and spatial estimation precision could reveal the role of system usability in influencing XR spatial perception.

Results and Discussion

Results Reliability

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
W1	7.2022321429	4.378	.191	.	.874
W2	7.3128141534	4.080	.391	.	.866
W3	7.2207506614	3.885	.578	.	.855
W4	7.3787202381	3.732	.545	.	.858
W5	7.3956349206	3.890	.513	.	.859
W6	7.3322585979	3.632	.811	.	.839
W7	7.4440641534	3.929	.470	.	.862
W8	7.2386904762	3.895	.736	.	.848
W9	7.3843915344	3.617	.741	.	.843
W10	7.2773478836	3.832	.648	.	.851
W11	7.3529761905	3.894	.620	.	.853
W12	7.3568121693	4.049	.400	.	.866
WO1	5.4316633598	3.223	.200	.	.798
WO2	5.5711144180	2.867	.554	.	.763
WO3	5.4502314815	3.059	.465	.	.773
WO4	5.4384093915	2.670	.698	.	.745
WO5	5.5424603175	2.620	.821	.	.732
WO6	5.4663194444	2.915	.507	.	.768
WO7	5.6253306878	3.095	.306	.	.789
WO8	5.4477843915	3.134	.342	.	.784
WO9	5.5599867725	2.673	.707	.	.744
WO10	5.5581018519	2.874	.620	.	.758
WO11	5.6574404762	3.314	.125	.	.803
WO12	5.8309854497	3.588	-.152	.	.824

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
TLX W1	3.9180390212	2.876	.762	.761
TLX W2	3.9581514550	3.239	.458	.794
TLX W3	3.9858796296	3.216	.617	.782
TLX W4	3.2423611111	3.813	.032	.816
TLX W5	3.9872850529	3.108	.675	.775
TLX W6	4.0984788360	3.696	.077	.823
TLX WO1	3.8630125661	2.846	.755	.761
TLX WO2	3.8851190476	2.853	.705	.766
TLX WO3	3.9464781746	3.043	.810	.765
TLX WO4	3.3450066138	3.835	-.062	.830
TLX WO5	3.8541170635	3.046	.503	.791
TLX WO6	4.0094907407	3.739	.003	.834

Figure 21. Reliability Test Results

At the beginning of the data analysis, we first analyzed the reliability of the questionnaire items. The results showed that the Cronbach's Alpha values for the IPQ questionnaire, NASA-TLX questionnaire, and the objective measurement data were all greater than 0.7, indicating reliability.

Objective measurement

Regarding the objective data measurement results, we primarily analyzed the absolute average and standard deviation of the values estimated by the participants for different sizes of armrest distances, with and without the addition of somatosensory. This aims to explore somatosensory's influence on spatial perception's accuracy and precision.

Univariate Tests

Source	Measure		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Within	SD	Sphericity Assumed	12.770	1	12.770	16.619	<.001	.419
		Greenhouse-Geisser	12.770	1.000	12.770	16.619	<.001	.419
		Huynh-Feldt	12.770	1.000	12.770	16.619	<.001	.419
		Lower-bound	12.770	1.000	12.770	16.619	<.001	.419
	ABSAV	Sphericity Assumed	2.454	1	2.454	1.587	.220	.065
		Greenhouse-Geisser	2.454	1.000	2.454	1.587	.220	.065
		Huynh-Feldt	2.454	1.000	2.454	1.587	.220	.065
		Lower-bound	2.454	1.000	2.454	1.587	.220	.065
Error(Within)	SD	Sphericity Assumed	17.673	23	.768			
		Greenhouse-Geisser	17.673	23.000	.768			
		Huynh-Feldt	17.673	23.000	.768			
		Lower-bound	17.673	23.000	.768			
	ABSAV	Sphericity Assumed	35.565	23	1.546			
		Greenhouse-Geisser	35.565	23.000	1.546			
		Huynh-Feldt	35.565	23.000	1.546			
		Lower-bound	35.565	23.000	1.546			

Figure 22. The Univariate Test Results of Objective Measurement

Univariate tests suggest that the difference in standard deviations (SD) between the two groups (with and without somatosensory) is significant (p<.001), but the difference in the absolute mean (ABSAV) is not significant (p=.220). This implies a significant difference in the variability of distance estimation between the two groups.

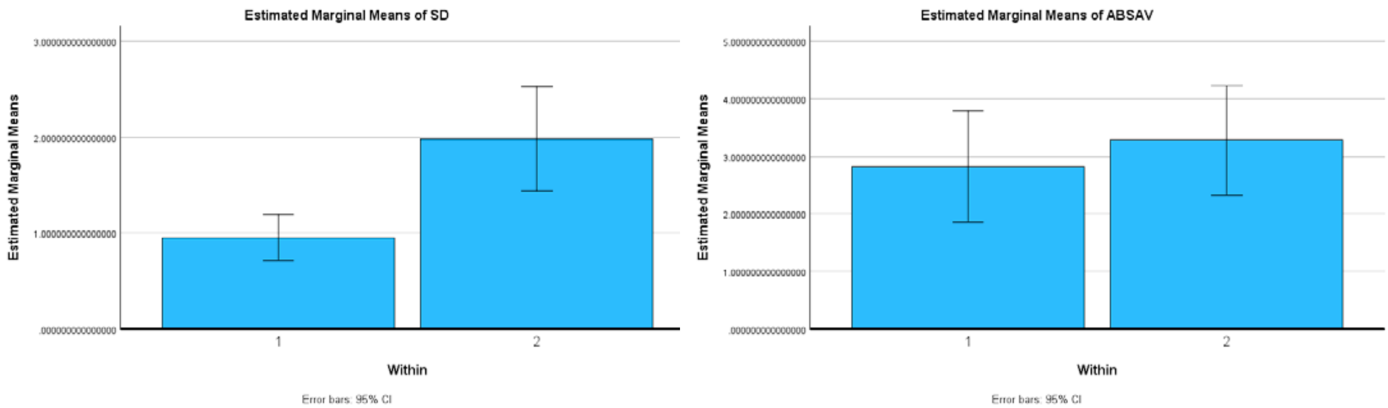


Figure 23. The Error Bars of Objective Measurement Results

The results show that adding somatosensory in an XR environment significantly affects the precision of how accurately participants can estimate the armrest distance. However, it does not significantly impact the overall accuracy of their estimates is insignificant. This suggests that while somatosensory might make a participant's estimates more consistent, it does not necessarily make them more accurate. This could indicate a direction for future research - looking at improving the accuracy of distance estimations in an XR environment, not just the precision.

IPQ Questionnaire

Pair	Test Type	Statistic	P-value
W1 - WO1	u-test	388.5	**0.04***
W2 - WO2	t-test	2.33	**0.02***
W3 - WO3	u-test	403	**0.02***
W4 - WO4	u-test	302	0.78
W5 - WO5	t-test	1.04	0.3
W6 - WO6	t-test	0.84	0.41
W7 - WO7	t-test	1.34	0.19
W8 - WO8	u-test	385	**0.05***
W9 - WO9	u-test	355	0.17
W10 - WO10	u-test	417.5	0.01**
W11 - WO11	t-test	3.14	0.0***
W12 - WO12	u-test	492.5	0.0***

Figure 24. The U-test of ipq Questionnaaire Results

This data suggests that incorporating somatosensory into XR environments can significantly enhance certain aspects of the sense of presence for users. However, it also indicates that other aspects of presence may be less affected by the somatosensory, which could be areas of focus for further research and development.

1. For questions about the general sense of being in the virtual environment (Q1, Q2, Q3), there appears to be a significant difference between the groups with somatosensory(W group) and those without it (WO group). This suggests that somatosensory may enhance users' sense of presence in the XR environment.
2. The results for the question about being "captivated" by the virtual environment (Q5) and being "deeply involved" (Q6) did not show a significant difference between the W and WO groups. This could indicate that somatosensory may not notably influence these aspects of the experience.
3. There is no significant difference between the groups' questions about natural interactions (Q7) and the feeling of visiting an airplane cabin (Q4). This suggests that the presence or absence of somatosensory might not significantly impact these particular experiences within this XR scenario.
4. For questions about the environment being lifelike and objects seeming real (Q9, Q10), only Q10 showed a significant difference. This might indicate that somatosensory more effectively enhances the realism of individual objects rather than the environment as a whole.
5. There is a significant difference between the groups for the last two questions about the simulation of specific somatosensory (Q11, Q12). This suggests that somatosensory significantly enhances the sense of realism in specific tasks or sensations within the XR environment.

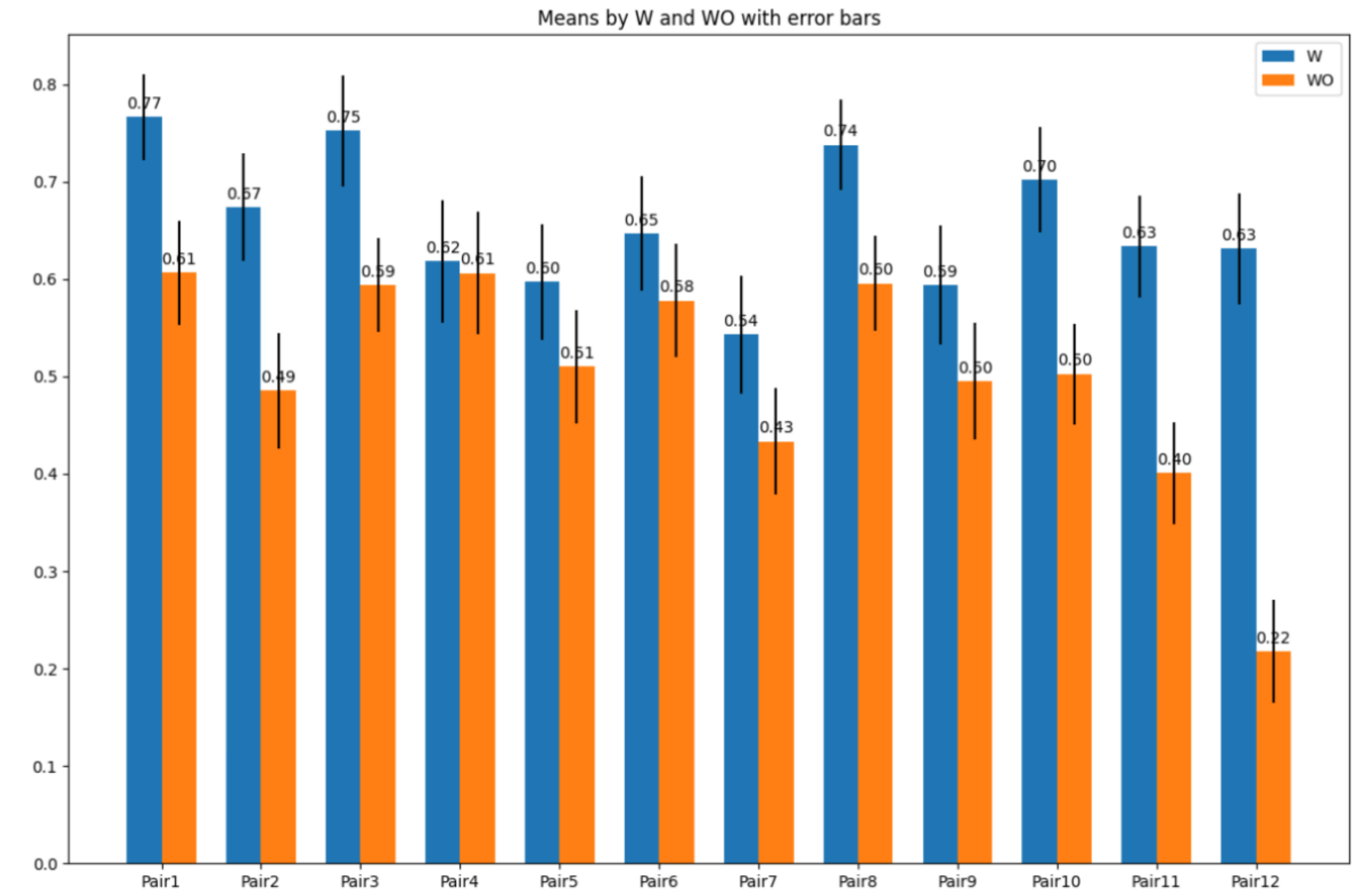


Figure 25. The Error Bars of ipq Questionnaire Results

In summary, somatosensory enhances certain aspects of presence and realism in an XR environment, such as the general sense of being there, the perceived realism of objects, and the replication of specific somatosensory. However, it may not impact other aspects like captivation, involvement, and the naturalness of interactions.

NASA-TLX

Pair	Test	Statistic	P-value
TLX W1 - TLX WO1	U-test	265.5	0.65
TLX W1 - TLX WO2	U-test	261	0.57
TLX W1 - TLX WO3	U-test	258.5	0.53
TLX W1 - TLX WO4	U-test	364.5	0.08
TLX W1 - TLX WO5	U-test	235.5	0.27
TLX W1 - TLX WO6	U-test	209	0.06

Figure 26. The U-test of NASA-TLX Results

1. For the question about how mentally demanding the task was (Q1), there was no significant difference between the TLX W group and the TLX WO group. Adding somatosensory in the XR environment may not significantly affect the mental demand of the task.
2. For the question about the physical demand of the task (Q2), no significant difference was found between the two groups. This suggests that adding somatosensory may not increase the perceived physical workload of the task.
3. The pace of the task, or how hurried or rushed the task was (Q3), also did not show a significant difference between the groups. This implies that the presence of somatosensory may not influence the pace of the task.
4. Regarding how successful participants were in accomplishing what they were asked to do (Q4), the p-value is slightly above the typical threshold of 0.05 for significance. Although not statistically significant at this threshold. However, it could indicate that participants in the TLX W group felt more successful in accomplishing the task than those in the TLX WO group, possibly due to the added somatosensory.
5. There was no significant difference between the groups for the question about how hard participants had to work to accomplish their performance (Q5). This indicates that the level of effort required might remain the same with the presence of somatosensory.
6. Finally, for the question about how insecure, discouraged, irritated, stressed, and annoyed the participants felt (Q6), the p-value is slightly above the typical threshold of 0.05 for significance. Although not statistically significant at this threshold, this result suggests a potential trend that may warrant further investigation. It may be that somatosensory could decrease negative emotional states during task performance, although more data is needed to confirm this.

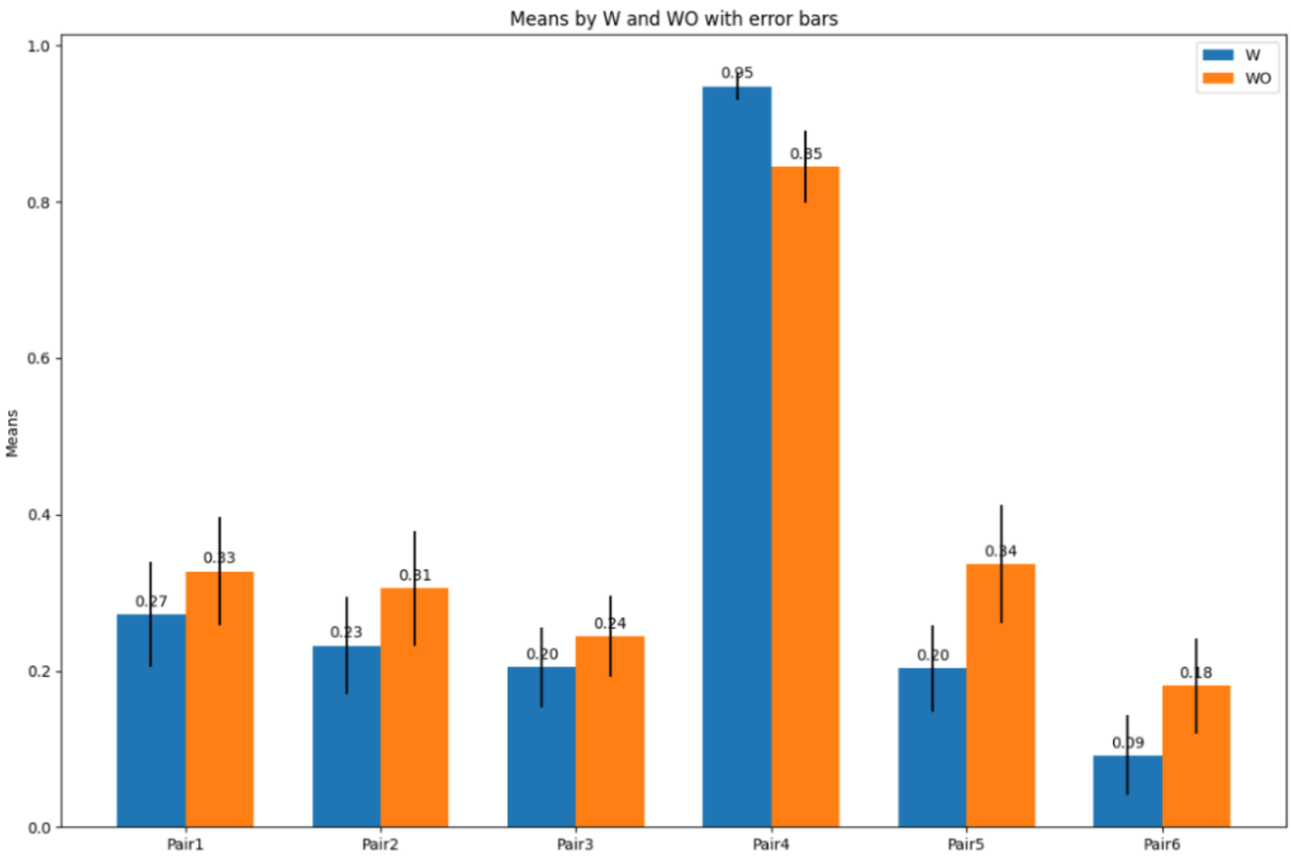


Figure 27. The Error Bars of NASA-TLX Results

In summary, these results suggest that adding somatosensory in the XR environment does not significantly impact the perceived mental and physical workload, pace, success, or effort required for the task. There might be a slight trend toward decreased negative emotional states with somatosensory, but more data is needed to confirm this.

Research Limitations

1. The study found that adding somatosensory in an XR environment significantly affects the precision of how accurately participants can estimate the armrest distance. However, it does not significantly impact the overall accuracy of their estimates. This indicates a limitation in the current study's ability to establish the relationship between somatosensory and distance recognition accuracy definitively.
2. The study's findings are based on a limited sample size, which may not represent the broader population. Future research should aim to include a more extensive and diverse sample to validate these findings.
3. The study primarily focused on the impact of somatosensory on the perceived mental and physical workload, pace, success, or effort required for the task. Other factors influencing the user's presence experience and spatial perception in the XR environment were not considered. Future studies should consider these factors to provide a more comprehensive understanding.
4. The study found a slight trend toward decreased negative emotional states with somatosensory, but more data is needed to confirm this. This indicates a limitation in the current study's ability to establish the relationship between somatosensory and emotional states definitively.

Suggestions

1. Future research could explore the impact of other sensory experiences on the user's presence experience and spatial perception in the XR environment.
2. Further studies could also investigate somatosensory's potential benefits in specific XR applications, such as gaming, education, or training simulations.
3. Given the potential trend towards decreased negative emotional states with somatosensory, future research could delve deeper into this aspect. Understanding how to reduce negative emotional states could enhance the user experience in the XR environment.
4. Future research should also focus on improving the accuracy of distance estimations in an XR environment, not just the precision. This could involve exploring different types of somatosensory or combining tactile feedback with other sensory inputs.

Conclusion

The study offers new insights into the intricate relationship between somatosensory and the user's presence experience and spatial perception in an XR environment. It uncovers the nuanced role of somatosensory in shaping the user's perception of the virtual environment and its interactions.

The study found that somatosensory significantly affects the precision of distance estimations but not their overall accuracy. This highlights the potential of somatosensory to enhance the user's spatial perception, particularly regarding precision. Also, it revealed that while somatosensory enhances certain aspects of presence and realism in an XR environment, such as the general sense of being there and the perceived realism of objects, it may not impact other aspects like captivation, involvement, and the naturalness of interactions. This suggests that the influence of somatosensory on the user's presence experience is complex and multifaceted, warranting further investigation. The study also found a potential trend toward decreased negative emotional states with somatosensory. This promising finding could have significant implications for enhancing user experience in the XR environment. However, more data is needed to confirm this trend. The last insight is that integrating somatosensory does not significantly impact the perceived mental and physical workload, pace, success, or effort required for the task. This suggests that adding somatosensory does not increase the cognitive or physical demands on the user, thereby maintaining the user-friendliness of the XR environment.

In conclusion, this study contributes to our understanding of the role of somatosensory in XR environments. It highlights that somatosensory significantly affects the precision of distance estimations and the potential of somatosensory to enhance certain aspects of presence and realism in the XR environment and possibly reduce negative emotional states. The ultimate goal is to create XR environments that are not only immersive and realistic but also user-friendly and conducive to the user's spatial perception and emotional well-being.

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Appendix

Appendix A. Project Brief

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: LI 6209

initials: X.L given name: Xiangyu

student number / street & no. / zipcode & city / country / phone / email: [redacted]

Your master programme (only select the options that apply to you):

IDE master(s): ★ IPD / DfI / SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: ★ Honours Programme Master

specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Wolf Song dept. / section: SDE

** mentor: Sandhya Santhosh dept. / section: SDE

2nd mentor:

organisation:

city: country:

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

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

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair ______________________ date 03 - 02 - 2023 signature ______________________

CHECK STUDY PROGRESS

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

Master electives no. of EC accumulated in total: 9 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 9 EC

List of electives obtained before the third semester without approval of the BoE

★ YES all 1st year master courses passed

○ NO missing 1st year master courses are:

name Robin den Braber date 09 - 02 - 2023 signature ______________________

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED ○ NOT APPROVED

Procedure: ★ APPROVED ○ NOT APPROVED

comments

name Monique von Morgen date 21 - 02 - 2023 signature ______________________

How it feels: the value and application of physical sensation in XR

project title

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

start date 01 - 02 - 2023

07 - 05 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The potential of VR/AR/MR was recognized since its first introduction, including the medical profession, engineering, architecture, education, etc.(Xanthidou et al., 2022) Usually, VR/AR/MR provides dynamic visual and auditory experiences in design studies. Such virtual-auditory-based experiences improve the feeling of immersion to emulate the real world (Mütterlein, 2018), thereby increasing the productivity of designers and engineers, e.g. make a better estimation of their design.
However, many rooms are left to improve the VR/AR/MR experience, such as introducing the touch, smell and taste senses. Studies have shown that the addition of multi-sensory can enable VR/AR/MR devices to provide users with better immersive experience, and can also improve the efficiency of remote collaboration (Piumsomboon et al., 2017).

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PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Physical sensation is an important part of the experience in VR/AR/MR , which further increases the feeling of immersiveness and enhances the feeling of reality (Noghabaei & Han, 2021). The lack of physical sensation may blur the boundary between the virtual and the real world, and it may influence the "total" product experience of the designers, and sometimes, it may even result in inappropriate behaviours of the user in designing, e.g. walking through models in the digital space without taking responsibility.

In this graduation project, we want to explore 1) how to introduce physical sensation as an extra part of the VR/AR/MR experience and 2) what are the added values of introducing such sensation for designers. As an initial idea, we set the project context as designing interiors of airplane, and the physical sensation we want to introduce is the sitting experience. However, the idea might evolve with the development of the project.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in “problem definition”. Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

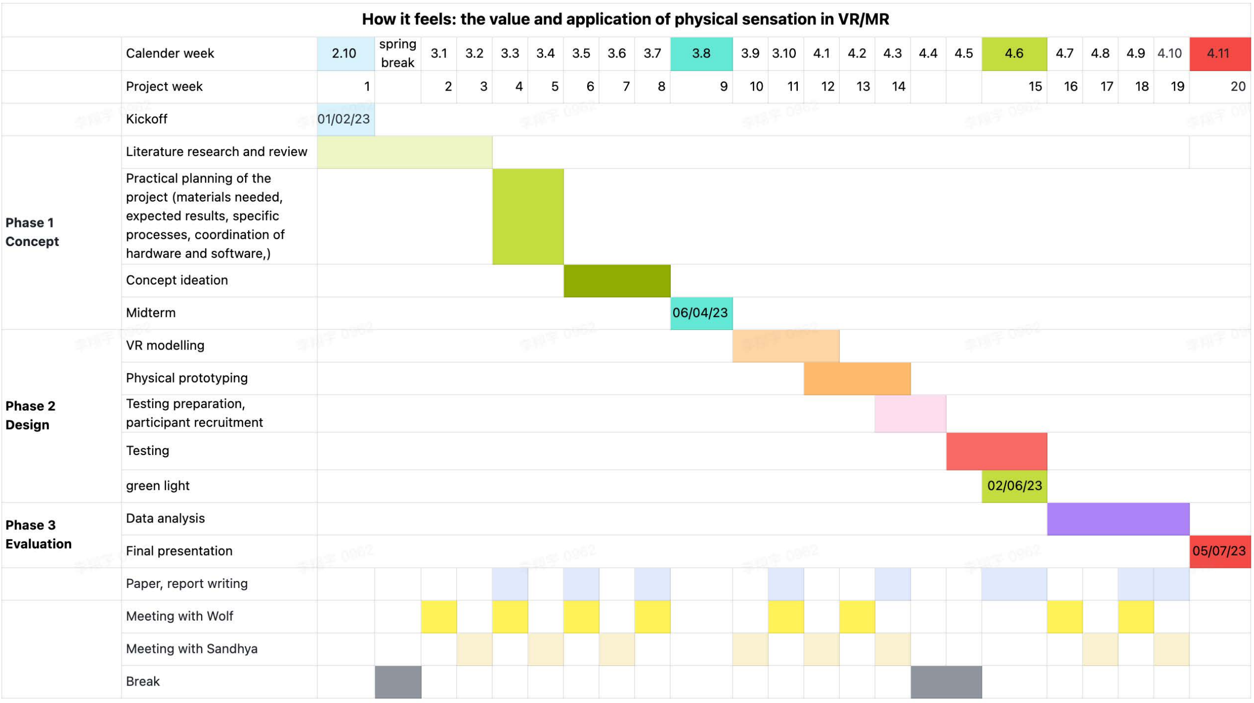
In this project, we aim to provide physical sensation experience to the designers/users in VR/AR/MR.

The initial idea is to design a portable force feedback device (Smart chair) that can be applied to different body parts and generate reasonable pressure. The smart chair and the users will be synchronized with the digital world (Aircraft interior) using the digital twin technology. Usability evaluation will be conducted for the outcomes of the project, and added values will be highlighted.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 1 - 2 - 2023 | 7 - 5 - 2023 end date



This graduation will be conducted in three phases: concept, design, evaluation.

In the concept phase, we will conduct a literature study, mainly focusing on the status of using physical sensation in VR/AR/MR, the needed hardware and software, and the evaluation methods. This phase will be concluded with a concept which satisfies the list of requirements.

During the design and prototyping phase, we will create a prototype, including both the digital and physical parts of the concept, e.g. a smart chair, a digital prototype of Aircraft interior.

During the evaluation phase, we will set up the experiment protocols, design the questionnaires, informed statements, test environments and other elements based on the requirements. With the approval of the HREC committee, we will recruit 30-32 subjects to validate the proposed concept.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

My aim in setting up this project was firstly to verify that I had become proficient in the skills I had learnt in IPD, such as research and study in specific areas, experimental design, collaboration between hardware and software, and project cycle management. Secondly, I chose the VR/XR as my graduation project because my future career plan is to continue in this field, so I want to use this project as a bridge from my academic to professional career, to be able to study this field in depth while maintaining good academic sensitivity and a positive working attitude.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix B. igroup Presence Qusetionnaire and Results

igroup presence questionnaire

	During -Test			*Post-Test*
	Spatial Presence	**Involvement**	**Realism**	**Influence of Somatosensory on Presence**
Q1	I had a sense of being in the virtual environment.	I was completely captivated by the virtual environment.	The virtual environment was lifelike.	The somatosensory enhanced my sense of being in the virtual environment.
Q2	I felt as though I was physically present in the virtual space.	I was deeply involved in the virtual experience.	The objects in the virtual environment seemed real to me.	I was more involved in the virtual environment when somatosensory were integrated.
Q3	The virtual environment seemed to surround me.	My interactions with the virtual environment felt natural.	The XR system effectively replicated the sensation of adjusting an airplane seat.	The somatosensory increased the realism of the virtual environment.
Q4	I felt like I was visiting the airplane cabin instead of just watching images of it.	I felt the XR system provided me with a persuasive simulation of an aircraft interior.	The physical sensations I experienced in the XR system were as I would expect in real life.	My ability to accurately perceive the dimensions of the virtual space improved with the addition of somatosensory.

Participant No:	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	AVW	AVDW
1	7	10	9	10	8	10	9	10	9	10	10	9	0.85	0.15
2	8	8	8	6	9	8	6	8	7	8	7	7	0.7857	0.10714285
3	10	8	8	8	7	5	5	6	4	7	8	7	0.4861	0.21296296
4	7	7	8	7	7	7	5	8	6	6	5	7	0.7333	0.15555555
5	7	8	7	5	6	6	5	7	5	5	7	8	0.4444	0.33333333
6	7	6	8	2	4	4	5	6	4	6	5	4	0.5139	0.21064814
7	7	7	6	7	6	6	7	7	6	7	7	6	0.2917	0.24305555
8	8	5	8	9	7	8	8	8	9	9	7	5	0.6458	0.26388888
9	8	8	8	7	9	8	7	8	7	7	6	7	0.625	0.16666666
10	10	6	8	9	10	8	4	7	7	6	4	8	0.5417	0.26388888
11	9	9	10	9	9	9	8	9	8	9	9	8	0.6111	0.13888888
12	8	6	7	4	4	6	5	6	7	7	6	6	0.5	0.20833333
13	6	6	5	5	5	5	5	5	6	5	5	6	0.4444	0.14814814
14	10	10	10	10	9	10	10	10	10	10	10	8	0.9643	0.05952381
15	7	7	7	7	6	7	7	7	7	7	7	7	0.9583	0.07638888
16	10	10	10	8	7	7	7	7	7	7	7	7	0.7593	0.12345679
17	4	4	6	6	4	4	10	6	4	9	6	6	0.5278	0.16203703
18	8	7	8	8	8	7	7	6	7	8	6	5	0.787	0.08487654
19	8	8	10	9	9	9	9	9	9	9	9	10	0.8	0.06666666
20	9	8	9	9	9	8	3	9	8	9	9	6	0.8571	0.16666666
21	7	8	8	6	6	7	8	9	8	9	8	9	0.6875	0.20833333
22	7	3	3	6	6	7	5	7	6	6	6	7	0.625	0.173611111
23	8	8	8	8	7	8	8	9	9	9	9	9	0.9167	0.06944444
24	10	9	10	8	9	10	9	10	9	9	9	9	0.625	0.25

Participant No:	WO1	WO2	WO3	WO4	WO5	WO6	WO7	WO8	WO9	WO10	WO11	WO12	AVWO	AVDWO
1	7	6	8	10	8	9	7	9	9	9	10	5	0.6167	0.25
2	2	7	7	5	7	9	8	8	7	8	7	5	0.6786	0.1726190
3	7	6	6	7	6	5	5	6	4	6	5	5	0.2778	0.1203703
4	7	7	8	7	7	6	5	4	6	6	4	3	0.5667	0.2444444
5	7	6	6	5	5	7	6	8	5	5	5	5	0.2778	0.2777777
6	7	3	4	2	3	3	5	6	4	3	5	3	0.3333	0.1944444
7	7	7	7	7	7	6	7	7	8	7	7	6	0.4583	0.1527777
8	8	7	9	9	7	8	8	9	6	6	5	5	0.5625	0.3125
9	8	8	7	9	8	8	7	8	7	7	6	5	0.5833	0.2083333
10	4	5	8	6	7	7	6	6	7	7	8	7	0.4167	0.1527777
11	8	8	8	7	7	9	8	8	7	7	8	8	0.25	0.1666666
12	6	5	7	6	4	5	4	6	6	6	4	7	0.375	0.2291666
13	7	4	5	6	6	5	5	5	6	5	6	5	0.4722	0.2175925
14	7	6	7	6	6	6	3	4	5	6	5	6	0.369	0.1269841
15	7	7	7	7	7	7	6	6	7	6	6	5	0.75	0.2916666
16	10	9	7	10	7	5	5	6	7	7	3	1	0.6019	0.2237654
17	4	4	4	7	4	5	10	6	3	5	3	1	0.4074	0.1790123
18	7	7	6	7	8	9	8	6	5	6	4	0	0.6759	0.1759259
19	8	8	9	8	8	8	8	9	8	9	8	5	0.6	0.1
20	7	8	8	9	7	7	2	8	7	8	7	6	0.7143	0.1428571
21	7	6	8	7	5	6	5	7	6	8	7	5	0.3542	0.2291666
22	8	2	3	6	7	6	6	7	6	6	5	5	0.5972	0.2037037
23	8	8	7	8	7	8	7	9	9	7	1	5	0.75	0.1666666
24	9	9	9	9	9	10	8	9	8	8	9	9	0.4167	0.2083333

Appendix B. NASA-TLX index and Results

NASA-TLX Table

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

What is your participant No:	TLX W1	TLX W2	TLX W3	TLX W4	TLX W5	TLX W6		TLX WO1	TLX WO2	TLX WO3	TLX WO4	TLX WO5	TLX WO6
1	3	2	3	7	2	2		6	6	5	7	6	5
2	3	5	7	7	2	2		3	8	3	6	7	1
3	1	1	5	9	1	0		2	1	1	7	2	1
4	1	1	1	9	1	1		5	4	2	7	3	2
5	0	0	0	10	0	0		1	0	0	10	0	1
6	1	7	2	8	1	1		0	0	0	9	2	0
7	6	7	3	8	2	1		7	8	5	8	2	1
8	3	2	2	9	1	0		2	1	1	9	1	0
9	2	2	0	8	0	0		4	5	4	7	7	1
10	1	2	0	10	0	0		0	1	0	10	1	0
11	1	1	3	7	1	0		1	1	4	7	2	1
12	6	3	5	7	6	7		6	5	6	6	3	5
13	1	1	1	6	1	1		1	1	2	2	1	7
14	0	0	0	8	0	2		0	0	0	10	0	0
15	6	6	5	6	6	3		6	5	5	6	5	3
16	1	1	1	5	2	4		2	2	2	2	2	2
17	0	0	0	10	0	0		0	0	0	9	0	0
18	8	3	4	7	5	1		5	8	4	6	7	3
19	2	2	1	9	2	1		2	1	1	8	1	1
20	1	0	0	8	1	0		1	1	0	10	0	1
21	3	5	2	7	5	2		2	4	2	6	7	2
22	8	4	4	7	5	2		9	2	5	7	5	2
23	1	1	1	7	2	0		3	1	2	7	7	7
24	1	0	1	9	0	0		0	0	0	9	0	0

Appendix C. Questionnaire Used in Testing

What is your participant No: *

您的回答

Have you had prior experience with any of the Extended Reality technologies such as VR or AR or MR? *

- ◯ Yes
- ◯ No
- ◯ Maybe

If yes, which XR device have you experienced?

- ☐ VR-Oculus Quest
- ☐ VR-HTC Vive
- ☐ AR/MR-Microsoft HoloLens 1&2
- ☐ Mobile/Tablet AR
- ☐ 其他:

If yes, What type of XR applications have you experienced?

- ☐ Entertainment and Gaming
- ☐ Healthcare
- ☐ Engineering & Manufacturing
- ☐ Education
- ☐ Retail
- ☐ Travel/Tourism
- ☐ 其他:

I rate my impression of XR using experience as

	0	1	2	3	4	5	6	7	8	9	10	
Negative	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Positive

IPQ with bodily tactile experience

Questionnaire to measure how immersive you are in an

I had a sense of being in the virtual environment.

	0	1	2	3	4	5	6
Negative	◯	◯	◯	◯	◯	◯	◯

I felt as though I was physically present in the virtu

	0	1	2	3	4	5	6
Negative	◯	◯	◯	◯	◯	◯	◯

The virtual environment seemed to surround me.

	0	1	2	3	4	5	6
Negative	◯	◯	◯	◯	◯	◯	◯

I felt like I was visiting the airplane cabin instead o

	0	1	2	3	4	5	6
Negative	◯	◯	◯	◯	◯	◯	◯

I was completely captivated by the virtual environm

	0	1	2	3	4	5	6
Negative	◯	◯	◯	◯	◯	◯	◯

I was deeply involved in the virtual experience.

	0	1	2	3	4	5	6
Negative	◯	◯	◯	◯	◯	◯	◯

XR environment

7 8 9 10

Positive

ual space.

7 8 9 10

Positive

7 8 9 10

Positive

f just watching images of it.

7 8 9 10

Positive

ment.

7 8 9 10

Positive

7 8 9 10

Positive

I was deeply involved in the virtual experience.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

My interactions with the virtual environment felt natural.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

I felt the XR system provided me with a persuasive simulation of an aircraft interior.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

The virtual environment was lifelike.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

The objects in the virtual environment seemed real to me.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

The XR system effectively replicated the sensation of adjusting an airplane seat.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

The bodily tactile experience I experienced in the XR system were as I would expect in real life.

	0	1	2	3	4	5	6	7	8	9	10	
Negative	○	○	○	○	○	○	○	○	○	○	○	Positive

NASA-TLX

How mentally demanding was the task?

	0	1	2	3	4	5	6	7	8	9	10	
Very Low												Very High

How physically demanding was the task?

	0	1	2	3	4	5	6	7	8	9	10	
Very Low												Very High

How hurried or rushed was the pace of the task?

	0	1	2	3	4	5	6	7	8	9	10	
Very Low												Very High

How successful were you in accomplishing what you were asked to do?

	0	1	2	3	4	5	6	7	8	9	10	
Very Low												Very High

How hard did you have to work to accomplish your level of performance?

	0	1	2	3	4	5	6	7	8	9	10	
Very Low												Very High

How insecure, discouraged, irritated, stressed, and annoyed wereyou?

	0	1	2	3	4	5	6	7	8	9	10	
Very Low												Very High

Influence of Tactile Experience on Presence

The bodily tactile experience enhanced my sense of being in the virtual environment.

	0	1	2	3	4	5	6	7	8	9	10	
Negative												Positive

I was more involved in the virtual environment when bodily tactile experiences were integrated.

	0	1	2	3	4	5	6	7	8	9	10	
Negative												Positive

The bodily tactile experience increased the realism of the virtual environment.

	0	1	2	3	4	5	6	7	8	9	10	
Negative												Positive

My ability to accurately perceive the dimensions of the virtual space improved with the addition of tactile experiences.

	0	1	2	3	4	5	6	7	8	9	10	
Negative												Positive

Appendix D. Objective Measurement Results

Objective Measurement

Participant NO.	Original data (in 44.45 mm)	Arm width	17W	17WO	18W	18WO	19W	19WO
1 WO / W	33	11.45	38	33	39.5	36	38	41.5
2 W / WO	41	3.45	40	39	44	43.5	45	44.5
3 WO / W	42.5	1.95	39.5	41.5	40.5	38.5	41.5	39.5
4 W / WO	32	12.45	28.5	34	33	40	33.5	43
5 WO / W	37	7.45	37	38.5	39.5	39	40.5	41.5
6 W / WO	45	-0.55	38.5	37.5	41.5	42.5	43	43
7 WO / W	51	-6.55	46.5	52.5	52.5	49	53	48
8 W / WO	37.5	6.95	41	38	44	47	47	45
9 WO / W	42	2.45	41.5	41	42	42.5	43	43
10 W / WO	42	2.45	43	43.5	48	42.5	49	46
11 WO / W	38	6.45	41	38	44	43	44.5	44
12 W / WO	40	4.45	37	36	41	39.5	43	42
13 WO / W	43.5	0.95	44	39	44.5	45.5	48	44
14 W / WO	55.5	11	56	48	58	56	59	58
15 WO / W	43	1.45	45.5	41.5	46.5	43	48	46.5
16 W / WO	37	7.45	37	35	41.5	35.5	43	40.5
17 WO / W	40.5	3.95	32	30	34	34	34.5	33
18 W / WO	43	1.45	40	40.5	43	43.5	44.5	43.5
19 WO / W	43	1.45	41	41.5	42.5	43	43.5	43.5
20 W / WO	58	13.55	51.2	51	52	55	58	54
21 WO / W	36.5	7.95	37	31	42	40	41	46
22 W / WO	36.5	7.95	37.5	36.5	39.5	39	41.5	41
23 WO / W	41	3.45	39	36.5	40	36	42	40
24 W / WO	37	7.45	38	30	40	32	41.5	39

Participant NO.	17W deviation	17WO deviation	18W deviation	18WO deviation	19W deviation	19WO deviation
1 WO / W	-5	0	-3.96	-0.46	-1.19	-4.69
2 W / WO	1	2	-0.46	0.04	-0.19	0.31
3 WO / W	3	1	4.54	6.54	4.81	6.81
4 W / WO	3.5	-2	1.54	-5.46	2.31	-7.19
5 WO / W	0	-1.5	0.04	0.54	0.31	-0.69
6 W / WO	6.5	7.5	6.04	5.04	5.81	5.81
7 WO / W	4.5	-1.5	1.04	4.54	1.81	6.81
8 W / WO	-3.5	-0.5	-3.96	-6.96	-5.69	-3.69
9 WO / W	0.5	1	2.54	2.04	2.81	2.81
10 W / WO	-1	-1.5	-3.46	2.04	-3.19	-0.19
11 WO / W	-3	0	-3.46	-2.46	-2.69	-2.19
12 W / WO	3	4	1.54	3.04	0.81	1.81
13 WO / W	-0.5	4.5	1.54	0.54	-0.69	3.31
14 W / WO	-2.5	1.5	-0.96	2.54	-1.19	0.31
15 WO / W	0	2	-1.96	4.04	-2.19	0.31
16 W / WO	8.5	10.5	9.04	9.04	9.81	11.31
17 WO / W	3	2.5	2.54	2.04	2.31	3.31
18 W / WO	2	1.5	3.04	2.54	3.31	3.31
19 WO / W	-0.5	5.5	-2.96	-0.96	-0.69	-5.69
20 W / WO	-1	0	-0.46	0.04	-1.19	-0.69
21 WO / W	2	4.5	3.54	7.54	2.81	4.81
22 W / WO	-1	7	-0.46	7.54	-0.69	1.81
23 WO / W	9.1	1.1	8.56	6.56	8.29	7.29
24 W / WO	1.8	1.6	0.06	3.06	4.79	0.79

Appendix E. Ethics Approval Application Form

Date 23-Jun-2023
Contact person [redacted]
E-mail

TUDelft Delft University of Technology

Human Research Ethics Committee TU Delft
(http://hrec.tudelft.nl)

Visiting address
Jaffalaan 5 (building 31)
2628 BX Delft

Postal address
P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: How it feels: the value and application of physical sensation in VR/MR
Applicant: Li, Xiangyu

Dear Xiangyu Li,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission to the HREC which has been approved. We do additionally note/advise the following:

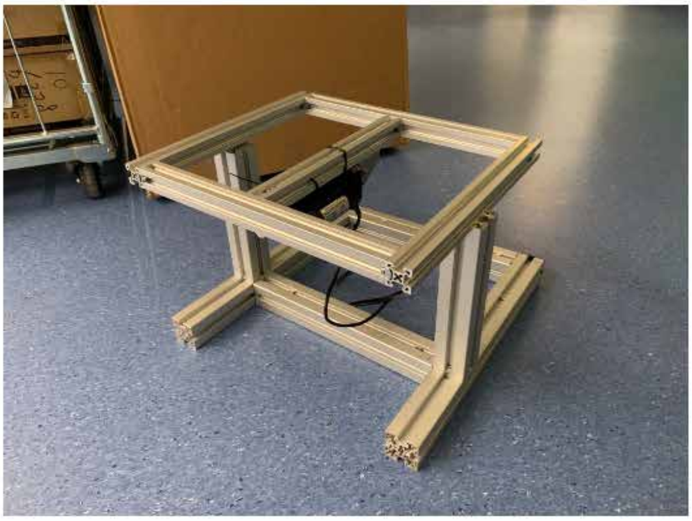
In addition to any specific conditions or notes, the HREC provides the following standard advice to all applicants:
• In light of recent tax changes, we advise that you confirm any proposed remuneration of research subjects with your faculty contract manager before going ahead.
• Please make sure when you carry out your research that you confirm contemporary covid protocols with your faculty HSE advisor, and that ongoing covid risks and precautions are flagged in the informed consent - with particular attention to this where there are physically vulnerable (eg: elderly or with underlying conditions) participants involved.
• Our default advice is not to publish transcripts or transcript summaries, but to retain these privately for specific purposes/checking; and if they are to be made public then only if fully anonymised and the transcript/summary itself approved by participants for specific purpose.
• Where there are collaborating (including funding) partners, appropriate formal agreements including clarity on responsibilities, including data ownership, responsibilities and access, should be in place and that relevant aspects of such agreements (such as access to raw or other data) are clear in the Informed Consent.

Good luck with your research!

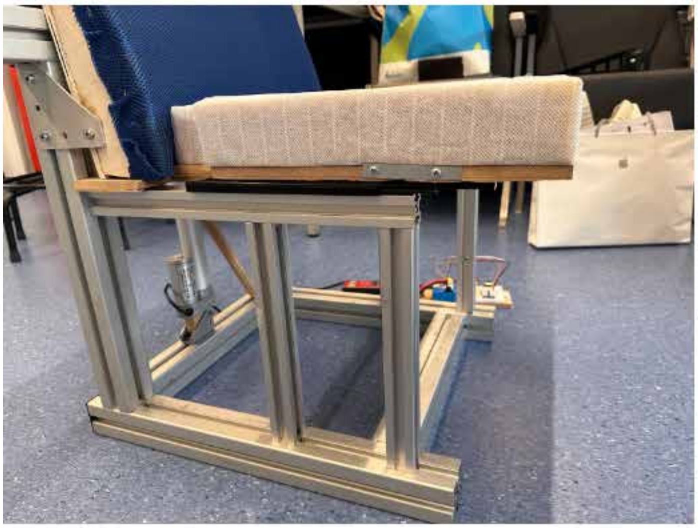
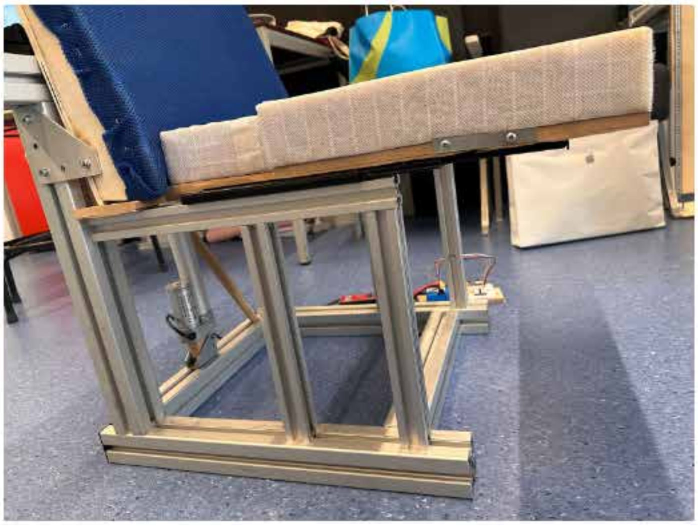
Sincerely,

Dr. Ir. U. Pesch
Chair HREC
Faculty of Technology, Policy and Management

Appendix F. Adjustable Chair Structure





Appendix G. Informed Consent

Informed consent

(04/05/2023)

Dear Participant,

Thank you for participating in our research on the topic: How it feels: the value and application of physical sensation in VR/MR. You have been invited to take part in this research project as outlined below. Please feel free to ask any questions you may have to the researcher. Our goal is to provide you with a comfortable, safe, and friendly environment.

Purpose of the research

This project aims to provide the designers/users with a tactile sensation in VR/AR/MR. In this context, we designed an airplane seat that can adjust size (e.g., armrest width and sitting depth). The research aims to assess this technique for its potential to improve immersion and realism, enhance interactivity, and advance the overall application of XR digital twins.

Participants will investigate the experience of physical sensations in mixed reality and evaluate seat comfort, passenger wellbeing and spatial recognition accuracy using Microsoft HoloLens2 devices and adjustable-size aircraft seats.

Benefits and Risks of Participation

You will be asked to follow the protocol as stated below. There are no risks associated with these tests. If at any point you feel uncomfortable (physically or mentally) while wearing the Mixed Reality device, you can stop the experiment. However, a training session will be conducted where you can try the device and give your consent before starting the tests.

As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by:

1. NOT recording your name and personal information;
2. Stopping the experiment if you do not feel comfortable;
3. Explaining the protocols and guiding you through the session;
4. Demonstrating the desired session;
5. Answering questions.

Withdrawal from the Study

Your participation in this study is entirely voluntary, and you can withdraw at any time during the process if so, any collected data will be destroyed on-site. Otherwise, we will pre-process the data in the coming month, and you can ask us to remove your data at any moment within this month based on the participant number in your informed consent. After one month, the data will be anonymized, and it will not be possible to remove your data from the dataset.

Protocols of the study

The correlation experiment will involve testing one participant at a time, who will assume two roles: a flight attendant and a passenger. You will be assigned a role and encouraged to think from that perspective. Feel free to share your opinions or thoughts on mission scenarios without any restrictions. The experiment consists of two phases, as described below:

Phase 1: Introduction and Briefing (10 minutes)
You may:
• Request to read and sign an informed consent form
• Be asked basic questions about your personal information (e.g., height and weight), anthropometry (e.g., shoulder width, hip width), and recent flight experiences
• Inquire about the relevant experience with XR use

Phase 2: XR Experience Testing and Evaluation (25-30 minutes, including training with MR devices)

Researchers will explain the Microsoft HoloLens2 mixed reality device and arrange training sessions for you to familiarize yourself with and explore the device. Once comfortable, you will initiate the associated app and begin your digital experience. You may:
• Request to speak loud your thought and answer questions
• Be guided through the scenarios first and then have free time to explore the digital scenarios/environments
• Be asked to complete a two-part questionnaire: (a) about seat comfort and (b) about XR experience

After the session, a final discussion will take place to collect your general comments on the experiment plan, XR system, and so on. All sessions will be recorded for further analysis by the researchers. In addition to subjective questions, objective data related to the testing process, such as walking trajectories, postures, and participants' height and weight while using the XR device, will be gathered for further analysis.

Anonymization, Storage, and Access to Data

The collected data will be anonymized in such a way that the names and addresses of the participants can no longer be identified. In the publication, only the following results will be published:

- Typical setups of the experiment (photos without personal identifiers, e.g., any faces will be masked);
- The statistical results of any subjective questions;
- The statistical results of any objective measurements;
- Models generated based on logical interpretation of the data or driven by the data;

The data will be stored on a secure server at TU Delft, which can only be accessed by the researchers. The data will be managed according to the data management plan (attached). The data will NOT be shared and reused by default. However, participants can voluntarily donate their data to the research team at TU Delft to be anonymously used in future research.

Consent Form for the project: How it feels: the value and application of physical sensation in XR

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [__/__/*2023*], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: [*see points below*]	☐	☐
• *Discussion on a topic* • *Filling a questionnaire* • *Wearing a Mixed Reality Device , Microsoft HoloLens2 and interacting with digital elements* • *Use a safety-certified adjustable airplane seat* • *The sessions are video recorded* • *Height, weight and body posture is collected*		
4. I understand that there will be no reward/ payment for my participation.	☐	☐
5. I understand that the study will end 15/07/2023		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks (**a**). I understand that these will be mitigated by (**b**)	☐	☐
a) physical or mental discomfort by wearing the Mixed Reality Device *b) stopping the experiment.*		
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed	☐	☐
Personally identifiable information • *Occupation* *We collected the following information, which we are not aware that if it is personally identifiable research data. However, we cannot rule out risks.* • *Age* • *Weight* • *Height* • *Popliteal height*		
9. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach	☐	☐
• *All PII (Participant number) will be destroyed two-month after data collection (after anonymization). All data will be stored in a TU Delft secure server and will be kept for research team only*		
10. I understand that personal information collected about me that can identify me, such as [*Weight, height, popliteal height*], will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed 2 month	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for [*see points below*]	☐	☐
Research publication may include the following information: • *The statistical results of the age, weight, height, popliteal height* • *The statistical results of any subjective questions* • *The word of the purpose during the experience session*		
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
14. I give permission for the de-identified Questionnaire and the objective measurement data that I provide to be archived in 4TU.ResearchData repository so it can be used for future research and learning. Attention: The data will NOT be shared and re-used by default. The default choice of this question is NO	☐	☐

Signatures

_____________________________ _____________________________ _________
Name of participant [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

___________________________ ____________________ _________
Researcher name [printed] Signature Date

Study contact details for further information:

Xiangyu Li
IPD Masters Student,
TU Delft

Y. Song (Wolf), PhD MSc BEng
Faculty of Industrial Design Engineering Landbergstraat 15, 2628 CE Delft
TU Delft

Appendix H. Device Report

Delft University of Technology
INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies[1].

The first part of the report has to be completed by the researcher and/or a responsible technician.

Then, the safety officer (Heath, Security and Environment advisor) of the faculty responsible for the device has to inspect the device and fill in the second part of this form. An actual list of safety-officers is provided on this webpage.

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. Information on ethics topics, including the application process, is provided on the HREC website.

Device identification (name, location): Aircraft Seats for Measuring Seat Comfort and Spatial Recognition Accuracy

Configurations inspected[2]: NA

Type of experiment to be carried out on the device:[3] Sitting

Name(s) of applicants(s): Xiangyu Li

Job title(s) of applicants(s): MSc student

(Please note that the inspection report should be filled in by a TU Delft employee. In case of a BSc/MSc thesis project, the responsible supervisor has to fill in and sign the inspection report.)

Date: 25/05/2023

Signature(s): [redacted]

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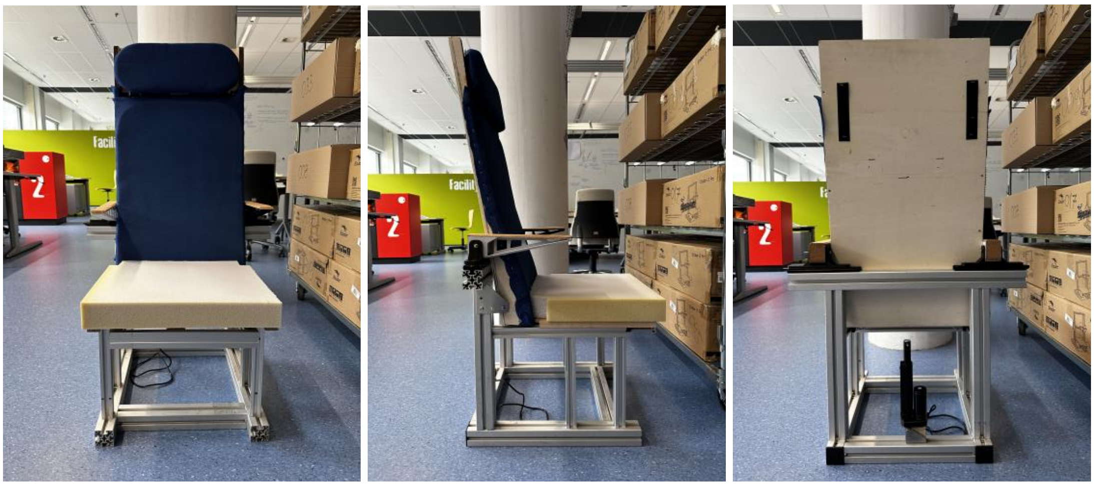
1 Modified, altered, used for a purpose not reasonably foreseen in the CE certification

2 If the devices can be used in multiple configurations, otherwise insert NA

3 e.g. driving, flying, VR navigation, physical exercise, ...

Setup summary



This experimental apparatus, designed for research testing within a master's graduation project, comprises an aircraft seat that can adjust the armrest distance and seat depth using linear actuators. Constructed primarily from aluminum profiles, the seat features a cushion composed of MDF and memory foam, while the backrest is made from wooden boards, PVC pipes, and elastic nets. The adjustable portion of the armrest includes two linear slides, a linear actuator, and a pair of connecting rods.

Primarily, this device functions within an environment that synchronizes physical changes with virtual environment modifications in Hololens. When the tester initiates a scene switch in the virtual environment, the Hololens scene alters accordingly. Simultaneously, a Bluetooth signal is dispatched to an external microprocessor, controlling the linear actuator's movement. Once the actuator has traveled a predetermined distance, a limit switch halts the process.

Usage scenario

Step 1

Have the participant sit in the chair and adjust to a comfortable position.

Step 2

Wear a HoloLens to the participant and have them do assigned tasks.

Step 3


When the participant presses the interactive button 1, the armrest will move outward for a certain distance.


When the participant presses the interactive button 2, the leg support will move forward a certain distance.

Risk checklist

Hazard type	**Present**	**Hazard source**	**Mitigation measures**
Mechanical (sharp edges, moving equipment, etc.)	movable armrest	May squeeze the participant	Move away from the participant. Cut off the power when the equipment does not stop in time.
Electrical	See appendix for details		Cut off the power when the equipment does not stop in time.
Structural failure	Seat pad weight	MDF panels may break when overloaded	The weight of the participant is controlled below 100kg. When the structure failure, stop testing and ask participants leave the seats immediately
Touch Temperature	N/A		
Electromagnetic radiation	N/A		
Ionizing radiation	N/A		
(Near-)optical radiation (lasers, IR-, UV-, bright visible light sources)	N/A		
Noise exposure	N/A		
Materials (flammability, offgassing, etc.)	N/A		
Chemical processes	N/A		
Fall risk	N/A		

Appendices

Electronic component list

Components	*Amount*	*Descriptions*	*Reference link*
Seeed Studio XIAO nRF52840 Sense	1	Most widely used single-board computer, operated by Linux and self-developed Python program	https://www.seeedstudio.com/Seeed-XIAO-BLE-Sense-nRF52840-p-5253.html?queryID=f5d881b916b9b5f4d22f4efc003dc73f&objectID=5253&indexName=bazaar_retailer_products
Micro Switch	3	Limit switch	https://www.tinytronics.nl/shop/nl/schakelaars/manuele-schakelaars/microschakelaars/micro-switch-met-hefboom
AUTOUTLET linear actuator	2	DC 12 V, 750 N, 100 m, 10 mm/s, electric cylinder, push rod moto	https://www.amazon.nl/-/en/dp/B07WLBHHSQ?ref=ppx_yo2ov_dt_b_product_details&th=1
MDD3A DC Motor Driver	1	Motor driver to drive the linear actuator	https://www.cytron.io/p-3amp-4v-16v-dc-motor-driver-2-channels

Device inspection

(to be filled in by the AMA advisor of the corresponding faculty)

Name: Peter Kohne

Faculty: 3mE-IO

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical testing, measurements for electrical safety etc.)

✓

Date: 30-05-2023

Signature: 

Inspection valid until[4]:

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

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4 Indicate validity of the inspection, with a maximum of 3 years