Design of a Multimodal Mixed Reality Work Environment with Wearable Technology

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Abstract

Issues relating to health and well-being at work have risen in prominence, exerting negative effects upon both individuals and organizations. Two main contributing factors are a lack of awareness of one's bodily status and a lack of accessible and effective adjustment mechanisms. Through a comprehensive literature review in the fields of Physiology and Biosensors, Mixed Reality, and Environmental Psychology, this study examines the impacts of environmental attributes and investigates how technology can be leveraged to provide solutions for coping with changes in bodily status caused by internal or external stressors. To address the problem, this study proposes and develops a hybrid wearable and Mixed Reality system prototype that enhances awareness of bodily status and provides mediation. This prototype can adapt to the individual's real-time biometric data through a wearable glove, and provide personalized feedback in a Multimodal Mixed Reality working environment. A small-scale user testing was conducted and has yielded positive feedback. Ultimately, this study highlights that the implementation of a wearable and Mixed Reality system has the potential to contribute to a healthier and more productive workplace for individuals and organizations alike.

Keywords: Environmental Psychology, Wearable Technology, Electronics, Mixed Reality, Augmented Reality, Human-Computer Interaction

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Table of Contents

List of Appendices

List of Figures

List of Tables

1. Introduction

1.1 Motivation

In today's fast-paced and technology-driven society, the pressure to excel in both personal and professional life has become increasingly intense. The constant demands of work and the rise of digitalization have led to increased work-induced illnesses and physical health problems. The relationship between health and work-life balance is critical, and achieving a balance between work and personal life is essential for maintaining physical and mental well-being.

The effects of the contemporary work culture can be seen in the growing prevalence of work-related stress and burnout, as well as physical health problems caused by sedentary work and lack of physical activity. This is often referred to as the ‘rat race’ (Gullotta & Lin, 2022) or ‘internalized capitalism’ (Dastagir, 2021), in which an individual’s self-worth is tied to productivity. Individuals thus feel compelled to constantly strive for success and material wealth, often at the expense of their own well-being. Criticizing a mentality or mode of a system may be easy, but implementing change requires much more effort and commitment. It is not practical for individuals to completely reject the productivity-driven mentality by abstaining from work, given that many still require financial stability to support themselves. Thus, finding a balance between work and well-being is not only advantageous but also essential.

As technology has become a key player in productivity, it has received tremendous praise but also numerous critiques. How to cooperate with it and use it to our own advantage remains the center of attention. As a designer, being able to merge one’s own thoughts with surrounding designed objects, tools and patterns is of tremendous importance. Designers are the ones who provide guidance on how humans and technology could interact, specifically to what extent, and in what way would technology be able to impact us. In this study, I am exploring two emerging technologies and the interaction between them: Mixed Reality and Wearable Technology. By integrating both with design thinking, I hope to find a solution to the identified problem space and generate potential creative interventions on the foundation of these technologies. Therefore, this study hopes to explore the possibilities of technology-assisted support for individuals and how that concept could be ideated, designed, developed, and implemented.

1.2 Problem Space

Workplaces in the majority of contemporary society are desk-based, with extensive sitting and little exercise during working hours. Given that physical activity can have positive impacts on musculoskeletal pain, depressive symptoms and anxiety, and work performance outcomes, this lack of physical activity and movement among desk-based workers is concerning (Ryde et al., 2020).

Since 1996, issues relating to health and well-being at work have risen in prominence. Particularly, the issues related to stress, exhaustion, and burnout have drawn a lot of attention. The problems associated with unhealthy working habits have become more frequent and manifest, including work-induced stress as one of the main identified problems receiving increasing attention (Schabracq et al., 2003).

Stress reactions can seriously disrupt people's adaptability to the environment, both personally and organizationally. On the personal level, stress has been observed to impede personal development and reduce creativity, thus incurring a detrimental impact on work motivation, satisfaction, and overall well-being. Stress can cause a variety of psychological and physical ailments and disorders, all of which may contribute to premature death (Wong et al., 2019). At the organizational level, stress can have a variety of repercussions that each have the potential to endanger the sustainability of any organization. Potential effects include low production quality and quantity, ineffective cooperation, and high turnover rates of competent employees. All these are detrimental to the reputation and development of an organization which entails further serious impacts (Schabracq et al., 2003).

Beyond stress, fatigue and muscular pain are among the most common work-related health problems. The modern industry faces a serious problem with worker fatigue, partly due to the high demand for employment, extended working hours, interference with circadian rhythms, and mounting sleep deprivation (Yazdi & Sadeghniiat-Haghighi, 2015). Work-related musculoskeletal problems encompass a broad spectrum of degenerative and inflammatory disorders and diseases. These diseases cause pain and functional impairment and can affect the neck, shoulders, elbows, forearms, wrists, and hands, among other places (Buckle & Devereux, 2002).

In sum, extended periods of working and unsustainable working habits bring tremendous negative effects upon individuals and organizations in various aspects. Key factors that contribute to the problem include 1) Inadequate or non-existent health and safety policies; 2) Poor communication and management practices; 3) Lack of support for employees; 4) Work performance pressure; 5) Job insecurity; 6) Lack of psychological safety; 7) Negative workplace environment.

1.3 Research Summary

This research aims to address the problem of unsustainable and unbalanced working modes that are prevalent among contemporary employees and workers. To accomplish this, the study dissects the problem into smaller components and attempts to identify creative interventions to address them. The intricate nature of work-related problems is influenced by various individual, cultural, societal, and institutional factors. Therefore, the research does not aim to suggest a complete overhaul of the system. Instead, it seeks to explore how current tools can be optimized to better aid workers and employees in achieving improved health and sustainable lifestyles on an individual level.

1.3.1 Problem Statement

As there are both internal and external factors that could be addressed from different levels of perspective, this research focuses on providing support on an individual basis to boost overall well-being and mitigate negative work-induced problems by enhancing awareness and nudging behavior change.

Body signals are easy to be ignored, and this is one of the main identifiable consequences when there are inadequate or non-existent health and safety policies at the workplace, work performance pressure, or a negative workplace environment. The lack of awareness hints at potential health drawbacks, overwork, and work-induced physical and psychological burden. In addition, a lack of available and affordable coping mechanisms in addressing these bodily responses also derives from the above-mentioned scenario, in addition to poor communication and management practices and a lack of support for employees. The lack of adjustment mechanisms reinforces identified physical and psychological burdens by posing difficulty for people to break out of the vicious cycle.

This thesis study will seek out design solutions in addressing two key identified problems:

1. Lack of awareness towards bodily status while working and;
2. Lack of accessible and affordable adjustment mechanisms at the working status.

1.3.2 Research Questions

This thesis attempts to explore the following research question:

How can the design of a Multimodal Mixed Reality Working Environment enhance body awareness and provide mediation?

1.3.3 Goals and Objectives

This study aims to address this pressing issue by exploring the potential of Mixed Reality and Wearable Technology as tools to enhance individual awareness of the bodily status and to mediate. By drawing on the theories of Environmental Psychology, this study delves into the influence of surrounding elements, including color, lighting and sound, on human behavior and bodily response. The goal is to use Mixed Reality spatial design as a new way to view architectural and interior spaces, adding another layer to the physical reality and becoming a new reality in itself. By considering the effects of our surroundings on our psychology and behavior patterns, Mixed Reality environments have the potential to generate positive effects for users through their immersive and embodied characteristics.

This study builds a working prototype of a hybrid Wearable and Mixed Reality system as a proof-of-concept. Through integrating wearable technology and embedded sensors, biometric values can be outputted and visualized into a Mixed Reality environment. Through this immersive environment, individuals perceive information via peripheral vision without interfering with the main area of focus. They will be able to acknowledge, understand, and respond to mechanisms in coping with potential work-induced negative consequences.

1.3.4 Contributions

The main contribution of this study is the design and development of innovative mechanisms to enable a Mixed Reality environment to modify its lighting, color, and sound in a responsive and adaptable manner, in order to capture and influence an individual's perceived bodily status and response.

Main contributions include the following:

1. This study introduces a prototype system that utilizes real-time monitoring of individuals' physiological signals to dynamically adjust.
2. This study incorporates principles from Environmental Psychology to enhance the interaction between individuals and space via Mixed Reality technology.
3. This study explores the potential of using a multimodal Mixed Reality setting for future workspace design.

1.3.5 Research Scope

This study is an attempt to address the two above-mentioned problems by exploring the overarching research question of optimizing health and productivity at a workplace through design interventions. In this study, the measurement of health will be captured into the format of biometric sensor data such as heart rate, body temperature, and galvanic skin response. This study will be conducted in a traditional table-oriented work environment to ensure consistency in design iterations and simulate real-world common office scenarios. The target audience for this study is people who work remotely at home offices or on-site in physical offices.

1.4 Chapter Overview

This study proposes the research question of *how can the design of a Multimodal Mixed Reality Working Environment (MMRWE) be able to enhance body awareness and provide mediation?* By incorporating wearable technology, biometric sensor data can be displayed and interpreted in a Mixed Reality environment, providing novel ways for individuals to gain insight into their own bodies. The aim of this study is to confirm the hypothesis that such a Mixed Reality environment could be a useful tool for enhancing individual awareness, providing ways to make adjustments, and improving overall health and productivity.

This thesis paper is divided into seven main chapters:

Chapter 1 introduces the personal motivation behind this project, the research summary, and provides a general overview of the structural components.

Chapter 2 presents a literature and contextual review that addresses relevant domains: Environmental Psychology, Physiology and biosensor, and Mixed Reality system. Through illustrating relevant works and studies, this chapter concludes by identifying the current research gap and contextualizing this thesis project in the wider academic landscape.

Chapter 3 discusses the research methodologies used as the foundation and guideline of this study. It addresses Research through Design, Interaction Design Frameworks, and Speculative Design, with a summary of how a combination of these methodologies is applied in informing the design processes.

Chapter 4 focuses on multiple iterations of prototypes created to address the research questions, ranging from low-fidelity prototypes to high-fidelity prototypes. This chapter also explains the rationale behind each design decision informed by user research and ends with a summary of the design iterations.

Chapter 5 covers the evaluation process of the final prototype. It presents evaluation criteria, user testing process, and outcomes. The results are analyzed and discussed to inform future design iterations and to highlight the successes and limitations of the design.

Chapter 6 concludes this thesis project by revisiting stated goals and contributions. The conclusion underlines future work based on findings of the evaluation process as well as potential technological advancement.

2. Literature and Contextual Review

This literature review examines the potential of Mixed Reality and wearable technology as tools to boost health and productivity in the face of the challenges posed by the rapidly advancing digital landscape and fast-paced modern society. To contextualize this investigation, relevant literature related to Physiology and biosensors, Mixed Reality (MR), and their applications in workspace and health are presented. The section also draws upon theories in Environmental Psychology, with a focus on the sensory aspects of color, light, and sound, to gain insights from interior and architecture designers on how environmental factors impact human behavior in informing MR environment design, with the potential to provide relief to users. Ultimately, this literature review sets the foundation for the investigation of interactive technology as a tool for enhancing body awareness and providing mediation.

2.1 Physiology and Biosensor Research

The study of physiology and biometric data is crucial in understanding human health and behavior. Biometric sensors have become an essential tool for monitoring individuals' bodily status, providing real-time data on vital signs such as heart rate, respiration, and skin conductance. These sensors serve as an entry point into knowing more about an individual's physical state and can provide valuable insights into their emotional and mental well-being. By incorporating biosensors, we can better understand the physiological responses towards different environmental stimuli and develop mediating mechanisms accordingly. This subsection explores the role of biometric sensors in this context and examines relevant literature related to the use of biosensors for physiological monitoring in the format of wearable technology.

2.1.1 Stress and Autonomic Nervous System (ANS)

The human nervous system can be viewed as a complicated system of specialized cells that transmit information about the individual and their environment (Maton et al., 1993). The nervous system is categorized into two main subsystems in gross anatomy: the Central Nervous System (CNS) and the Peripheral Nervous System (PNS). The autonomic nervous system (ANS) is a branch of the PNS and a control system that operates unconsciously and manages bodily functions in response to internal or external stimuli (Waxenbaum et al., 2022). Multiple internal organs are connected through ANS as well as functions like heart rate, digestion, contraction force, respiratory rate, urination, and sexual arousal. The sympathetic nervous system employs spinal nerves to bridge between the internal organs and the brain. When these nerves are stimulated, the organism adapts to stress by increasing heart rate, increasing blood supply to the muscles, and decreasing blood flow to the skin.

The stress response is initially adaptive as it prepares the body to handle challenges presented by internal or external stressors, such as the physiological response to trauma or surgery to reduce further tissue damage. However, if the exposure to a stressor is perceived as intense, repetitive (repeated acute stress), or prolonged (chronic stress), the stress response becomes maladaptive and can be harmful to physiology, causing maladaptive reactions such as depression, anxiety, cognitive impairment, and heart disease (Chu et al., 2022). Chronic stress can lead to dysregulation of the ANS, with an overactive sympathetic response and an underactive parasympathetic response, which can result in a range of physical and psychological health issues (Won & Kim, 2016).

Wearable devices, such as smartwatches and fitness trackers, have become increasingly popular for monitoring ANS activity in daily life. Wearables can provide continuous monitoring of biometric signals and alert users to changes in their ANS activity, such as changes in heart rate, that may indicate stress or anxiety (Mahmud et al., 2019). Additionally, wearables can provide feedback to users to help them regulate their ANS activity and improve their overall health and well-being.

2.1.2 Biosensor Research and Wearables

Biosensor research in the area of human-computer interaction has been ongoing for quite some time. Wearable biosensors have gained significant attention in recent years due to their potential to provide real-time physiological information for healthcare applications. Earlier approaches in this field were centered on physical sensors that tracked essential parameters such as steps taken, calories burned, and heart rate. Recent developments in electrochemical and optical biosensors have enabled non-invasive monitoring of new biomarkers, ranging from metabolites to bacteria and hormones (Kim et al., 2019). Biosensor research has focused on improving accuracy, reliability, and wearability, while also addressing the challenges of non-invasiveness and better integration.

These sensors can provide continuous and real-time monitoring of various bodily functions. Some common ones include heart rate, respiration, galvanic skin response (GSR), blood pressure, and oxygen level. Heart rate sensors are among the most common biometric sensors, measuring the heart rate of an individual by detecting the electrical activity of the heart. Respiration sensors measure the rate and depth of breathing, providing information on the individual's respiratory activity. Galvanic skin response sensors measure the electrical conductance of the skin, which changes with emotional arousal and stress. Blood pressure sensors measure the force of blood against the walls of arteries, providing information on an individual's cardiovascular health. Lastly, oxygen level sensors measure the saturation of oxygen in the blood, providing information on an individual's respiratory and cardiovascular health.

2.1.3 Affective Detection

Affect is a significant aspect of our daily experiences and is commonly described in literature as an impulsive mental feeling or state (Jerritta et al., 2011). The impact of emotions can be overwhelming for the human body, which reacts through various physical and physiological signals. Affective detection is a field of research that focuses on the development of technologies that can detect and interpret human emotions (Calvo & D'Mello, 2010). These technologies use various sensors to measure physiological signals such as heart rate, skin conductance, and facial expressions, which are then analyzed to determine the emotional state of the individual. The goal of affective detection is to create systems that can recognize human emotions and respond to them in real-time, leading to more empathetic and personalized interactions between humans and machines.

From a theoretical perspective, affect detection is essentially a challenge in signal processing and pattern recognition, as it involves creating a classifier or regressor to identify an unclear phenomenon (affect) from observable signals. This is an exceptionally difficult problem because affective states are psychological constructs or conceptual variables that are not directly observable and are part of a complex and context-dependent expressive and communicative system that has evolved over millions of years (Schmidt et al., 2018). Traditional affect detection modalities, such as physiology, face, and voice, as well as emerging research on novel channels such as text, body language, and complex multimodal systems are all adopted methodologies across ongoing research of affective detection.

2.1.4 Case Studies

Pulse Topography is an interactive installation that explores the concept of biometric signals. The installation consists of thousands of light bulbs suspended at different heights, creating a landscape visitors are invited to traverse. Each light bulb is linked to a different participant's pulse, recorded by custom-made pulse sensors. As participants interact with the installation, their pulse is added to the sequence of recordings, with the newest replacing the oldest (Lozano-Hemmer, 2021). The installation translates an interior force, the heartbeat, into an exterior form, creating a tangible representation of an otherwise invisible phenomenon. The combination of light and sound creates an immersive experience that highlights the collective and connective nature of biometric signals. *Pulse Topography* serves as a platform for self-representation and makes tangible the idea that individual heartbeats can come together to form a chorus of light and sound. This work showcases how biometric signals and the creation of a connective arrangement highlight the potential for wearable technology to be used in this context. The translation of an interior force into an exterior form highlights the importance of biometric data in creating an immersive and personal experience.

An interactive ambient lighting system called *MoodLight* (Snyder et al., 2015) reacts to information from biosensors about the user's current degree of arousal. The system's light hue changes in response to changes in arousal levels, modifying the immediate surroundings in ways that are closely tied to the user's internal state. *MoodLight*'s use of biosensor input and ambient display of personal information provides an opportunity to observe the mechanics of technology-mediated self-awareness and the negotiation of automated disclosure in face-to-face social engagement. The passive nature of data capture and ambient display of personal information also revealed tensions between control over self-presentation and passive sensing devices. As personal informatics displays are increasingly embedded in daily work and living environments, addressing these tensions will become increasingly important.

2.2 Mixed Reality

By delving into biosensors, we gain a deeper understanding of how the human body responds to environmental stimuli. However, for individuals to effectively perceive and interact with these mediated environmental changes, additional interactive technologies are necessary. The present study places a specific focus on the implementation of MR technology as both the mode of output and communication channel between individuals and their surroundings, allowing for the exertion of designed interventions.

The incorporation of MR technology in this research study is driven by two main concerns: 1) to provide multimodal stimulus to users while minimizing disruption in the work setting, and 2) to utilize MR technology as a technological solution, as its features align well with the study's design goals in terms of wearability, usability and convenience.

2.2.1 Definition of Mixed Reality

MR is a technology that blends physical and virtual environments, enabling real-time interactions between physical and virtual objects. MR refers to a more expansive notion of virtual reality (VR) compared to augmented reality (AR), which adds artificial electronic data to the real world. Augmented virtuality (AV), on the other hand, incorporates or improves the virtual environment (VE) using real-world data (Tamura et al., 2001). In 1994, Paul Milgram introduced the concept of the Virtuality Continuum, which refers to the spectrum that ranges from fully virtual to fully real, with MR being an in-between state where real and virtual objects are presented together (Milgram & Kishino, 1994).

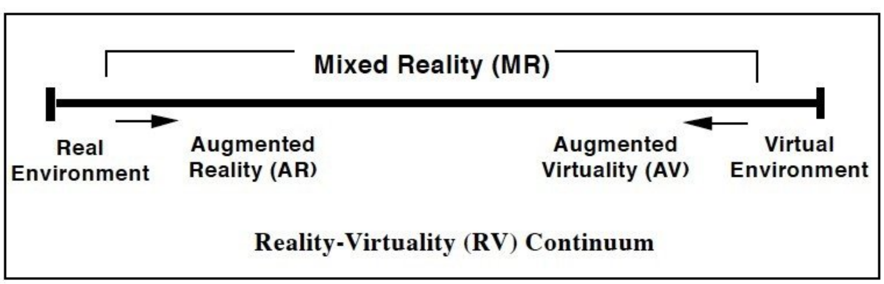


Figure 1. Reality–Virtuality Continuum adapted from Milgram & Kishimo (1994)

From a survey conducted by researchers from the University of Michigan in 2019, it concluded that there is no universally agreed-on, one-size-fits-all definition of MR. However, it is crucial to be clear and consistent in terminology and communicate one's understanding of MR to avoid confusion and ensure constructive discussion (Speicher et al., 2019).

2.2.2 Virtual Embodiment

The ideas of embodiment or virtual embodiment, which refer to the experience of having control over one's virtual body and sense of self-location, are also widely studied in MR research. While technology integration offers exciting opportunities for MR, it also has the potential to cause dissociative experiences and experiential distortions (Ziker & Dodds, 2021). Numerous studies have shown that virtual embodiment can influence cognitive processes and increase emotional responses in terms of arousal, dominance, and valence (Gall et al., 2021).

An embodied mixed reality space integrates embodied computing with MR techniques (Cheok et al., 2002). Embodied computing, as defined by Paul Dourish, integrates various aspects of ubiquitous computing, tangible computing, and social computing to create a new computing paradigm (Dourish, 2001). It involves the integration of computation and interaction with the environment, as well as incorporates the sociological organization of interactive behavior. By integrating MR with embodied computing, it becomes possible to establish a dynamic and immersive environment, where virtual objects can be embedded and manipulated through natural interactions, fostering a collaborative experience with the real-world (Cheok et al., 2002).

2.2.3 Multimodal Mixed Reality Work Environment (MMRWE)

Multimodal communication is the use of multiple modes or channels of communication in a single context, which can include visual, auditory, haptic, and other sensory inputs (Turk, 2014). When utilized as a means of mediation, it can enhance the user experience and improve the effectiveness of information delivery. A Multimodal MR Environment is a type of environment that combines MR technology with multiple models of information delivery, creating a hybrid reality that can provide new and innovative means of mediation. MMRWE refers to the type of environment specially designed for the working scenario.

In this study, multimodal communication is used to present information through a diverse set of representations, which can engage different senses and create a more holistic experience. The use of MR technology allows for the integration of digital information with the physical world, further enhancing the potential for effective mediation.

2.2.3 Case Studies

Recently, there has been an increase in MR research projects, including studies that employ AR to increase attention by minimizing peripheral distractions in the workplace and enhancing the work experience (Lee et al., 2022). Researchers have also explored various applications of MR, such as mood detection using heart rate, reducing anxiety, promoting relaxation, and sensing brain waves with different sensors (Lietz et al., 2019).

In the field of VR, medical VR has seen significant advancements in rehabilitation, surgical simulators, and telepresence surgery in recent decades. For example, the *Meditation Chamber*, an immersive VR environment designed to reduce stress, was created in 2003 and demonstrated that participants were able to regulate their stress levels while monitoring the changing visual stimuli in the VE, making it more effective than biofeedback alone for the control group (Shaw et al., 2011). In 2015, the *Virtual Meditative Walk* system was created to assist patients in shifting their focus inward through mindfulness practices, combining physiological sensors, stereoscopic audio, and an immersive VR environment (Tong, 2015).

Another study carried out by Ashita Soni and Shriyash Shete proposed the use of MR technology as a stress relief tool (Soni & Shete, 2020). The product design is based on the idea that people cope with stress by switching contexts and engaging in activities that are cognitively less demanding. With the help of a wearable headset, users can change their surroundings and escape the stressors in their immediate environment. By integrating MR and wearable sensors (EEG signals) into stress relief techniques, they aim to provide an innovative and effective way for employees to reduce stress in the workplace. Featured functions include soundscape, meditative imagery such as natural scenes. The limitation of this project lies in the fact that it is a design proposal rather than a functional prototype, which may hinder its ability to be thoroughly evaluated (Soni & Shete, 2020).

2.3 Environmental Psychology

Environmental psychology is a discipline within psychology that focuses on understanding the complex relationship between human beings and the world around them, including both the natural and built environments. It investigates how these environments impact our mental and emotional well-being, as well as how we, in turn, influence and shape our surroundings. Environmental psychology also sheds light on the ways in which our environment affects our behavior, attitudes, and cognitive processes (Russell & Ward, 1982).

This subsection aims to review the relevant literature on the impact of environmental factors on human behavior in the context of MR and wearable technology. Drawing upon the insights from interior and architecture designers, this subsection aims to provide a comprehensive understanding of how to design a MMRWE that effectively mediates and enhances body awareness for improved health and productivity.

2.3.1 Principles of Interior Design

It has been demonstrated that the environment controls significant facets of psychological impact. For instance, light has quantifiable effects on social behavior (Magielse & Ross, 2011), job enthusiasm (Boyce et al., 2006), and mood (Davis et al., 2012). Human physiology also reacts to its surroundings, either directly or indirectly, in a dynamic interplay. Noise, for example, frequently causes excitation, and for an extended period of exposure, would likely lead to chronic stress (Ising & Kruppa, 2004). Light, on the other hand, has immediate effects such as raising subjective alertness and boosting psychomotor performance (Figueiro, 2013).

Environmental psychology suggests that individuals have the ability to shape, and be shaped by the sensory environmental stimulus, which can subsequently affect their emotional states (Schreuder et al., 2016). Indoor environments, in particular, possess standardized elements and distinct patterns that can impact human emotions and behavior in various ways. Therefore, when designing indoor environments, it is crucial to consider the interplay between the environment and its effects on people's mental states, as well as the reciprocal relationship between the two.

The principles of interior design play an important role in shaping the look and feel of an interior space. The principles provide guidelines for designers and architects in creating functional, aesthetically pleasing, and emotionally appealing spaces. By understanding and applying these principles, designers can create spatial designs that meet the needs of the people who use them, while also creating an aesthetically pleasing environment.

The importance of interior design has been examined across different physical scenarios in establishing the relationship between artistic stimuli (i.e., interior design) and a person's mental responses. For instance, in a commercial store setting, cool tones assist people to feel restored while warm tones cause a higher level of anxiety and induce distraction. In the case of lighting, the brightness of lighting in comparison to surrounding spaces also evokes different responses among people. Thus, the appropriate balance of lighting becomes extremely important in achieving an ideal restorative effect across different scenarios (Kim & Heo, 2021).

2.3.2 Psychological and Behavioral Impact of Light

Light can trigger bodily processes which activate us. Via photosensitive receptors in the eye, we are able to perceive the world around us with light and visual information first and foremost. Light can influence our regulation of the biological clock and the secretion of hormones like melatonin and cortisol. Lighting technologies have transformed human society as many research studies have delved into this field, which consists of four main categories: research on the visual, psychological, physiological, and behavioral effects of light (Magielse, 2014). Besides the commonly acknowledged visual and physiological effects of light, there are many psychological and behavioral implications as well. Several studies looked into the impact of light in a workplace setting. According to van Bommel and Völker, lighting has an influence on productivity factors including productivity and errors (Bommel et al., 2002; Völker, 1999).

2.3.3 Dynamic Lighting and Color Temperature

Concentration on tasks and relaxation are both essential in a workplace. In order to create good conditions, both color and the intensity of artificial illumination need to be taken into consideration.

Dynamic lighting is a form of lighting that mimics the natural rhythm of day and night which the human body responds to. By positively affecting the biological clock, dynamic lighting is able to stimulate well-being and keep people alert and refreshed. In a traditional office setting, such a lighting system works by automatically altering color temperature and light intensity throughout the day with optics technology to generate varied balances of cool and warm illumination.

Natural daylight is inherently comfortable and suitable for human bodily sensations. However, despite its proven effectiveness in small-scale dynamic lighting installations, this study recommends limiting the range of variation in level and color temperature when creating artificial lights to avoid disturbing colleagues in the same workspace (Bommel, 2006). The study discovered that workplace lighting and color can have a significant impact on a worker's mood. The ideal lighting that elicited the highest mood was the one that was deemed 'just right,' while mood levels decreased when the lighting was too dark or too bright.

2.3.4 Color and Arousal

Color is a key aspect of human visual perception. Its complex nature plays an important role in art, culture, psychology, and religion. The aesthetic satisfaction provided by colors and their impact on the human mind are subjects of many researched hypotheses and presumptions (Kaplan, 1987).

It is widely conceived that some colors are more arousing than others. The arousal effect of color may alter a person's cognitive and psychomotor abilities. Warm colors, like red, are specifically thought to arouse human responses more than cool colors, like green and blue. By incorporating Galvanic Skin Response (GSR), Wilson discovered that participants were more aroused when exposed to red slides as opposed to green slides (Robinson & Hall, 2004). Berlyne examined visual complexity and how it connects to human visual preferences while discussing visually-related environmental stimuli. He proposed that preferences for visual complexity are related to an individual's level of arousal. In other words, those who experience higher levels of arousal are predicted to choose reduced visual complexity to get back to their ideal levels; while for people with lower levels of arousal, the opposite is true (Berlyne, 1968).

Color, from the interior and environmental perspective, can be used to address visual complexity and individual environmental sensitivity. As it has been proved that working space design affects job performance and satisfaction, many studies have been examining color in order to identify a working environment that boosts working productivity and is comfortable for the employees at the same time. Ravi Mehta and Rui Juliet Zhu find that the color of a wall in an educational facility or a commercial setting can influence a person's mood and performance on various tasks (Mehta & Zhu, 2009). Red is more suitable for tasks that require vigilant attention, while blue is more beneficial for tasks that require creativity and imagination. The results have implications for daily life, as the right color can enhance persuasion, creativity, and other desired outcomes. In addition, researchers have found that being in an environment where cool colors are dominant, such as those used on walls, gives us a feeling of being cooler. Conversely, being in a space where warm colors are prevalent has the opposite effect (Augustin & Coleman, 2009).

2.3.5 The Impact of Noise and Sound

Many people are concerned about noise in offices due to the correlation between noise and individual comfort, health, and productivity (Rasheed, 2021). These concerns have prompted a number of studies into noise issues in the air-conditioned office setting. Leaman explored the correlation between dissatisfaction and office productivity, hypothesizing that the latter was caused by controllable indoor environmental conditions such as temperature, air quality, lighting, and noise (Leaman, 1995). A study in Hong Kong has shown that noise sources such as background noise, doors closing, human activity, and other unspecified noise sources from inside and outside the office can easily influence people toward low levels of productivity (Mak & Lui, 2012).

Besides noise, there are a number of research studies that aim to induce relaxation through sound design. The BrightHearts Research project, for instance, is examining the use of heart-rate-controlled artworks as a biofeedback-assisted relaxation-training tool to assist children who endure recurrent painful operations manage their pain and anxiety (Khut, 2016). The visual is generated in combination with soothing sounds to help regulate breathing and heart rate. Sonic Cradle is an example of how physiological signals can regulate the architectural environment. A person's breathing pattern generates sound which feeds back to help enter a meditative state (Vidyarthi, 2012).

2.4 Related Works

In recent years, there has been a surge of interest in utilizing technology to enhance the healthcare system or workplace productivity. Through this examination of related works, this subsection seeks to provide a comprehensive understanding of the current state of research in this field and identify potential gaps for further investigation. In this section, two of the most relevant and promising works are presented and discussed.

In the workplace setting, researchers at MIT Media Lab have explored personalized control of the ambient atmosphere, including sound, lighting, and projection to support well-being and productivity (Zhao et al., 2017). The *Mediated Atmosphere* workspace prototype is an innovative approach to addressing the growing need for worker satisfaction and productivity in the knowledge economy. This study approach involves utilizing a modular real-time control infrastructure that integrates biometric sensors, controllable lighting, projection, and sound. The integration of biometric sensors enables the system to respond to individual physiological signals, providing personalized feedback to promote relaxation, focus, and stress regulation. Overall, the Mediated Atmosphere approach represents an exciting development in the field of workplace technology-assisted healthcare, providing a promising avenue for enhancing worker satisfaction and productivity (Zhao et al., 2017).

This study is highly relevant to my research area with its identified components on Mediated Atmosphere and dynamic monitoring of physiological signals. My research is based on the fundamental assumption that environmental attributes can significantly affect human perception, emotions, and behaviors. However, while this study effectively uses projection mapping to control entire room space, this approach is not practical for open public workspaces where individual separation is necessary. To address this issue, I plan to extend the concept from the physical world to the virtual environment using MR technology. Specifically, my research will focus on exploring the potential of MR-mediated environments on an individual basis, without interfering with others in the shared workspace.

Researchers from Meta Reality Lab have carried out a recent study on VR workplace and provided a series of guidelines on workplace design and optimization to improve employee productivity and satisfaction (Aufegger et al., 2022). This paper conducted three studies, which included expert interviews and observations of knowledge workers in various office layouts and environments. The studies highlighted the importance of natural elements, ergonomics, ambient conditions, accessibility, and the fusion of residential and commercial design, also known as resimercial design, in workplace design. Based on their findings, the researchers developed an Ecology of Work model, which combines work systems and pillars of performance success. However, the study acknowledges the limitations of its snapshot observations and suggests future research to confirm these observations with more objective and long-term evaluations. It concludes that future research should evaluate the impact of VR workspaces on various aspects, including coordination, communication, cohesion, mutual trust, satisfaction, productivity, and identity. Assessing these dimensions comprehensively will provide a better understanding of the benefits of VR for work and its overall return on investment (Aufegger et al., 2022).

This study is a great reference and guideline for designing workspaces in a VR environment. The study identifies several key aspects of the pillar of success in well-being that are highly informative for the design and evaluation of my research study. The insights gained from this study will be instrumental in creating effective interventions that promote well-being in mediated environments.

In the field of healthcare, a study carried out by researchers from the University of Helsinki found that visualizing breathing rates and approach motivation from EEG frontal asymmetry, and dyadic synchrony of these signals between users, increased physiological synchrony and self-reported empathy (Järvelä et al., 2019). The authors suggest that this approach could expand the possibilities of biofeedback in affective computing and VR solutions for health and wellness. The VR environment incorporates biofeedback technology to capture users' respiration and brainwave patterns, which are visualized in real-time. In a multi-user setting, the presence of avatars in the virtual space facilitates low-level social interactions and targets for compassion. In sum, the findings of the study have important implications for the development of VR solutions for mental health and wellness and could help to address some of the challenges associated with traditional therapeutic interventions.

The findings of this study have important implications for my research study as it emphasizes the crucial role of biosensors in designing effective interventions for promoting mental health and wellness in mediated environments. By incorporating biosensors affective detection in my research study, I can gain a deeper understanding of the impact of environments on human behavior and emotions and how to creatively represent biometric signals to enhance awareness of emotions and physiological responses.

2.5 Contextual Summary

The contextual summary for this research builds on the interdisciplinary fields of physiology and biosensor research, Mixed Reality, and Environmental Psychology. Each of these fields has substantive studies related to health monitoring and visualization. By exploring these areas, this research aims to identify their potential to inform the biofeedback-informed MMRWE.

The study of Environmental Psychology has yielded insights into how physical surroundings can impact human behavior and well-being. In the realm of interior and architecture design, designers and architects strive to create a comfortable and soothing environment for potential users. Specific elements such as lighting, color, sound and noise, agents, and other environmental concerns have all been taken into consideration. By understanding how these environmental factors are casting an impact on individuals, designers can create spaces that promote relaxation, reduce stress, and increase overall well-being.

Physiology and biosensor research has contributed to the development of technologies that can track and monitor physiological signals. Wearable biometric sensors have been used to construct user experiences and provide feedback to enhance awareness. Past studies have focused on wearable technology design, mobile applications and tablets, IoT networks or hospital infrastructure (Hiremath et al., 2014). The use of these technologies can promote awareness and provide feedback to help individuals understand and regulate their physiological responses.

In the field of MR, researchers have explored the potential meditative and therapeutic effects of these technologies. MR technologies have the ability to create highly immersive experiences that promote relaxation and calmness by providing users with multimodal environmental stimuli. In this research study, MR technologies are selected as the channel of delivering output as it aligns well with the design goals of the study, particularly in terms of usability, wearability, and convenience.

In terms of usability, MR allows users to interact with their real-world environment while also integrating additional elements of designed virtual objects. For example, a user can operate a laptop to perform daily work tasks while also being able to access virtual objects or interfaces that enhance their work experience. This approach is more affordable and accessible compared to incorporating Internet of Things (IoT) objects and converting a physical space completely. Regarding wearability, current MR technology in the form of optical head-mounted displays, such as helmets and glasses, allows users to operate normally with both hands, without having to employ other body parts. This means that users can still perform tasks at hand, such as typing on a keyboard, writing, or picking up a phone. Finally, MR provides personal support for individual workers, without causing disruption or inconvenience to other individuals in the shared workspace. As a head-mounted display, users are able to move freely and are physically liberated from being attached to a certain location or space. This means that users can work from any place as it is a portable device, whether it's at home, a coffee shop, or a physical workspace.

In sum, despite extensive studies in these fields of physiology and biosensor research, Mixed Reality, and Environmental Psychology separately, there are few studies exploring the intersection of all these areas. Some related works addressed the intersection of one to two areas. There is a research gap in exploring MR and wearable systems specifically designed for the working scenario. This research aims to develop an integrated system that can enhance user well-being in work environments, via developing a MMRWE with wearable technology that promotes overall productivity and well-being via body awareness enhancement and mediation in work environments. By creating an innovative solution that leverages the intersection of the above-mentioned fields, this study hopes to make a meaningful contribution to the field of Wearable and MR systems to facilitate real-time interaction between users and the environment.

3. Research Methodology

The research methodology employed in this study provides a framework for answering the research questions and achieving the study's objectives. The methodology is informed by a specific theoretical perspective and underlying philosophical assumptions that guide the study's design, data collection, and analysis methods. Through a combination of Research through Design, Interaction Design, and Speculative Design methodologies, the study aims to propose design solutions for a MMRWE with wearable technology.

3.1 Research Methods

This thesis project aims to address work-related problems by experimenting with design iterations for desk-based work scenarios. Through the iterative design process, the study aims to answer the stated research question and contribute to the specific domain knowledge, while also informing future studies.

The study envisions building a working prototype of Mixed Reality (MR) and wearable systems as a proof-of-concept. By integrating wearable technology and embedded sensors, biometric values can be outputted and visualized into an immersive MR environment. This environment allows users to widen their scope of information gathering by utilizing their peripheral vision without interfering with their main area of focus (Nakao et al., 2016). Through this MR environment, users will be able to acknowledge, understand, and interact with suggested meditative mechanisms for coping with potential work-induced negative effects.

In addition to a proof-of-concept prototype, this study proposes several iterations of multimodal MR sketches in the workspace scenario. These iterations explore the complex interactions and possibilities between human and technological interfaces. The iterative design process will involve evaluating these design prototypes to inform future iterations and contribute to domain-specific knowledge.

Through a multifaceted approach that incorporates research methodologies and iterative design practices, the study aims to develop design solutions that promote better mental and physical health for individuals in the workplace while contributing to domain-specific knowledge and informing future studies in the field of interaction design.

3.1.1 Research through Design

Research through Design (RtD) is a method of scientific investigation that makes use of the distinctive insights gained via design practice to offer a deeper comprehension of intricate and far-reaching problems in the design industry (Zimmerman & Forlizzi, 2014). Recently, it has primarily been utilized and discussed in the field of Human-Computer-Interaction. It is also a method of study that is becoming more widely accepted in many other design fields which respects the contributions that active practice makes to knowledge. RtD involves designing a solution, typically of an experimental nature, which includes a realization or prototype. Unlike other uses of the term 'design' that may only propose a vision, illustration, or storyboard, in RtD, the struggle with realization is considered an important part of the work. The aim of designing can be to improve existing problems or to explore new opportunities and can result in various outcomes such as a product, software, service, or system (Stappers & Giaccardi, 2017).

However, while most researchers and practitioners are quite supportive and optimistic about the prospects of RtD, there are still challenges and obstacles that hinder the development of a well-defined paradigm. Some major critiques include a romantic view of design, which inhibits its development as there exists a gap between the ‘rigor’ and ‘logic’ of traditional scientific research; a lack of theoretical development and critical analysis also needs to be taken into consideration that broader and more comprehensive methodological framework has been called upon (Zimmerman, 2010).

Nonetheless, for this thesis project, RtD fits well as a design and research method in guiding the iterative design and reflection of and on this study. As design research is more interested in the ‘actual’ than the ‘truth’, a macro model of knowing in design inquiry put forth by Wolfgang Jonas offers insights into how designers shift their attention from the true to the real (Jonas, 2006). Jonas establishes three steps in the model:

1. Analysis, which is concerned with how things are currently (the truth);

2. Projection, which is concerned with how things could be (the ideal); and

3. Synthesis, which is concerned with how things will be (the real).

This thesis study will follow the three steps:

1. Analysis: identify user demands and figure out workable solutions;

2. Projection: design and develop a workable prototype which solves the problem; and

3. Synthesis: reflect on the usability and functionality of the designed prototype and envision new iterations.

3.1.2 Interaction Design

Interaction Design (ID) is a discipline that focuses on the design of interactive products and systems. It involves the design of the interactions between users and technology and the creation of user interfaces that are intuitive and easy to use (Saffer, 2010).

There are several approaches to ID, including user-centered design, participatory design, and design thinking. The user-centered design approach involves designing for the needs, goals, and behaviors of the users. Steps include user research, prototyping, and evaluation. Participatory design involves involving users in the design process. This approach seeks to empower users and involve them in the co-creation of the design, which can be achieved through various methods such as workshops, focus groups, and user testing. As an important component of ID, design thinking is a problem-solving approach that involves a creative and iterative process, including identifying the needs of the users, generating ideas, prototyping and testing, and refining the design based on user feedback (Sharp et al., 2019).

ID is an important aspect in approaching the design of a MR and wearable technology systems. By considering the needs and goals of the users and involving them in the design process, it is possible to create systems that are intuitive and easier to use. This can improve the effectiveness of the systems and enhance the user experience. The design of this thesis study will also be guided by the ID methodology in creating a user-friendly interaction.

3.1.3 Speculative Design

Speculative Design (SD) is a methodology that involves creating fictional design proposals to explore potential futures and the implications of different design choices (Auger, 2013). It focuses on generating a range of possible futures, rather than predicting a single, probable outcome. The approach is often used to prompt critical reflection, exploration, and experimentation to imagine possible futures and question the implications of existing and emerging technologies, social and cultural norms, and values (White, 2016).

This thesis project can benefit from SD methodology to explore how people might operate and utilize a MR workspace system in the future. Given that MR technologies are not yet widely adopted in current society, SD can help in considering various scenarios and factors that may influence the use of such a system when MR technologies become more mature. Through such exploration, a better understanding of the potential benefits and challenges of MR and virtual workspace technology can be gained. By having foresight on these issues, it is possible to take more factors into consideration before the technology is widely adopted and to design the system in a way that maximizes the benefits and minimizes the potential negative consequences. Hence, this study encourages reflection and debate on the potential benefits and risks of MR and wearable technology, to challenge assumptions and encourage creative thinking about their possible applications.

3.2 Summary

The design process that guide this thesis project is based on a combination of methodologies, including RtD, ID, and SD. These methodologies enable the project to depart from the identified problem scope and audiences and undergo a series of exploratory research, followed by multiple stages of design iterations and evaluations.

Following RtD, multiple iterations of the MMRWE design are created following the process of 1. Analysis, 2. Projection, and 3. Synthesis. This study includes feedback from users and experts to refine and improve the design iteration. ID principles guide the design of the system's interface to ensure that it is intuitive and accessible. It informs the exploratory research process with a user-centric approach, through constructions on user persona, empathy mapping, and information architecture. The outcome of this exploratory research largely informs the early iteration of low-fidelity prototypes. Finally, SD methodology is used to envision future scenarios that inform the potential benefits and challenges of the MR working environment, allowing the study to identify preferred attributes that fit the environment and influence system use.

4. Design Iterations and Prototypes

This section explores the iterative design process and prototype development for a multimodal MR working environment with wearable technology. Adopting RtD methodology, the iterative design process starts with 1) Analysis: I identified user demands and figured out workable solutions through the exploratory research guided by the ID principles; 2) Projection: I designed and developed a workable prototype which attempts to provide a solution towards identified problem; and 3) Synthesis: I reflected on the usability and functionality of the designed prototype and envisioned new iterations, ranging from low-fidelity to high-fidelity prototypes. In the end, the final prototype is presented, synthesizing and integrating all previous design iterations into a functional hybrid wearable and MR environment.

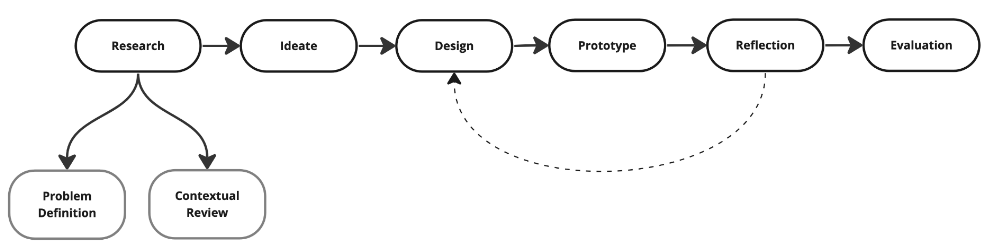


Figure 2. Iterative design process

4.1 Exploratory Research: Need Finding

The need-finding section of the design process departs from ID principles and adopts a user-centric approach. This approach leverages user personas, journey mapping, empathy mapping, and information architecture to gain a comprehensive understanding of the user's needs and demands.

To create user personas, I took into account target users' demographics, behavior patterns, and needs. Empathy mapping allowed me to step into the user's shoes and gain a deeper understanding of their experience. Information architecture was used to structure system content and functionality in a clear and intuitive way, providing guidance for designing the system interaction. These methods ensured that the user's needs and demands were prioritized throughout the design process. This section of exploratory research provided a solid foundation for the development of design iterations.

4.1.1 User Persona

User personas are fictional but accurate profiles of the target audience (Nielsen, 2019). They serve as a versatile tool for a number of essential product development tasks, including user scenario production, function generation, and feature prioritization. Personas are developed from complex user data in a way that makes sense to the researchers and developers, while at the same time fostering user empathy, ensuring that the users are the center of this study.

In this design study, user personas represent different types of users who might interact with the MR and wearable technology system. By creating user personas that represent the different types of users who might use the system, it is possible to better understand their needs and design the system in a way that meets their goals.

For this study, three personas: Leanna, Rom, and Emory were developed. Each embodies a specific group of target users with unique demographics, social characteristics, and behavioral patterns. These personas represent students, computer-based professionals, and standard office workers, who are the primary target users of this problem space and the intended beneficiaries of the design solution. It's worth noting that the personas have a moderate to high level of technical literacy, which makes them more adaptable and accepting of wearable and MR technologies.

Persona	Demographic characteristic	Social characteristic	Behavior Pattern
Leanna	24 years old college student, female.	Studying economics and art history. Spends the majority of her time working on a laptop, either in her dormitory, the library, or in classrooms.	Easily gets stressed during midterms and finals and works out at the gym 1-2 times per week to manage her stress.
Rom	33 years old machine learning engineer at a major tech company, male.	Has a computer science background and works in a high-concentration, sedentary job that requires him to spend long periods of time in front of a computer.	Since the pandemic, he has been working remotely from home and has a partner and two children. In his free time, he enjoys watching football matches and playing PS4 games. He is slightly overweight due to a lack of physical activity.
Emory	40 years old human resources professional, queer.	Works on computers and conducts tasks such as checking emails, responding to communications, and facilitating meetings. Works in a hybrid mode, either on-site at the office or at home.	Has a partner and enjoys shopping and doing yoga in their free time. Is looking for ways to improve their work-life balance and maintain good health.

Table 1. User personas generated following Interaction Design Principles

4.1.2 Empathy Mapping

By definition, an empathy map is a collaborative representation that is used to illustrate what we know about a specific type of user. Through externalizing user knowledge, they help to foster a shared understanding of user demands and aid in the decision-making process. Traditional empathy maps divide the user or persona into four quadrants: Says, Thinks, Does, and Feels. Empathy maps, which are not chronological or sequential, provide a glimpse into who the user is as a whole.

For each user persona, the empathy map can be created by filling out the following categories:

1. Thoughts: What the user is thinking about their work and health situation.
2. Feelings: How the user is feeling about their work and health situation.
3. Actions: What the user is doing to manage their work and health situation.

4. Needs: What the user needs in order to improve their work and health situation.

Persona	Thoughts	Feelings	Actions	Needs
Leanna	Leanna likes to move from place to place to do work, but sometimes hopes the environment to be quieter so she can focus.	Leanna feels stressed and overwhelmed during midterms and finals.	Leanna works out at the gym 1-2 times per week to manage her stress.	Leanna needs a way to manage her stress levels in a more effective and efficient way.
Rom	Rom is overall satisfied with his working environment. He enjoys working from home which saves money and time for commuting.	Rom is sometimes overwhelmed and stressed by the demands of his job, especially when working on tight deadlines. Rom may also feel frustrated by the lack of physical activity in his life and the impact it is having on his health.	Rom tries to take short breaks to stretch or move around, but often finds it difficult to be fully disconnected from work.physical activity.	Rom needs external help to remind him to take a break, either from his family or from assistive devices. Rom also wants to be more aware of his bodily status.
Emory	Emory wants to stay healthy as getting older. He is concerned about maintaining good health and finds ways to improve work-life balance.	Emory is tired of work and personal responsibilities.	Emory does yoga in their free time and reads articles about work-life balance and health.	Emory hopes to boost overall well-being at work and find ways to balance work and personal life.

Table 2. Empathy map for target user personas including thoughts, feelings, actions and needs

By conducting empathy mapping on Leanna, Rom, and Emory, a deeper understanding of their experiences and perspectives related to work and health is gained. Identified shared needs of the three representatives of the working professional user group are: 1). Be more aware of one's bodily status; 2).

Be able to provide timely alerts for breaks and exercises; and 3). Provide effective management and mediation techniques.

These empathy maps highlight the challenges and motivations of these three personas and provide valuable insights for the design of a MMRWE that addresses their needs, including providing timely alerts, effective management and mediation and boosting overall well-being. By considering the experiences and perspectives of target users, we can better understand the potential benefits and limitations of incorporating MR technology into the design of the working environment and how this technology can support individuals.

4.1.3 Information Architecture

Traditional information architecture of technological systems performs two key functions: 1). Identification and definition of site content and functionality 2). Identification of the relationships between a site's content/functionality through the underlying organization, structure, and nomenclature (Rosenfeld & Morville, 2002).

In the context of a MR and wearable system, information architecture is important because it helps to ensure that the system is easy to use and that users can find the information they need. Deriving from the insights generated from Empathy Mapping, I identified the following user needs which inform the following content and functionality requirements.

User Needs	**Content and Functionality Requirements**
Be more aware of one's bodily status.	<u>Physiological monitoring:</u> A module that continuously monitors and records users' physiological signals, such as heart rate, respiration, and skin conductance. This module will allow the system to adapt to users' physiological state in real-time.
Be able to provide timely alerts for breaks and exercises.	<u>Multimodal feedback:</u> A module that provides feedback to users in multiple modalities, such as visual, auditory, and haptic, to enhance the experience of the system. <u>Biometric sensor data visualization:</u> A module that presents users with a visual representation of their physiological signals and the environment, allowing them to understand the impact of their interactions on their well-being.

Provide effective management and mediation techniques.	Environment mediation: A module that dynamically adjusts the environment, such as the lighting, temperature, and sound, to support users' physiological and psychological well-being.

Table 3. Content and functionality requirement derived from user needs

4.2 Design Iteration Overview

The iterative design process involves multiple stages of prototypes, each aimed at testing and refining the proposed MMRWE. The iterations apply the RtD methodology and embrace 2). Projection: design and develop a workable prototype that solves the problem; 3). Synthesis: reflect on the usability and functionality of the designed prototype and envision new iterations.

The first stage involves low-fidelity paper prototypes, which allow for quick and easy exploration of different design options. These prototypes are used to test the general layout and functionality of the system, as well as to identify any potential design issues or limitations.
Next, the design process moves on to sensor explorations, where different biometric sensors are tested for their suitability in the proposed MR environment. This stage involves selecting the most appropriate sensors for detecting bodily changes, such as the GSR sensor, PPG heart sensor, temperature sensor, and ultrasonic proximity sensor. These sensors are then integrated into a wearable glove, which is designed to provide users with real-time feedback on their bodily changes while allowing for maximum hand and finger movement.

The wearable glove prototype is developed simultaneously with the MR environment sketches. The MR sketches provide a means for the rapid prototyping and experimentation of various visual feedback options and serve as a testing ground for refining the overall design of the MR environment.

Finally, the design process concludes with the creation of the final prototype of a MMRWE with wearable technology. This prototype allows real-time reflection of biometric signals and integration between the physical and digital worlds. The final prototype is later evaluated in small-scale user testing to ensure that it aligns with the goal of enhancing awareness of bodily changes and providing mediation, as well as identifying any potential design issues or limitations that need to be addressed.

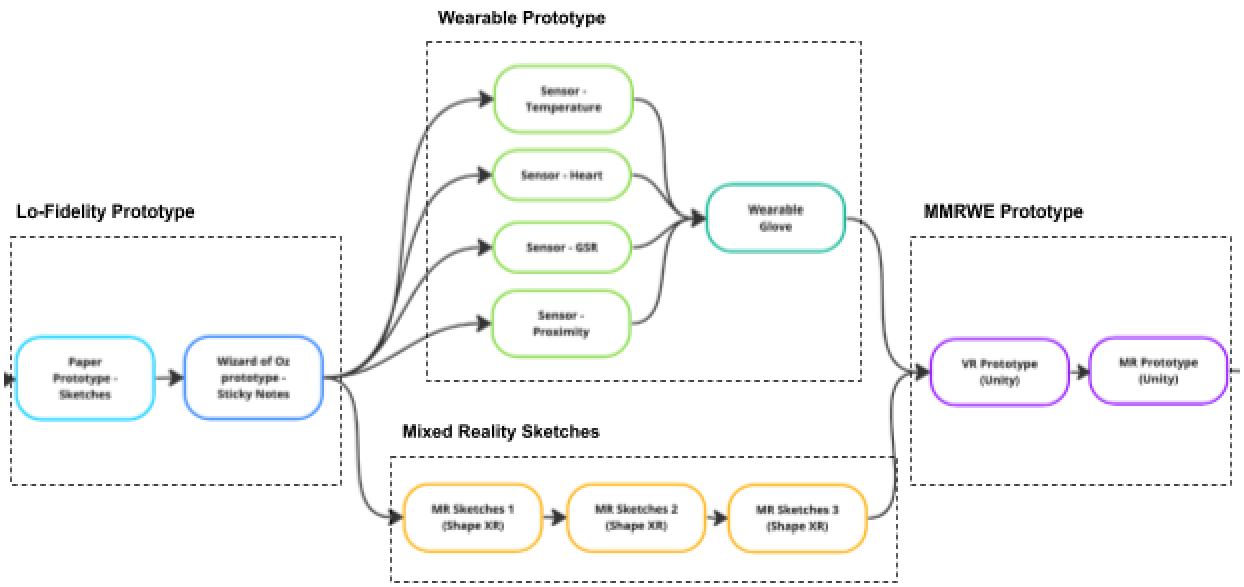


Figure 3. An overview of design iterations across multiple stages

4.2.1 System Diagram

The proposed MMRWE is designed to enhance users' awareness of bodily changes and support mediation. The system includes two main components: 1). Biometric signal collection and processing via a wearable glove and 2). Multimodal MR output via a Head Mounted Display (HMD).

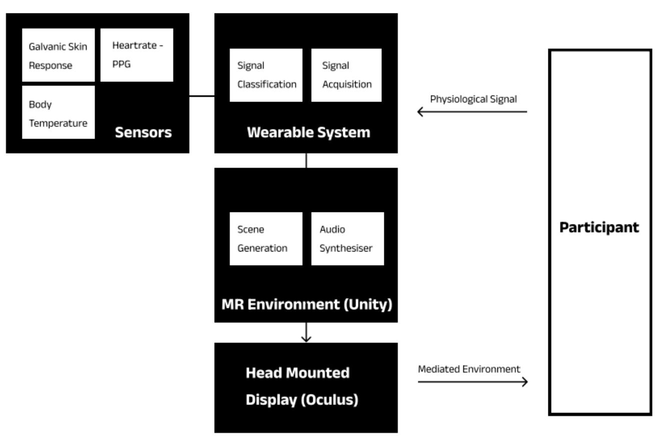


Figure 4. Wearable and MR environment system diagram

The input includes biometric sensors being integrated into a wearable glove, which is bridged with the MR system to enable users to be cognizant of their current arousal, heart status, and near-skin temperature while maximizing hand and finger movement. The MR environment's actuators output real-time multimodal feedback, such as visuals and audio through an HMD.

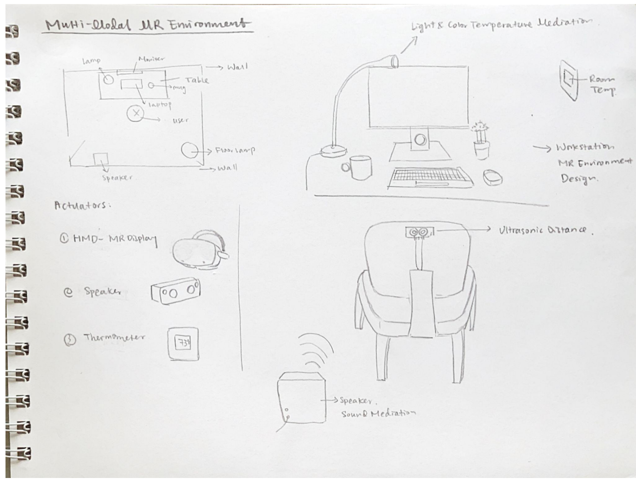


Figure 5. Sketch of MMRWE

The proposed interior layout for the MR environment is designed to accommodate a standard workstation setup, complete with essential components such as a chair, table, monitor, mouse, and lamp. This layout is suitable for both office and remote work scenarios. For users in a home office setting, the HMD's audio feedback can be replaced by a speaker and room temperature can be manipulated via a connecting thermometer as Internet of Things (IoT) devices.

4.3 Low-Fidelity Prototype and Sensor Exploration

This stage of design prototypes focuses on sensor exploration and low-fidelity prototyping. It is beneficial in facilitating quick ideation through rapid prototyping. The exploratory methods employed in this stage include paper sketches, Wizard of Oz prototypes, visual designs with 2D interfaces, and sensor explorations.

The primary purpose of sensor exploration is to inform the initial stage of wearable design choices by identifying suitable sensors and determining their mapping and rationale. This stage of exploration is critical in laying the groundwork for future design directions. It enables the identification of new design constraints related to sensor choices and design guidelines, such as the principles of calm technology.

Despite the exploratory process being broken down into less connected pieces, it plays a crucial role in bringing everything together for the later stages of prototyping. This stage of exploration has laid the important groundwork for future design directions by identifying new design constraints and developing guidelines that will inform future design decisions.

4.3.1 Paper Prototype and Design Sketches

The early-stage prototype is designed to facilitate ideation, generate rapid prototyping and inform iterative designs. It utilizes a combination of paper prototypes and Wizard of Oz prototypes (Maulsb & Mande, 1993) with sticky notes to integrate the inputs of four signal parameters: heart rate, respiration, temperature, and GSR arousal. The interface has been split into a left and right panel, with the left one displaying the biometric indicators and functioning as a menu. The right panel showcases potential mediation effects and system prompts, including textual and visual feedback.

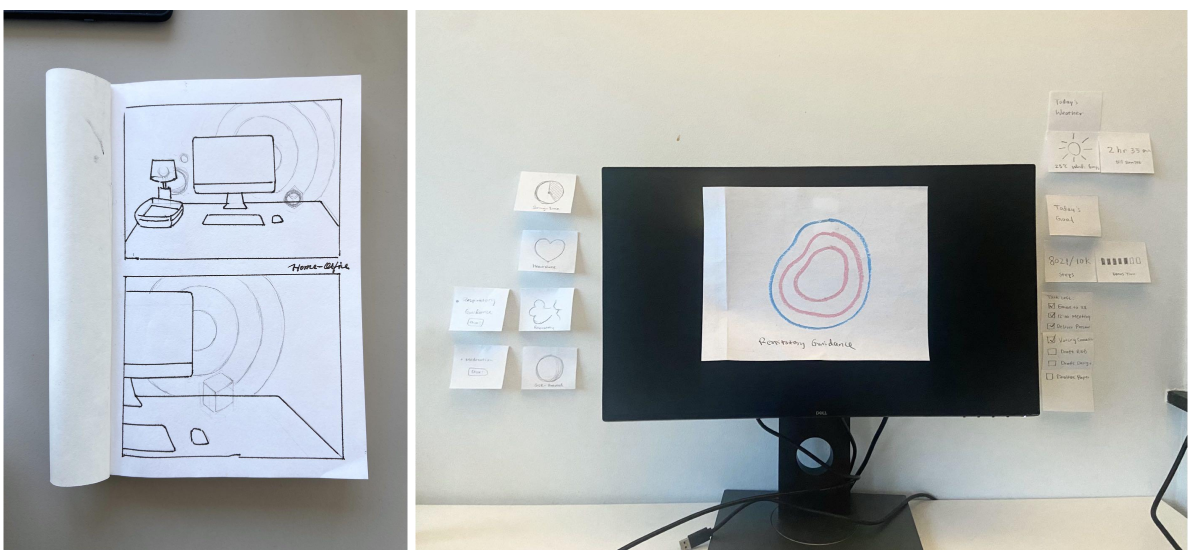


Figure 6. Paper and Wizard of Oz Prototypes of MR user interface

These early-stage prototypes employ a minimalistic design, which aims to reduce distraction and minimize interference with the user at a working status. The design approach and aesthetics adhere to the calm technology principles, which aim to create technology that is minimally invasive, informative, and calming (Case, 2015). The principles suggest a minimalist approach to technology that supports human needs and complements our lives rather than dominating them. The Wizard of Oz prototype limits the number of visual elements and complications that could potentially impede the user's performance. The use of a grid structure to align visual elements is a deliberate reference to the traditional desktop interface, which provides a familiar and intuitive experience for users. This approach also aims to effectively organize complex sets of information, as it allows users to quickly scan and locate specific functions.

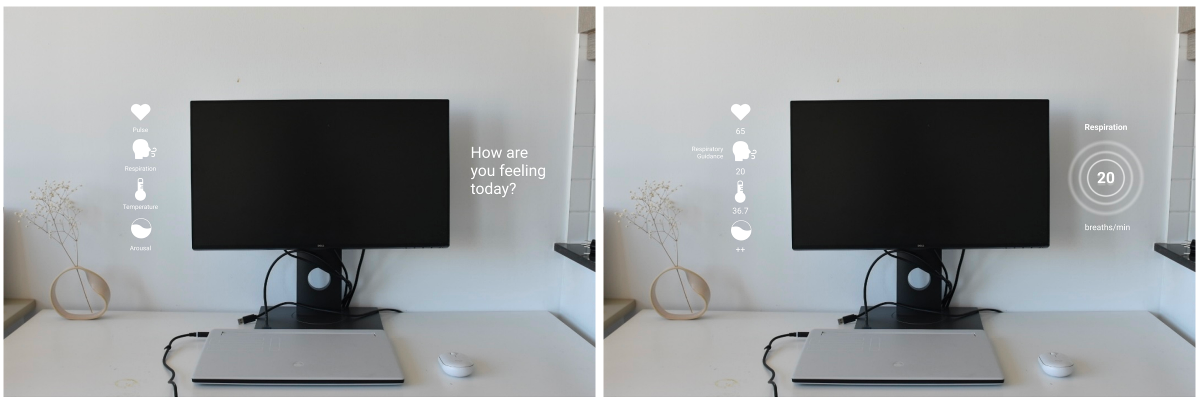


Figure 7. Visual interface design on biometric signal visualization (Figma)

The Wizard of Oz prototypes inform the next iteration of the design prototype. This interface design features four icons on the left side of the screen that represents four biometrics: heart rate, respiration, body temperature, and GSR. On the right-hand side of the screen, an animated text prompt appears alongside the audio output. The triggered output based on biometric signals is designed in a minimalistic and non-invasive way, such as a breathing guide triggered only when the user's heart rate raises abruptly. Compared to the previous paper and Wizard of Oz prototypes, this iteration reduces the visual complexity of synthesizing multiple bodily information at once and outputting single feedback at once to the user.

In summary, while early-stage prototypes can be useful for ideation and rapid prototyping, there are some areas for improvement in the designs. These prototypes adhere to calm technology principles and minimalistic aesthetics, which are beneficial for work-related tasks and provide guidance for future iterations. However, creating prototypes on a 2D interface can be limiting, hindering the exploration of dimensionality and spatial design elements. Additionally, 2D-based prototypes are less immersive and interactive, resulting in decreased user engagement and embodiment, and making it not ideal for user testing and evaluation. To address these limitations, it is important to create design prototypes in a 3D environment. This approach provides a more intuitive perspective for envisioning the MR working environment and allows users to interact with the system in a more natural, engaging, and interactive manner.

4.3.2 Heart Sensor Exploration and Mappings

The Photoplethysmography (PPG) sensor is a device that measures the blood flow in the capillaries of the skin. This is achieved by shining a light onto the skin and detecting the changes in light absorption that occur as a result of blood flow change. The sensor consists of a light source and a photodetector. The absorption of light by the blood in the capillaries is affected by the volume of blood in the capillaries and the absorption properties of the blood (Alian & Shelley, 2014). When the heart pumps blood, the volume of blood in the capillaries increases, resulting in an increase in the amount of light absorbed. Conversely, when the heart relaxes, and the volume of blood decreases, the amount of light absorbed also decreases. By analyzing the changes in the amount of light over time, it is possible to infer the heart rate of the individual.

Figure 8. Exploration with DFRobot Gravity heart rate sensor

This study employs the use of a DFRobot Gravity heart rate sensor, which is a miniature, thumb-sized heart rate monitor that is integrated with Arduino microcontrollers. The sensor operates by detecting each heartbeat through signal peak discernment and transmitting data via the serial port from

Arduino to Unity. The PPG heart sensor is capable of detecting heartbeats through peak value detection, which enables it to calculate Beat Per Minute (BPM) and classify abnormal signals. The PPG sensor is useful for this study as it allows for continuous monitoring of an individual's heart rate. This can be valuable in detecting changes in cardiovascular health and providing warning signs of protective health issues. By utilizing the PPG sensor to continuously monitor heart rate, it is possible to provide timely interventions and help individuals obtain optimal health.

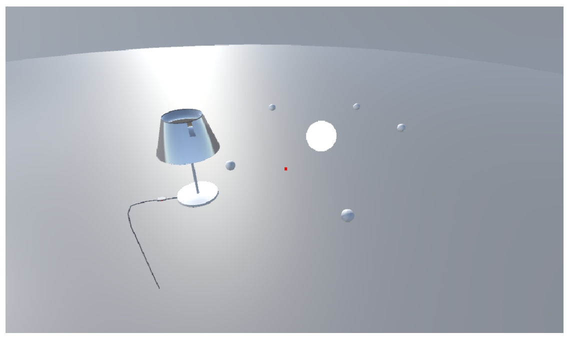


Figure 9. Exploration in Unity for heartbeat visualization - with no heartbeat detected

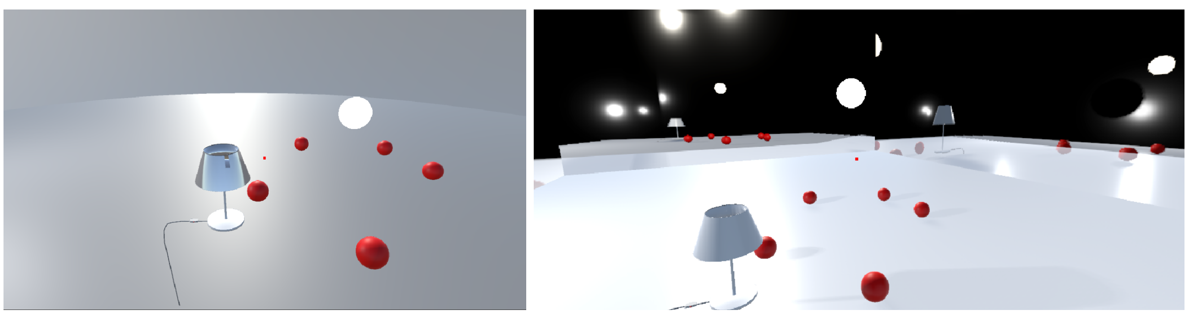


Figure 10. Exploration in Unity for heartbeat visualization - with heartbeat detected

Figure 9 captures the initially established connection between Arduino and Unity. Through the use of scripting in Unity, the sensor signal input is programmed to trigger various output responses. Specifically, the heart signal is mapped onto a white illuminated sphere, which rhythmically bounces on the floor, corresponding to measured heartbeats. The sensor status is visually represented by the color changes of five surrounding spheres, with red indicating the active reading of sensor values, signaling body presence on the PPG sensor. By placing the finger or wrist on the sensor, the real-time heartbeat is visually displayed within the Unity scene. This experimentation serves as a fundamental starting point for further exploring the communication between Arduino and Unity, illustrating the potential for viable output formats for signal visualization.

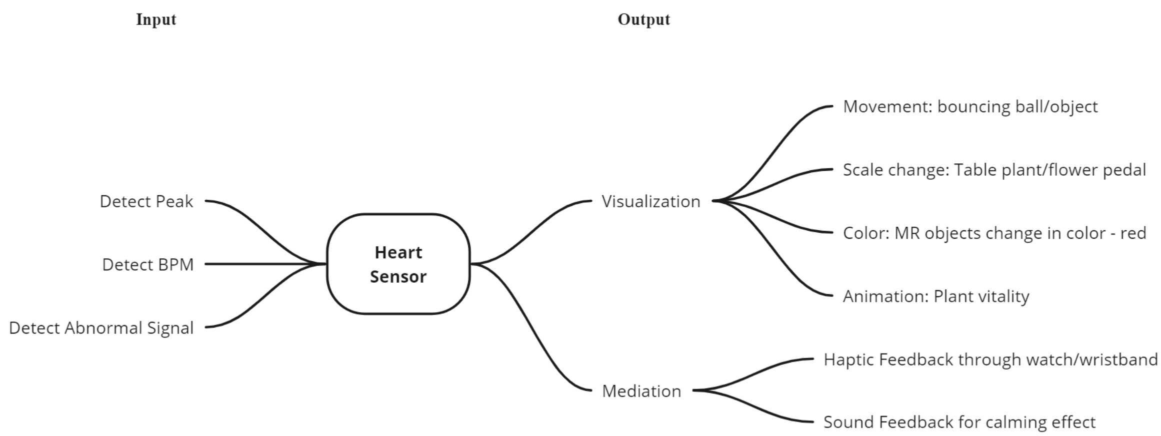


Figure 11. Heart sensor signal mapping

This figure illustrates design ideations involving potential inputs and outputs utilizing the PPG sensor and heart signals. Inputs encompass detecting peak, BPM, and abnormal heart rate, while outputs are considered from functional perspectives, namely visualization and mediation. Visualization supports the objective of enhancing awareness of bodily status, whereas mediation addresses the issue by providing users with coping mechanisms.

Upon reflection on the Unity prototype iteration, valuable insights into real-time signal communication and mapping possibilities were obtained. However, further considerations and design thinking are necessary. Based on peer feedback, it was determined that a bouncing ball or drastic color change might be too distracting for users, and a more subtle change would be preferable. Therefore, table plants could be integrated with heart status to reduce visual attention, with the vitality of plants serving as an analogy and representation of human health. With regard to mediation, visualization output could be activated only when the heartbeat exceeds a certain threshold, with the table plant responding with a guided slower heartbeat to soothe the user. Alternatively, mediating effects could be generated through non-visual signals, such as haptic feedback via wearable watches or sound feedback to produce calming effects.

4.3.3 GSR Sensor Exploration and Mappings

The Galvanic Skin Response, also known as GSR, refers to changes in sweat gland activity in response to emotional arousal (Montagu & Coles, 1966). The GSR sensor works by applying a small electrical current to measure the resulting resistance. It consists of two electrodes placed on the skin, typically on the fingertips or the palm area. When an individual becomes more aroused, the sweat glands in the skin become more active, resulting in a decrease in skin resistance. This change in skin resistance can be measured by a GSR sensor and is thus used to infer the individual's level of arousal.

GSR sensor is incorporated in designing this study because it serves as a non-intrusive means of measuring an individual's emotional state and arousal level (Shi et al., 2007). By continuously monitoring skin resistance, it is possible to detect changes in arousal in real-time by providing appropriate means of mediation to help individuals cope with abnormal bodily status.

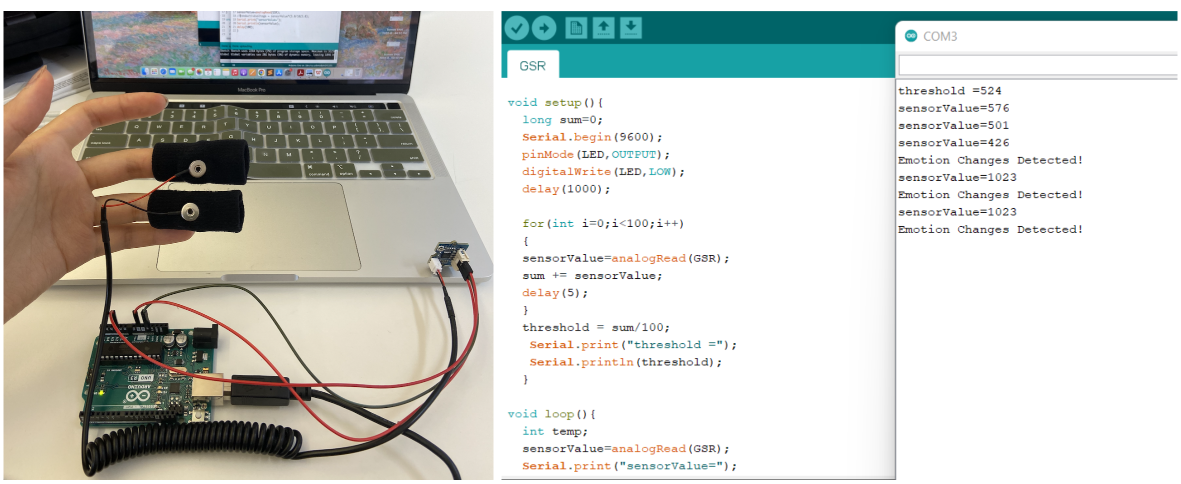


Figure 12. Exploration with Grove GSR sensor

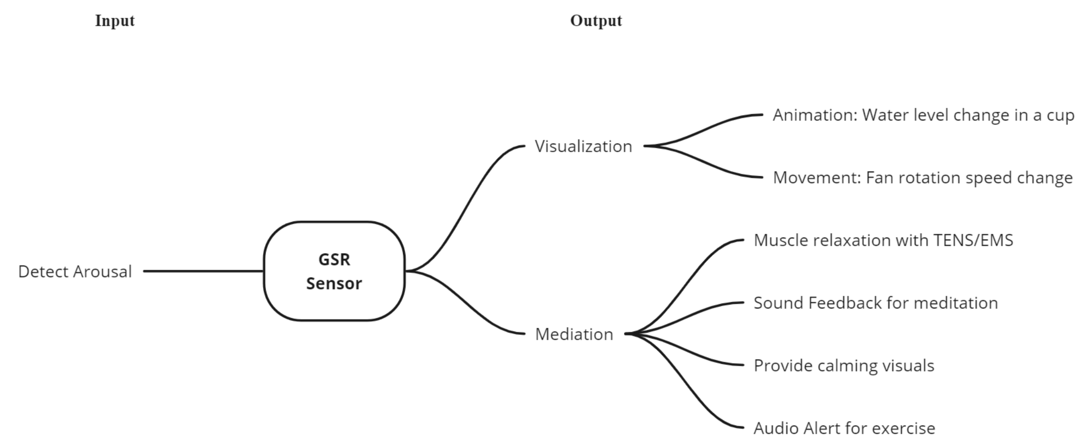


Figure 13. GSR sensor signal mapping

The mapping of the Galvanic Skin Response (GSR) sensor is similar to that of the PPG heart sensor, whereby inputs are limited to detecting the arousal status, and outputs are designed from visualization and mediation perspectives. One ideated visualization is to represent the arousal level by the water level in a cup. The cup is a common desktop object, and water level changes can be tied to the emotional status of the user, whether positive or negative. The GSR sensor could also be mapped to other objects, such as a table fan, where the speed of rotation could be correlated with the arousal level, with faster rotation indicating higher arousal. Additionally, mediating effects could be applied through various feedback mechanisms, including haptic, visual, and audio feedback. Devices such as Transcutaneous Electrical Nerve Stimulation (TENS) or Electrical Muscle Stimulation (EMS) could be explored to generate muscle relaxation and promote a more calming environment. Audio effects could also be triggered to generate calming effects or provide timely alerts for exercise. Calming visual elements, such as natural scene photography, could also be incorporated.

4.3.4 Temperature Sensor Exploration and Mappings

Temperature sensor TMP 36 is a low voltage, precision centigrade temperature sensor that provides a voltage output that is linearly proportional to the Celsius temperature (Raghavan &

Shahnasser, 2015). It has a range of -40°C to +125°C and provides a low output impedance that enables direct interfacing to ADCs and microcontrollers.

The basic working mechanism of the TMP 36 sensor is based on the principle of bandgap temperature sensors. It works by measuring the voltage drop across a diode. The voltage drop is proportional to the temperature, and by comparing the voltage drop with a reference voltage, the temperature can be calculated. TMP 36 sensor can be used to measure the human body's near-skin temperature by placing the sensor in direct contact with the skin (Kioumars & Tang, 2011). The temperature of the human body can be measured accurately as the temperature of the skin is relatively constant and provides a stable reference temperature.

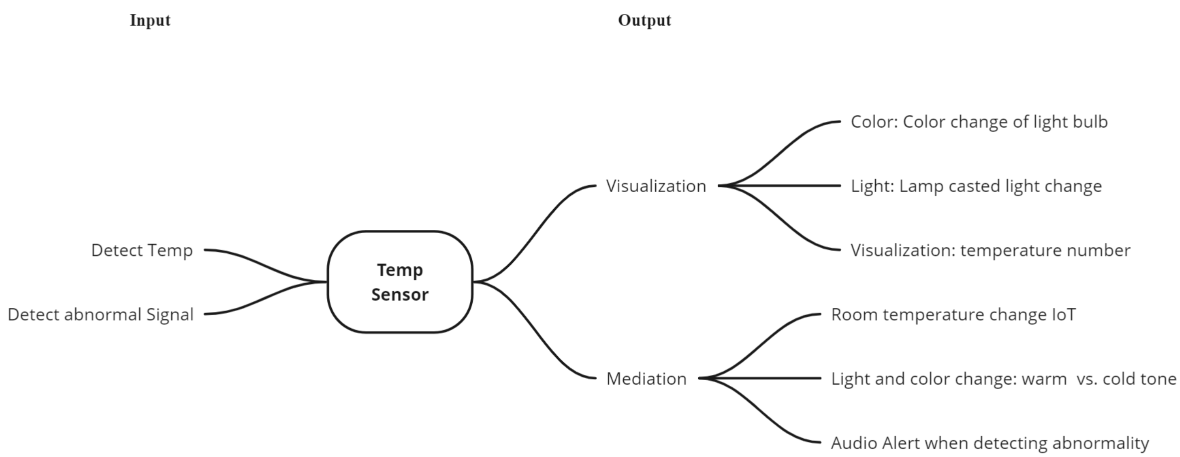


Figure 14. TMP 36 temperature sensor signal mapping

To conclude, a TMP36 temperature sensor is utilized in this study to detect body temperature. Inputs include the temperature values and abnormal signals which could be classified based on temperature values over time. On the output side, one possible visualization is to use a light bulb that changes color, with warmer colors indicating higher temperatures and cooler colors indicating lower temperatures. Changes in light and shadow cast by the lamp could also be used for temperature visualization. Additionally, a numerical representation of temperature could also be provided for a more quantitative understanding. On the other hand, mediation effects could be incorporated through various means, including IoT devices that allow for automatic changes in room temperature as an adjustment mechanism. The color and tone of the room lighting could also be adjusted accordingly, with audio alerts employed to notify users of abnormal temperature levels.

4.3.5 Proximity Sensor Exploration and Mappings

The ultrasonic proximity sensor is a device that uses ultrasonic waves to measure distance. It works by emitting a high frequency sound wave and measuring the time it takes for the wave to bounce back after it hits an object. By analyzing the time delay between the emission of the sound wave and its return, it is possible to calculate the distance to the object (León-Martínez et al., 2018).

The present study incorporates the HC-SR04 ultrasonic sensor to enhance the monitoring of user activity beyond biometric signals. This sensor is connected separately from the other three biometric sensors and is intended to be placed at the back of the user's chair to measure the distance between the user and the chair back, enabling the evaluation of the duration of the user's sitting time. By quantifying the length of time spent sitting in the workspace, this sensor provides a reliable means to assess the negative effects of prolonged sitting on physical health. Moreover, the ultrasonic sensor generates alerts to the system when the user's sitting time reaches a certain threshold, which prompts mediation effects that encourage the user to take breaks and engage in physical activity.

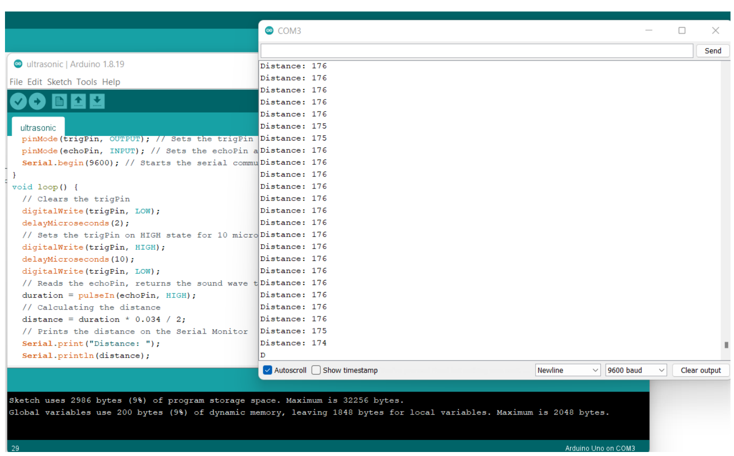


Figure 15. Exploration with HC-SR04 sensor

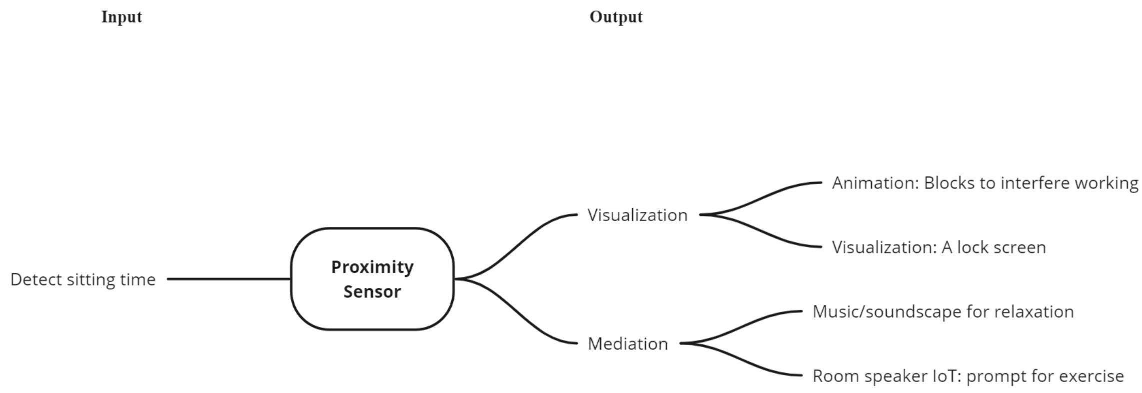


Figure 16. HC-SR04 ultrasonic sensor signal mapping

The mapping of an ultrasonic proximity sensor based on the input of user sitting time. From the output perspective, visualization could be represented by the animation effect of blocks or bans that interfere with the user's work or displaying a lock screen that prompts users to stand up, while mediation effects could be generated through various means, such as audio or sound effects that alert the user to their sitting time and remind them to stand up. However, if the audio effects are connected to IoT room speakers, the mobility of the user would be limited by the requirement of an isolated space. Additionally, since the proximity sensor operates independently of the glove, the sensor has more flexibility in terms of placement and modes of interaction.

4.3.6 Design Synthesis

Sensors	**Integration**	**Inputs**	**Outputs**	**Design Rationales**
Heart Sensor	Wearable glove	Peak; BPM; Abnormal signal (above 100 bpm or below 60 bpm)	Visualization: Bouncing objects, table plant; Mediation: Breathing guide, haptic feedback, audio feedback.	Based on the Principles of Calm Technology, a more subtle change is preferable. Table plant is a less invasive representation of heart status, which will be incorporated with pedal movement as a breathing guide for mediation.
GSR Sensor	Wearable glove	Arousal status (20%	Visualization: Water cup, table fan;	The classification of arousal is highly ambiguous, meaning that

		deviation from average)	Mediation: Calming visuals, audio alert, sound feedback, muscle relaxation.	it could indicate either positive or negative emotions. Therefore, a high level of arousal may not necessarily be negative. The designed output, therefore, emphasizes visualization, with the aim of drawing the users' attention to and increasing their awareness of their arousal status, rather than attempting to mediate it. Both the visualization output of the water cup and table fan is explored in the following iterations.
Temperat ure Sensor	Wearable glove	Temperature value; Abnormal signal (above 99.0°F(37.2 °C) or below 97.5°F (36.4°C))	Visualization: Lamp light bulb, casted light, text; Mediation: Color tone and light, room temperature change, audio alert.	Based on Environmental Psychology, color temperature, lighting, and color tones all have an influence on the individuals. Being in warm light makes us feel warmer, and sitting in cool light tricks us to feel cooler (Augustin & Coleman, 2009). Thus a cool tone is used for mediating higher body temperature and vice versa.
Proximity Sensor	Chair	Sitting time (beyond 45 minutes)	Visualization: Animation blocks, lock screen; Mediation: Music/soundscape, audio alert.	Based on Environmental Psychology, it is widely recognized that noise can have a detrimental effect on performance and productivity. Therefore, the general MR environment will be maintained in silence. However, when the system detects that the user has been sitting for an extended period of time, a sound alert will prompt them to take a break and engage in physical activity.

Table 4. Individual mapping choices for selected sensors and design rationales

4.4 Mixed Reality Design Sketches

The Mixed Reality Design Sketches stage builds on the previous stage's sensor exploration and low fidelity prototyping by exploring spatial design options in Mixed Reality (MR) using ShapeXR and Unity. While visual design in a 2D interface allows for rapid prototyping and iterations, it falls short in demonstrating the depth and complexity of spatial objects and experiences. MR design sketches, on the other hand, facilitate thinking through design choices and playing with element layouts in a 3D format.

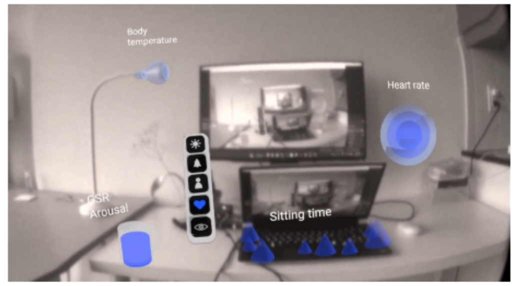
The four MR design sketches are designed and developed in ShapeXR or Unity, with each iteration informing the next as the outcome is discussed and reflected upon. This stage is crucial in the overall design process, as it largely informs signal mapping, visualization, and multimodal design from a theoretical level to an embodied design. The insights gained from this stage ensure that the final product is more engaging and better aligned with user needs and design goals.

4.4.1 Design Sketch 1: Workstation Enhancement First Iteration

This iteration of the 3D design sketch centers on a typical workstation table, complete with standard objects such as a lamp, a monitor, a laptop, a water cup, and a mouse. When users first enter the scene, they will see a menu on the left-hand side of the MR environment. This menu displays various functions, including weather, alerts, profile, health status, and passthrough enabling, all of which are represented by UI buttons. By enabling the health status icon, which takes the form of a heart, users can visualize different bodily statuses in the MR environment.

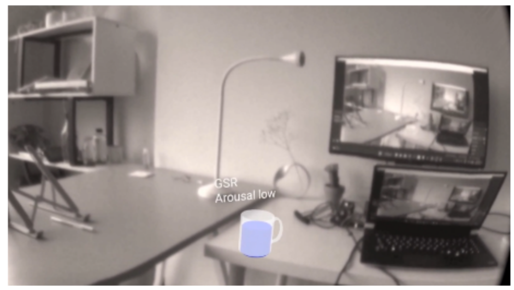
The temperature sensor TMP36 is used to map body temperature onto the light bulb of a table lamp, with the color change generating mediating effects. The choice of color for these effects is based on research showing that low color temperature lighting is more crucial than reducing illuminance. These findings indicate that low color temperature lighting leads to a gradual decrease in central nervous system activity, making it an ideal option for promoting relaxation (Noguchi & Sakaguchi, 1999). The GSR signal input is mapped onto an existing water cup. Water level changes serve as an analogy of changes in the GSR signal, with the spilling water effect being triggered by high arousal and still water representing a relatively stable state. The heart rate signal measured by the PPG heart sensor is mapped onto 3D semi-transparent spheres, allowing for the visualization of the heart rate in real-time. This approach triggers mediating effects to help regulate the user's heart rate. When a higher heart rate is detected, the spheres will expand and shrink at a slower pace of 60 bpm, which helps alter the user's breathing and slow down their heart rate. This mapping is based on research showing that engaging in slow breathing can lead to enhancements in respiratory and cardiovascular functions while reducing the impact of stress on the body (Turankar et al., 2013). The visualization of the heart rate on the 3D spheres provides a more immersive and engaging experience for the user, and the mediating effect helps improve their well-being by promoting relaxation and stress reduction. Finally, the ultrasonic proximity sensor is used to measure sitting time, a crucial factor in maintaining physical health. The sensor is mapped to triangular protrusions, which emerge from the keyboard in an animated format to alert users of overwork. Upon detecting an extended period of sitting time (over 45 minutes), the system triggers the triangular protrusions to generate an animation that prompts the user to stand up and engage in physical activity. This feature aims to promote work-life balance and physical health by encouraging the user to take breaks from prolonged sitting, which is known to have negative health consequences.

Mixed Reality Scene - Full Display

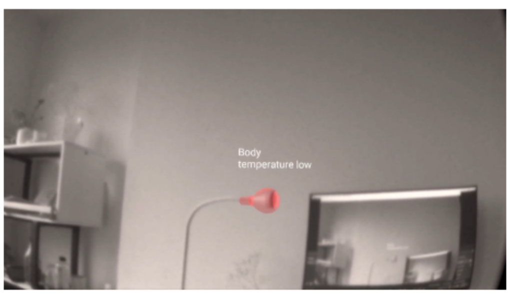


Mixed Reality Scene with Labels

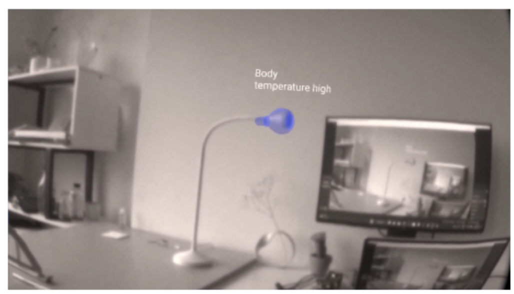
Mapping GSR signal: High Arousal - water spilling effect



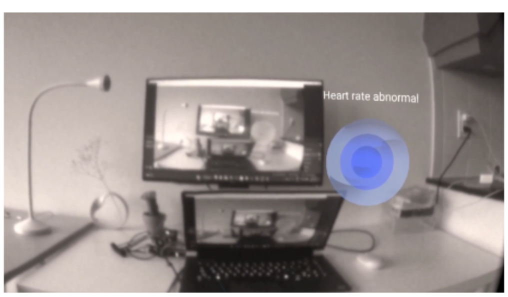
Mapping GSR signal: Low Arousal - still water cup



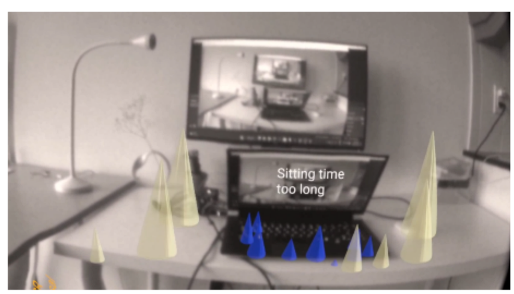
Mapping temperature: Low Body Temperature to warm color light bulb



Mapping temperature: High Body Temperature to cool color light bulb



Mapping heart rate: Abnormal generates mediating effect - rippling



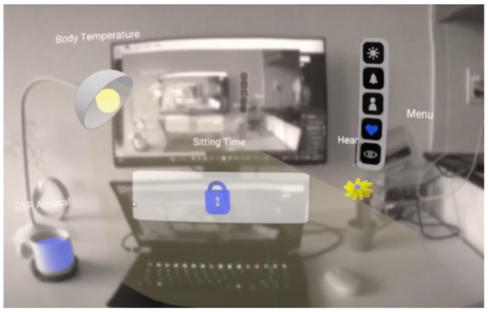
Mapping proximity: Over-time sitting time trigger animation that disrupts user from long-time sitting

Figure 17. Design sketches on workstation enhancement, the first iteration (ShapeXR)

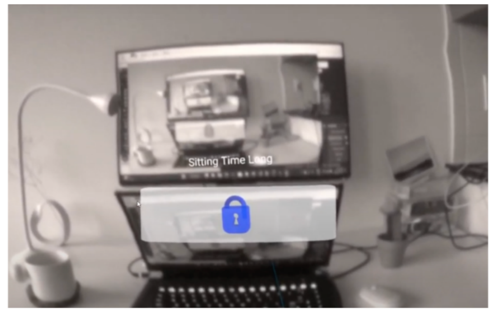
4.4.2 Design Sketch 2: Workstation Enhancement Second Iteration

The second iteration of the MR design for enhancing the workstation incorporated modifications based on feedback from peers, potential users, and the supervising team. These modifications were aimed at adhering to the calm technology principle, which seeks to minimize emotional burdens and distractions for users through a seamless integration of technology into their environment. Additionally, the design was refined to better align with the physical environment by merging virtual elements with existing workstation objects.

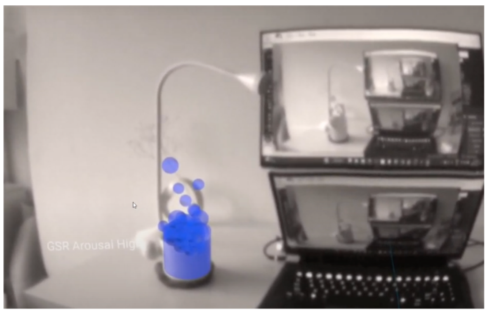
Specifically, changes were made to the visualization of the temperature sensor by adding a color tone to the lighting effects cast onto the table, and by placing the lightbulb inside a lampshade. The GSR signal was still mapped to a water cup, but the virtual cup was removed and instead overlaid on top of the existing physical cup object in the scene, with the animation changed to a bubbling water effect. Additionally, the mapping of the proximity sensor was modified by replacing the original protrusions with a still lock screen featuring soothing sound or music. In terms of displaying heart status, a 3D virtual flower was recreated from a physical flower on the table. The vitality of the flower corresponds to the user's heartbeat, with the flower appearing healthy when the heartbeat is normal and the petals beginning to fall when the heartbeat becomes abnormal. These modifications improved the design by creating a more seamless integration between the virtual and physical environment, while also reducing emotional arousal and distress for the user.



Mixed Reality Scene - Full Display with labels



Mapping proximity: Over-time sitting triggers lock-screen effect

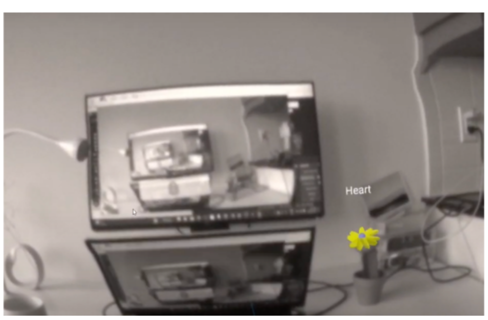


Mapping GSR signal: High Arousal - water bubbling

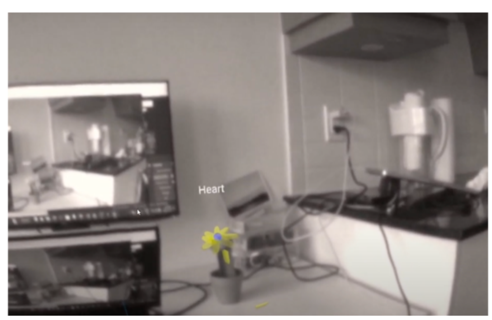
Mapping GSR signal: Low Arousal - still water cup

Mapping temperature: Low Body Temperature to warm color light bulb and shadowing

Mapping temperature: High Body Temperature to cool color light bulb and shadowing



Mapping heart rate: Normal heart rate displays a healthy flower



Mapping heart rate: Abnormal heart rate displays a flower with falling pedals

Figure 18. Design sketches on workstation enhancement, the second iteration (ShapeXR)

4.4.3 Design Sketch 3: Embodied Natural Elements

Design Sketch 3 is an MR design that explores the integration of natural elements into the system. The aim is to provide an immersive and unique environment for users to engage with by mapping physiological status onto natural scenes. In this iteration, heart status is represented by the fruit on trees. The fruit changes color and size based on the user's heart rate, providing an intuitive visualization of their heart status. Additionally, prolonged sitting time triggers a bird chirping sound to prompt the user to engage in physical activity, reducing the risk of negative health outcomes. The river in the scene reflects the user's arousal state, with the water level increasing as the user becomes more aroused and decreasing as they become more relaxed.

This design iteration demonstrates the potential of mapping physiological status onto natural elements in the MR environment, providing an innovative and engaging way for users to interact with their own bodily signals. The use of natural scenes and elements offers a unique approach to communicating complex physiological information in a way that is intuitive and immersive for users.

The exploration of Design Sketch 3 reveals potential future prospects for incorporating natural scenes and elements into game-based environments by mapping physiological status onto natural elements. Such integration has the potential to offer an interactive experience for users to engage with their bodily signals in real-time. However, it is essential to acknowledge that incorporating natural elements could increase visual complexity and result in potential disruptions that are not conducive to the working scenario. Therefore, this study does not pursue this direction of exploration. Nonetheless, this exploration provides valuable insights into the potential applications and possibilities of wearable to MR systems.

Natural Scene 1: Overhead Cloud

Natural Scene 1: Embodied Natural Elements - Forests

Natural Scene 2: Tree as biometric signal visualization

Natural Scene 2: Tree as biometric signal visualization

Figure 19. Design sketches with embodied natural elements (ShapeXR)

4.4.4 Design Sketch 4: Virtual Workstation Environment

Design Sketch 4 represents a significant step forward in the development of wearable to MR systems. This iteration of the prototype was implemented in a virtual environment built in Unity, which allowed users to experience the mediated environment in real-time by putting on a headset. By incorporating various sensor inputs and considering multimodality, the prototype was able to provide a more immersive experience for the user.

One of the key features of Design Sketch 4 was the mapping of different sensors onto virtual objects in the environment. For instance, the heart rate sensor was mapped onto a bouncing ball on the table, which expanded and contracted in real-time in response to changes in the user's heart rate. This visual representation of the user's physiological state provided quick and intuitive feedback, enabling the user to become more aware of their own bodily signals.

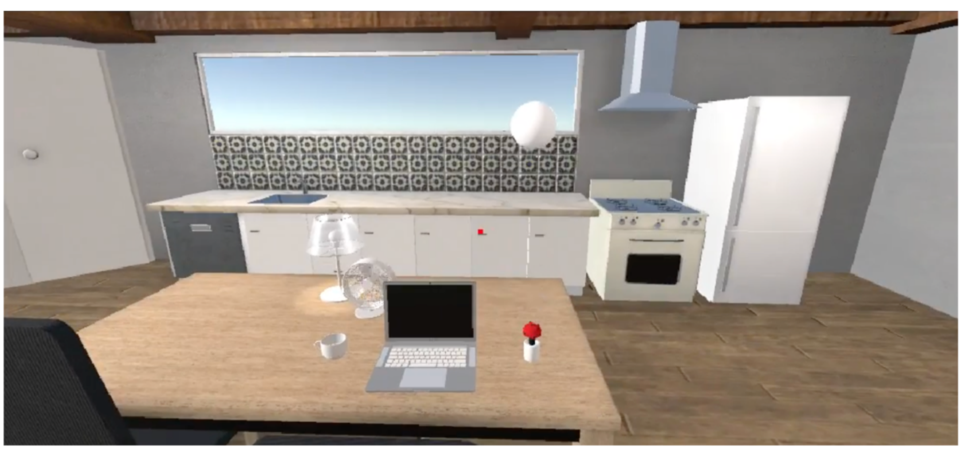
Similarly, the GSR sensor level was mapped to the rotation speed of a virtual table fan. This allowed users to see and hear the effects of their physiological state in an immersive and visually engaging manner. The temperature sensor signal was mapped to the color of a virtual table lamp, which changed in real-time to reflect the ambient temperature. Finally, the proximity sensor was used to alert users of extended sitting time by generating a meditative bell sound.

It's worth noting that this iteration of the prototype was implemented in a virtual environment, rather than an MR environment. This was because the Oculus passthrough feature would have added another layer of complexity, making it more difficult to generate quick feedback and iterate on the design. Nonetheless, this virtual environment proved to be a suitable choice for prototyping at this stage of the project.

Overall, Design Sketch 4 represents an important step forward in the development of MMRWE. By incorporating various sensor inputs and considering multimodality, the prototype was able to provide users with a more immersive and responsive experience. The use of a virtual environment enabled designers to quickly iterate on the design, providing critical feedback for the development of a final prototype.

Virtual Environment Mockup in Unity

Lamp color change in response to body temperature signal; Fan rotation speed controlled by GSR level



Bouncing sphere in response to heart beat detection; Mushroom color represents sensor is being connected

Figure 20. Design prototype in a virtual workstation environment (Unity)

4.4.5 Design Synthesis

The four MR design sketches explore the potential of wearable and MR technologies to create immersive and responsive environments that enhance individual awareness and provide mediation. Each sketch explores different aspects of this potential, from physiological sensing and feedback in Design Sketch 1, to the use of natural elements to symbolize bodily status in Design Sketch 3, to the multimodal approach and virtual environment of Design Sketch 4. While each iteration represents a varied design approach, all share a common goal of creating an immersive, responsive, and intuitive user experience.

The design sketches also highlight some challenges and limitations that must be taken into account when designing these technologies. For example, mapping different sensors onto virtual or natural elements, as seen in Design Sketch 3 and 4, can create visual clutter and potentially disrupt the user experience. Despite these challenges, the design sketches offer valuable insights and inspiration for informing the final prototype with a focus on user-centered design and multimodal approaches to create immersive and responsive environments. Overall, these sketches serve as a critical step towards the development of a final prototype that maximizes the potential of MMRWE in enhancing individual awareness and providing mediation.

4.5 Wearable Glove Design and Prototype

The integration of wearable and MR technology has the potential to revolutionize how we interact with the environment around us. In particular, the development of biofeedback-informed wearable devices has gained traction in recent years as a means to enhance user well-being and comfort. This section will explore the design and development of a wearable glove prototype, which integrates biometric sensors and MR technology to enhance user comfort and body awareness in work environments. The wearable glove is designed to incorporate sensors that measure heart rate, GSR arousal, and body temperature, which are then connected to an Arduino Uno board for data collection and processing (see Appendix F). The following section will discuss the design process and considerations involved in constructing the wearable glove, as well as the potential applications and benefits of such technology.

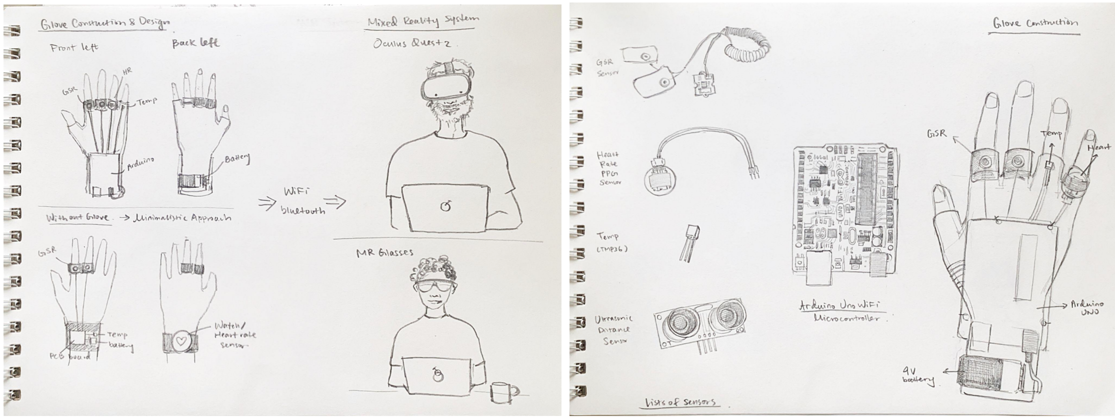


Figure 21. Sketches of glove design and construction

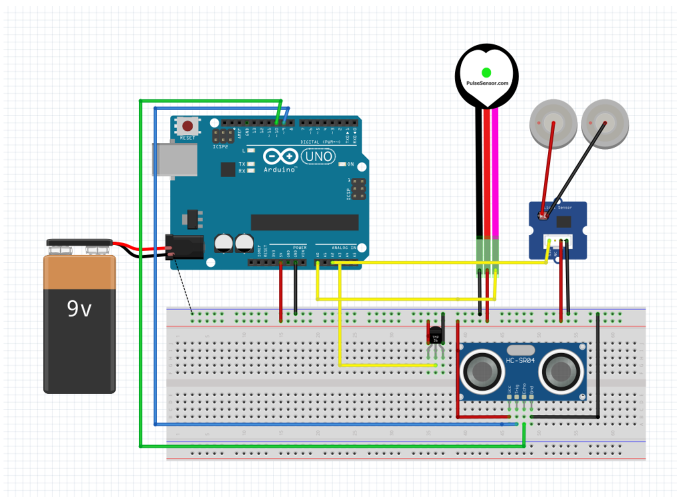


Figure 22. Circuit diagram of designed wearable

The wearable glove was constructed by placing the GSR electrodes on the index and middle fingers, heart rate sensor on the little finger, and temperature sensor on the ring finger. A half-finger glove was chosen in order to refrain from limiting the user's finger dexterity, which can be crucial for operating at work or typing on a keyboard. The sensors are connected to an Arduino Uno board, which can be powered either by a laptop and a cable or by a 9V battery attached to the glove and communicated via WiFi. The proximity sensor is attached to the back of the chair, and the collected data can be transmitted to the MR environment for output.

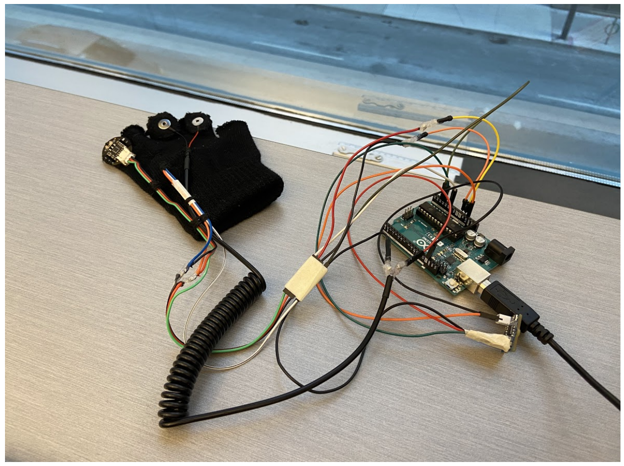


Figure 23. Wearable glove prototype with sensors and Arduino microcontroller

Figure 24. Wearable glove prototype, front and back

In this study, the constructed wearable serves as a proof-of-concept for integrating physiological sensing and feedback into a wearable glove for workplace mediation. It is important to note that this prototype has certain limitations in terms of sensor accuracy and stability. The signals collected by the PPG, GSR, and temperature sensors can be affected by environmental factors such as noise, interference, and signal drift. These factors can potentially affect the accuracy of the physiological sensing and feedback provided to the user.

To overcome these limitations, future iterations of the design could incorporate more advanced sensors, including commercial wearables, to improve the accuracy and stability of the sensing system. Additionally, making the microcontroller and battery smaller would improve the overall integration and user comfort of the device. These improvements could lead to a more reliable and robust sensing system, providing accurate and stable physiological feedback to the user.

4.6 Final Prototype

This final prototype represents the culmination of the research, design, and testing conducted in this thesis study. The MMRWE design aims to provide a real-time reflection of biometric signals and integration between the physical and digital worlds to enhance awareness of bodily changes and provide mediation.

In terms of technical specifications, the wearable glove is equipped with sensors that measure heart rate, GSR arousal, and body temperature, which are then connected to an Arduino Uno board for data collection and processing. A proximity sensor is also placed on the back of a chair to measure sitting time. The MR environment is generated using Head-Mounted Displays (Oculus Quest 2 and Quest Pro), providing multimodal feedback to users via visual and audio feedback. The software used in this prototype is Arduino IDE and Unity, with the connection built via serial port communication through USB and Quest link cables (See Appendix G).

The prototype's features and functionality enable real-time adaptation to the user's biometric data, providing personalized feedback in a MMRWE to enhance awareness of bodily status and provide mediation. The user interface of the wearable and MR display allows for both tangible and virtual interaction with the prototype, providing an additional layer of dimension to the user's workspace.

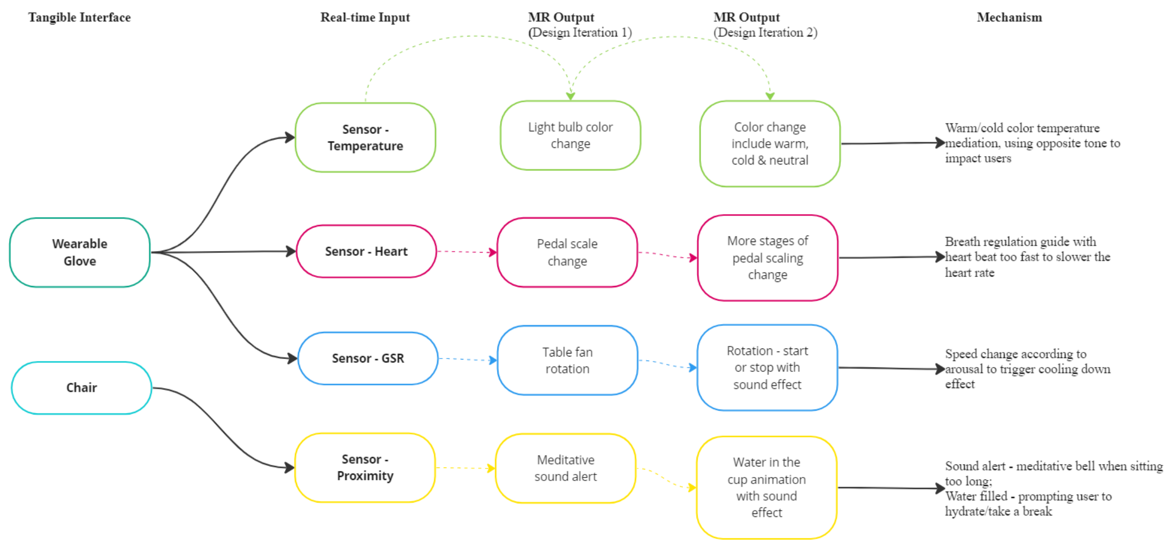


Figure 25. An overview of signal mappings from wearable to MR

The design approach and aesthetics of this prototype adhere to the calm technology principles, which aim to create technology that is minimally invasive, informative, and calming while balancing minimalist design with interesting and engaging MR environments.

The manufacturing process of this prototype involved the integration of multiple components, hardware, and software, requiring the process to be broken down into smaller pieces. Throughout the design and prototyping phases, certain iterations were undertaken concurrently, such as the simultaneous exploration of sensors and the wearable glove alongside the development of design sketches for the MR environment using ShapeXR. The final prototype effectively interconnects all constituent components into a MMRWE with wearable technology.

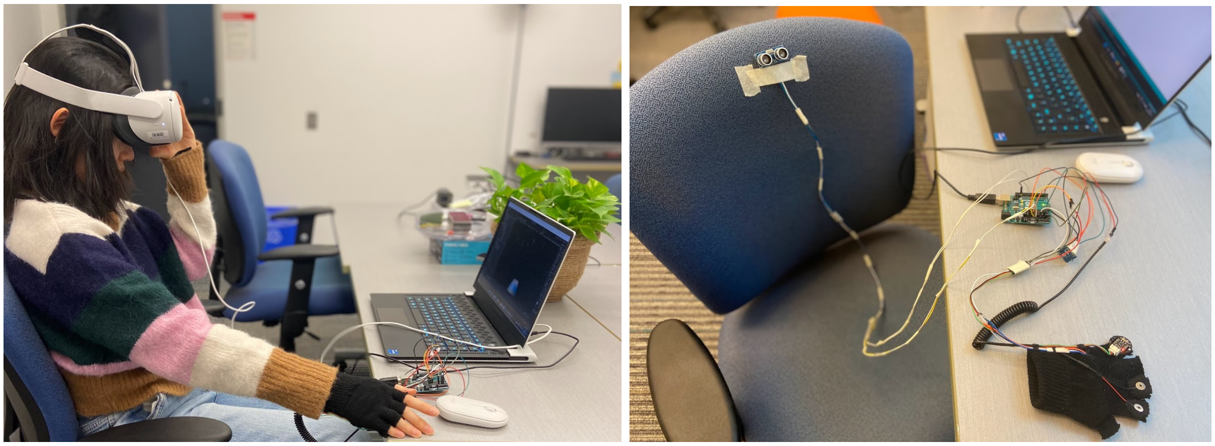
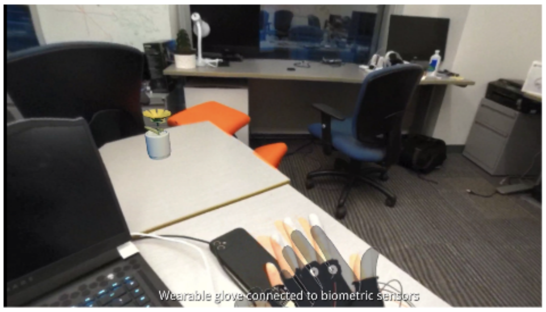


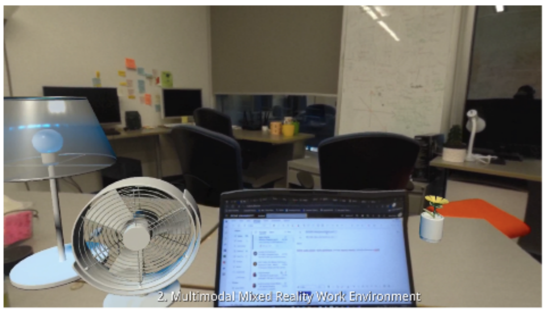
Figure 26. Physical setup and testing of MMRWE final prototype

In the next chapter, a small-scale user testing is conducted to evaluate the design choices and inform future development. The testing and validation process aims to provide feedback on the prototype's functionality and identify any potential design issues or limitations that need to be addressed. This final prototype is the result of all the design thinking, feedback, and reflections integrated into a single iteration, representing the culmination of this thesis study.



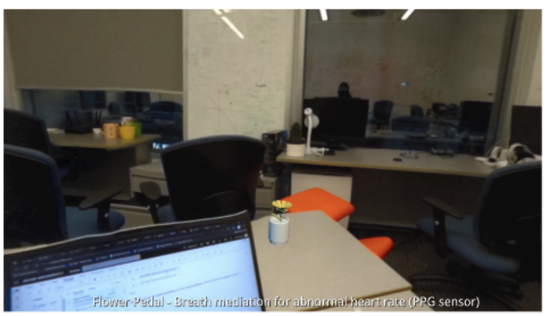
Wearable glove connected to biometric sensors

Ultrasonic proximity sensor attached to the chair backrest



Multimodal MR work environment

Lamp color and lighting: body temperature mediation



Flower pedal: breath mediation for abnormal heart rate

Fan rotation: visualization of GSR arousal to enhance awareness

Figure 27. MMRWE final prototype

4.7 Summary

The design process involved multiple stages of prototyping, starting with paper sketches and moving on to Wizard of Oz prototyping, MR sketches in Shape XR, VR design, wearable design and final prototype. Environmental Psychology and interior design perspectives informed the creation and refinement of the wearable and MR environment, providing a framework for understanding the role of light, color, temperature, and audio effects in shaping human physiological and emotional responses. The exploration of sensors and signal processing was also a crucial aspect of the design process, with threshold setting enabling the classification of bodily status beyond normality.

Incorporating the elements from the sensor exploration stage, the wearable device was adjusted and connected to Unity and Oculus Quest 2/Quest Pro to create a functioning prototype that provided continuous output based on sensor input. The prototypes offer proof of concept for a wearable and MR system that can monitor and regulate physiological responses in real-time, aiming to promote wellness and productivity in the workspace scenario.

The design processes employed in this thesis project are based on RtD, ID, and SD methodologies. These approaches facilitate exploratory research, design iterations, and evaluations that depart from the identified problem scope and audiences. The RtD methodology informs the creation of the MR workspace system, while the ID principles guide the intuitive and accessible interface design. The exploratory research, conducted with a user-centric approach, informs the early low-fidelity prototypes. Finally, the SD methodology envisions future scenarios, identifies potential benefits and challenges of the MR environment, and determines preferred attributes that influence system use. The use of these methodologies ensures that the design process follows research methodologies, resulting in prototypes that effectively address the identified problem scope and audiences.

5. Evaluation and Discussion

The Evaluation and Discussion section aims to provide a thorough analysis of the design and user testing process, as well as the outcomes of the evaluation using predetermined criteria. The primary goal of this section is to examine the design's strengths and limitations, and to identify areas for future improvement. The section presents the evaluation criteria used in both the wearable and the MR system, as well as the user testing process and outcomes. By analyzing and discussing the results, the section aims to inform future design iterations and highlight the successes and limitations of the design. Through this evaluation process, we can gain a better understanding of how users interact with the design and identify areas that require further attention.

5.1 Evaluation Criteria

The evaluation of the final prototype employs RtD and ID methodologies. RtD involves creating and refining design artifacts through a continuous process of analysis, projection, and synthesis, where each iteration of the design is informed by user feedback and reflection. In this study, the evaluation of the wearable glove and MR environment served as an integral part of the iterative design process, aimed at measuring the effectiveness of the system in enhancing bodily awareness and providing mediation.

The evaluation criteria used for the wearable glove include comfort, reliability, functionality, and user satisfaction:

1. Comfort: The comfort of the wearable glove was evaluated based on the fit and weight of the sensors, as well as the material of the glove.
2. Reliability: The reliability of the wearable glove was evaluated based on the accuracy and consistency of the sensor data, as well as the connectivity and stability of the hardware.
3. Functionality: The functionality of the wearable glove was evaluated based on the ease of use and control of the sensors, as well as the adaptability of the glove to different hand sizes and shapes.
4. User Satisfaction: The satisfaction of the users with the wearable glove was evaluated based on their feedback on the glove's design, functionality, and effectiveness.

The evaluation criteria for the MR environment include usability, effectiveness, immersiveness, and user satisfaction:

1. Usability: The usability of the MR environment was evaluated based on the ease of use and navigation of the system, as well as the clarity and relevance of the information displayed.
2. Reliability: The reliability of the MR environment was evaluated based on the ability of the system to provide mediating effects to users, as well as the accuracy and responsiveness of the system.

3. Functionality: The functionality of the MR environment was evaluated based on the ability of the system to provide a realistic and engaging experience for users, as well as the level of sensory immersion.
4. User Satisfaction: The satisfaction of the users with the MR environment was evaluated based on their feedback on the system's design, functionality, and effectiveness.

By evaluating both the wearable glove and MR environment based on these criteria, we can gain a comprehensive understanding of the effectiveness and overall user satisfaction with the system.

5.2 User Testing

The user testing section is a critical part of the evaluation process, aimed at assessing the effectiveness and usability of the developed prototype. It involves recruiting participants based on their experience working in onsite and remote settings and gathering information about their work patterns, behaviors, bodily awareness, and coping mechanisms through a preliminary survey. The testing procedure involves participants interacting with the prototype while observations are made to capture their reactions, behaviors, and comments. The post-study survey is conducted to evaluate the product and gather quick feedback from the participants. Additionally, semi-structured interviews are carried out to provide more in-depth feedback, suggestions, and insight. The user testing section is crucial as it provides an understanding of how users interact with the prototype, identifies areas that require improvement, and informs future design iterations.

5.2.1 User Testing Procedure

To evaluate the effectiveness and usability of the developed prototype, a user study was carried out. This section describes the design of the user testing, including participant recruitment, data collection methods, and analysis techniques.

1. Participant recruitment: Participants were selected based on their experience working onsite and remote settings (see Appendix A). Seven participants were selected for small-scale user testing under their acknowledgment and consent. Participants were enlisted one to two weeks prior to the user testing.
2. Preliminary survey: A preliminary survey was conducted before the testing to gather information about the participants' work patterns, behaviors, bodily awareness, and coping mechanisms (see Appendix C). This information provided insight into how each participant operates in a working environment and their average awareness level.
3. Prototype testing and observation: Participants were asked to interact with the prototype to test its functionality and effectiveness. During the testing, observations were made to capture the participants' reactions, behaviors, and comments. Participants were encouraged to share their thoughts or ask questions during the process.
4. Post-study survey: Following the testing, an exit survey was conducted to evaluate the product and gather quick feedback from the participants (see Appendix D). This survey included questions related to changes in participants’ bodily awareness and emotions, as well as questions related to the participants' immediate responses towards the prototype.
5. Semi-structured interview: In addition to the survey, a semi-structured interview was conducted with each participant to collect more in-depth feedback, suggestions, and insight (see Appendix E). These interviews lasted approximately 20 minutes and were designed to provide a detailed understanding of the participants' experiences with the prototype.

During the testing and data collection process, participant anonymity was maintained. Any feedback or data collected was presented anonymously and disseminated with the participant's consent (see Appendix D). Participants had the option to choose whether or not they wanted their feedback to be presented anonymously.

5.2.2 User Testing Process

To assess the effectiveness and usability of the prototype, seven participants were enlisted for the user testing session. In the context of usability testing, "magic" numbers are guidelines for sample sizes. For formative usability testing, the most widely recognized magic number is 5 (Nielsen & Landauer, 1993), although other researchers have suggested that the magic number could be 8 (Spool & Schroeder, 2001) or 10 (Hwang & Salvendy, 2010). Thus, the sample size of seven falls within the range of commonly accepted sample sizes for user experience testing.

The user testing sessions were conducted individually, following a planned procedure that included a preliminary survey, prototype testing, post-study survey, and semi-structured interview. During and after the process, insightful feedback and suggestions were collected from the participants. The goal of the user testing was to inform the next iteration and explore the potential of MMRWE, rather than treating it as a finished product. This approach allowed participants to provide feedback with a more open mindset and offer creative solutions.

User Testing Session 1

User Testing Session 2

User Testing Session 3

User Testing Session 4

User Testing Session 5

User Testing Session 6

User Testing Session 7

User Testing Session 7

Figure 28. User testing sessions (1-7)

5.2.3 Feedback and Results

This section presents the outcomes of the user testing, including feedback and insights gained from participants regarding the prototype's design and functionality. Feedback is gathered from two surveys and one semi-structured interview. Overall, the wearable design was deemed comfortable and functional, while the MR environment received positive feedback with some room for improvement.

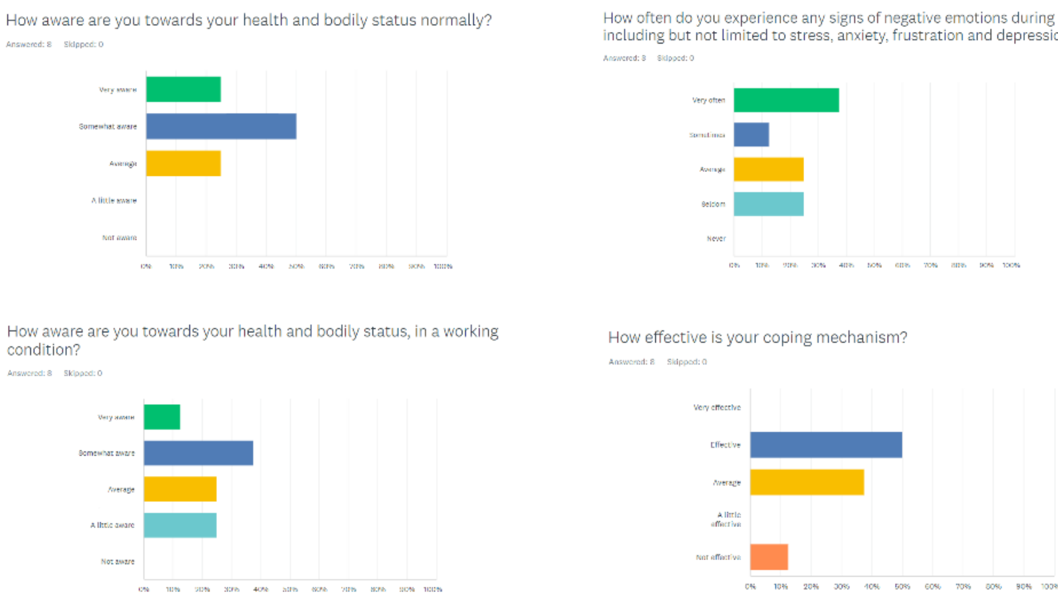


Figure 29. Preliminary survey data analysis

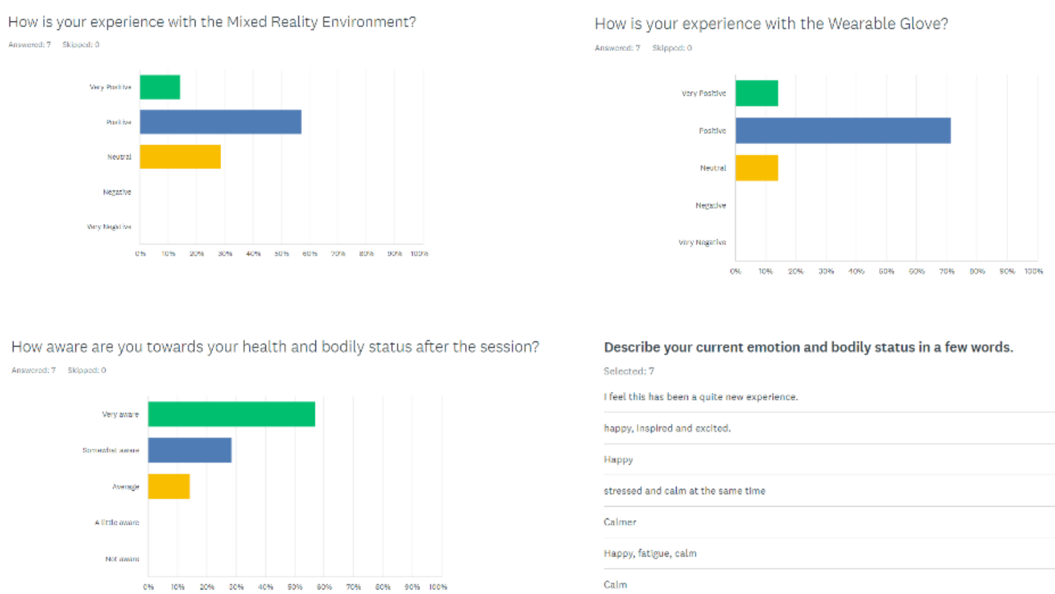


Figure 30. Post-study survey data analysis

The results of two surveys suggest that the prototype has enhanced participants' awareness of their health and bodily status. Specifically, the proportion of participants indicating a high level of awareness increased from 25% before the testing to 57.14% after the testing. Additionally, participants' experiences with the wearable glove and MR environment were generally positive, with 85.71% and 71.43% rating the experience as positive or very positive, respectively. Furthermore, participants reported feeling calmer and more satisfied emotionally after experiencing the prototype.

The post-study semi-structured interviews provided valuable insights into the design prototype and its future development. Participants generally recognized the effectiveness of the prototype and expressed a positive attitude towards adopting the system for individual use in a working environment. In particular, the wearable design was appreciated for its comfort and construction, which allowed for mobility and flexibility of desktop operations. However, the reliability of the wearable was found to be limited, with occasional sensor instability caused by hand movement.

Regarding the MR environment, the subtleness of mapped multimodal output was appreciated by most participants. However, one participant indicated a preference for more animated, interactive, and visually dynamic output. The prototype collects signals every 30 seconds, with the design consideration of reducing noise and providing more subtle and smooth mediation effects. While four participants found the time lag reasonable, three suggested shortening the time between signal intakes to better support users in identifying the trigger of bodily responses. In terms of individual sensor mappings, temperature to lamp light and heart status to plant were found to be the most intuitive and fitting, while the mapping of arousal level received some critiques. Specifically, participants without an arousal level change found it difficult to figure out which visualization represented slow or fast. To address this issue, participants suggested reducing the size of fans and placing them further away from the user, as the fan rotation could sometimes be distracting and decrease user focus. Overall, the wearable design was deemed comfortable, functional, and satisfying for users, with some limitations in terms of reliability, while the MR environment received positive feedback with some suggestions for improvement.

5.3 Findings and Discussions

The evaluation of the wearable glove and MR environment resulted in positive feedback based on four evaluation criteria, indicating high user satisfaction. However, sensors' lack of stability and accuracy greatly reduces their reliability. To improve its reliability, integrating more mature and stable biometric sensors and a more refined signal processing system is necessary. On the other hand, the HMD's comfort is the primary concern in the MR design, with several participants experiencing motion sickness and lagging, which restricts head flexibility and movement. Taking breaks during the user testing process was suggested to address this issue. Future technological advances or an alternative HMD solution, such as MR glasses, could potentially overcome this disadvantage.

Evaluation Criteria	**Wearable Glove**	**MR system**
Comfort	5/5	2/5
Reliability	3/5	4/5
Functionality	4/5	4/5
User Satisfaction	4/5	4/5

Table 5. Evaluation criteria for wearable glove and MR system

The user testing session provided valuable insights into the design, development, and integration of the prototype. As a proof of concept, the MMRWE served as an effective starting point for obtaining feedback from the target audience. The testing highlighted the importance of achieving all four aspects - comfort, reliability, functionality, and user satisfaction - to create a positive user experience. However, it should be noted that the sample size for this study was relatively small and may not represent a broader audience. A more diverse pool of participants would provide a comprehensive perspective on the design concept and prototype integration. Additionally, it is important to acknowledge that the user testing was conducted for a relatively short period of time due to the potential risks associated with HMDs, while the design concept is intended for long-term use. Thus, long-term effects were not evaluated, which could offer further insights for improving the design.

5.4 Personal Reflection

Through multiple stages of design development and iterations, I have come to realize that our perception of the environment is not merely passive but is actively shaped by the way we interact with it. This study provides an opportunity to explore the dynamic interaction between the external and internal worlds and the way in which they shape our experiences.

In the traditional sense, we perceive the environment as a static and objective reality, imposed upon us by pre-established objects or infrastructures. However, these explorations of prototypes brings forth an alternate reality, a personalized world that reflects our inner representation of self onto the external world. In this way, the inner world - the invisible and the internal - is projected into the outer world, the visible and the external, forming a symbiotic relationship between the two.

MMRWE prototype enables us to become active agents of our own perception, no longer passive perceivers of the environment but creators of our own reality. It provides a new sense of agency, allowing us to act on changes to a fixed environment in a more malleable way and ultimately feeds back to ourselves. In this way, we become both internal and external, receiving and creating affects that shape our perception of the world. Moreover, lighting, color, sound, odor, and tactile intake are crucial elements of our perception, and their intricate yet subtle changes have the power to affect our mental and emotional state. By incorporating these elements into the MMRWE prototype, we can create embodied personalized worlds that stimulate our senses and evoke new affects.

However, it is essential to critique the ethical implications of our design choices and the incorporation of technology into our lives. The MMRWE prototype poses fundamental questions about the relationship between technology and the self. Does it enhance or detract from our ability to sense? Does it augment us to become more powerful and sensible humans, or does it generate fake illusions that lure us into self-indulgence and detachment from the real world?

In conclusion, the MMRWE prototype is a fascinating tool for exploring the dynamic interaction between the external and internal worlds and the way in which they shape our experiences. It provides a new sense of agency and creative potential that allows us to become creators of our own reality, blurring the boundary between inner and outer reality. However, it is crucial to critique the ethical and philosophical implications of our design choices and the role of technology in shaping our perception of the world.

6. Conclusion

The start of this study can be traced back to a personal motivation to confront the challenge of balancing productivity with self-care. Over time, the study has undergone multiple iterations of construction and deconstruction, from defining the problem to delivering the final outcome. At each stage, the research question was re-evaluated, and the value of the study was examined. It would be oversimplifying to label the MMRWE final prototype as the ultimate outcome, as the study is an ongoing process that continues to evolve with each new development. In essence, the outcome is still in the making, and the exploration is constantly advancing.

6.1 Revisiting Goals and Objectives

This study aimed to design a MMRWE with wearable technology that enhances body awareness and promotes relaxation in work environments. The project identified a research gap and aimed to contribute to biofeedback-informed MR applications for work scenarios.

The MMRWE prototype developed in this study has successfully achieved the goals and objectives. The prototype utilizes embedded sensors in the wearable glove to output and visualize biometric values into the MR environment. Environmental psychology and interior design principles were adopted into the design of the MR environment, that elements such as color, lighting, and sound, have been incorporated into the prototype design.

Overall, this working prototype serves as a proof-of-concept that highlights the potential of wearable and MR technology to enhance individual awareness and mediate potential negative consequences induced by work. With further development and refinement, MMRWE has the potential to become a valuable tool in various industries to promote a healthier and more productive work environment.

6.2 Outcomes and Contributions

The key contributions of this project include the introduction of a prototype system that dynamically mediates its environment based on real-time monitoring of users' physiological signals, the incorporation of principles from Environmental Psychology in the design of MR technology and human-computer interaction, and an investigation of the possibility of future workspaces design in a multimodal MR setting.

The small-scale user testing conducted provided positive feedback and generated valuable insights into how biofeedback-informed MR applications can be designed for work scenarios. Further research could build upon this study by engaging a greater number of audiences and applying the design mechanism to other scenarios.

6.3 Limitations

This study has several limitations and constraints that must be acknowledged. These include limitations in hardware resources, data acquisition and processing, and user testing.

Hardware limitations relate to HMD, specifically Oculus Quest 2 and Quest Pro which were used in this study. While the headset provides an immersive and engaging experience, it also has potential effects on the human body, such as motion sickness and eye strain. Additionally, the headset's comfort level and accessibility may be limited for some users. This could affect the overall effectiveness of the system and may reduce its potential impact.

While the PPG heart sensor, GSR sensor, TMP36, and Ultrasonic Proximity sensors are all effective tools for physiological monitoring, they have some limitations. Data acquisition and processing need to be evaluated in terms of sensor stability and accuracy. There may be some discrepancies between the measured data and the actual physiological responses of the user. This could result in delayed or inaccurate feedback, which may limit the effectiveness of the system. Despite the limitations of the selected sensors, they were chosen for this study due to their affordability, ease of use, and reliability. The use of customized sensors allowed for a proof-of-concept product to be developed quickly and efficiently, without the need for extensive resources and time.

Furthermore, user-testing limitations relate to time constraints and small-scale testing. While the user testing provided valuable insights into the usability and effectiveness of the system, it was limited to only seven participants. This small sample size may limit the generalizability of the results and the overall effectiveness of the system. Additionally, the time constraints of the project may have limited the length and depth of the user testing, which may have affected the reliability of the results.

6.4 Future Development

This project builds on the assumption that MR technology and headset will become more affordable, comfortable, and accessible. Future development should take the development of relevant technology into consideration and be prepared to alter design decisions based on alternative hardware and form factors. This would ensure that the system remains relevant and effective as technology advances.

At the current stage, the wearable sensors and other hardware used in this study can be replaced by more stable and developed products that would largely boost the accuracy of signal input and effectiveness. User testing can be extended into measuring the detection of physiological status changes and automatically feeding back into the system to create a more intelligent environment. This would enable the system to provide a more personalized and effective experience for the user, tailored to their individual needs. Additionally, the wearable to MR prototype could be connected with IoT devices such as room thermometers, speakers, and other smart devices in constructing a smart environment or workstation. This would provide a more comprehensive solution to physiological monitoring and stress management, incorporating real-time data from wearable and external sensors.

The potential applications of the developed biofeedback-informed MR system are vast and varied, extending beyond workspaces to healthcare facilities, rehabilitation centers, assisted living communities, and in-home use for patients and aging populations. By using this system, healthcare professionals can monitor and track the patient's physiological status in real-time, providing personalized treatments and interventions. Patients with disabilities and accessibility requirements can benefit from this system, as the multimodal MR system can be customized to meet their specific needs and limitations. For example, the system can be adapted to guide patients through exercises for physical rehabilitation, reducing the risk of injury and providing a more effective treatment process. In assisted living communities and elderly care facilities, the system can be used to improve the quality of life of the residents by enhancing their physiological and psychological status, thereby reducing the incidence of falls and the onset of chronic conditions.

Furthermore, the development of biofeedback-informed MR systems has vast creative potential in generating affect and creating an embodied alternative reality of oneself as one's own reflection. The system can be used to create immersive artistic experiences that go beyond traditional forms of art, enabling users to interact with and alter their environment in real-time. Through the incorporation of multimodal sensors and wearable technology, users can create personalized environments that respond to their physiological and psychological states, generating affect and promoting emotional well-being. MMRWE can also connect and communicate with others through the embodiment of the self. By creating avatars or virtual representations of oneself, users can interact with others in an immersive and embodied way, transcending the limitations of physical distance and enhancing social communication. The system has the potential to revolutionize the way we interact with each other, allowing for a deeper and more meaningful connection between individuals.

6.5 Final Remarks

This study makes a significant contribution to the field of wearable technology and Mixed Reality systems for body awareness enhancement and mediation. The innovative design framework and insights from user testing and feedback provide a strong foundation for future research and development, pushing beyond defined problem spaces and exploring new avenues for creativity and expression.

The exploration experience has been rewarding, challenging traditional notions of reality and offering a deeper understanding of human power and the ability to shape and remake nature. The potential for wearable technology and Mixed Reality systems to enhance emotional well-being, creative expression, and our understanding of the world offers exciting possibilities.

As we look towards future development, it is essential to continue discussing the ethical implications of technology and the two layers of self-representation. We must carefully consider the potential for Mixed Reality systems to create a second-order nature.

Overall, this study opens up new opportunities for research and development, offering exciting potential for enhancing body awareness and exploring new possibilities for technology. By pushing the boundaries of traditional design and continuing to explore new possibilities, we can create a more dynamic and meaningful relationship between ourselves and the world around us.

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Appendices

Appendix A: Recruitment Materials

Appendix A: Recruitment Materials

Call for participation

Recruitment for the user testing will be carried out as follows:

1. Social media and email advertising image/poster will include a link to an application form hosted on SurveyMonkey to capture applicant name, email address, contact information and brief reason for participation.
    2. Poster text: “Call for study participants! An exploration on enhancing awareness of body status via wearable sensors and Mixed Reality technology.” Followed by sign-up QR code and contact information (email).
    3. Poster image:

Appendix B: Consent Form

Appendix B: Consent Form

Key Contacts:

Dr. Alexis Morris, Principal Investigator
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OCAD University
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Dr. Claire Brunet, Co-Supervisor
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ellieh@ocadu.ca

DATES
Mar 6, 2023 - Mar 17,2023

INVITATION
You are invited to participate in a study that involves research. The purpose of this project is to explore and study how to create a Multimodal Mixed Reality Work Environment. This project serves as a research through design study that produces processes, data, and visualization that can inform iterative development as well as build knowledge to inform future designs.

WHAT'S INVOLVED
This study will present a working prototype for user testing. If you consent to participate in this research study, you will: interact with and evaluate the prototype; complete preliminary and post-study surveys; and participate in a semi-structured interview.

During the testing process, you will be observed by the researcher and your operations will be noted. The research generated in this project will be used to better understand whether and how the designed prototype is able to enhance body awareness for participants, resulting in new knowledge to create Mixed Reality and Wearable Technology design.

POTENTIAL RISKS AND BENEFITS

Possible risks of participation in the user testing include:

- Use of VR equipment carries some risk of motion sickness resulting from immersion in a VR headset, this is minimized by the active nature of creation. You can take breaks from VR to reduce potential for motion sickness.

Possible benefits of participation in the user testing include:

- Documentation support, including photos and videos that participants can use for personal means;
- The opportunity to contribute to research publications;
- The ability to influence and inform future research.

It is possible that you will not experience any or all of the potential benefits or risks listed above.

CONFIDENTIALITY & ANONYMITY

This project collects two different types of data: material generated by the research which will not be confidential and shared with the public for project exhibition, and raw data that will be kept confidential. Dissemination of research includes Thesis dissertation, exhibition, publication (if applicable) and website. Project documentation will be shared during the OCAD graduate thesis exhibition, which includes anonymized recordings of participant interaction and artistic visualization with no identifiable personal data. This raw data identifies project participants (email addresses, contact details and biometric data). This personal data will be kept on a password protected cloud drive for a maximum of one year post study.

VOLUNTARY PARTICIPATION

Participation in this study is voluntary. You may decline to answer any questions and/or participate in any component of the study. You may decline to have your image taken. You may decide to withdraw from this study at any time prior to March 17, 2023. If you choose to withdraw, any relevant information will be destroyed.

CONTACT INFORMATION AND ETHICS CLEARANCE

If you have any questions about this study or require further information, please contact Ellie Huang (Student Investigator) using the contact information provided above. This study has been reviewed and received ethics clearance through the Research Ethics Board at OCAD University [Number 2023-04]. If you have any comments or concerns, please contact the Research Ethics Office through research@ocadu.ca.

CONSENT FORM

I agree to participate in the study described above. I have made this decision based on the information I have read in this Consent Form. I have had the opportunity to receive any additional details I wanted about the study and understand that I may ask questions in the future. I understand that I may withdraw this anytime prior to March 17, 2023.

General Participation

❏ Yes, I consent to participation in this study. I understand that questionnaire responses and observational notes will be confidential. I also understand that all resulting process and prototype documentation (including photos and audio feedback, and video interaction) will not be confidential and may be published in reports, professional and scholarly journals, conferences, and project documentation.

❏ No, I do not wish to participate in this study.

Attribution

❏ Yes, I wish to receive attribution for my feedback or documentation images/videos. You may use my name as listed below alongside images or videos of the prototypes.

❏ No, I do not wish for my name to be used in association with images or video in this project.

Images of You

❏ Yes, I consent to appear in photographs and/or videos that may be published in reports, professional and scholarly journals, conferences, presentations and online project documentation.

❏ No, I do not consent to appear in photographs and/or videos.

Name:_____________________________

Signature: _____________________________ Date: _____________________________

Thank you for your assistance in this project. Please keep a copy of this form for your records.

Appendix C: Preliminary Questionnaire

Appendix C: Preliminary Questionnaire

The 15-minute survey will be hosted on SurveyMonkey or on paper and be completed individually.

1. How would you rate your awareness of body and health status? (scale from 1 - 10)
2. How much are you aware of your distinct body reactions when you are stressed or fatigued? (scale from 1 - 10)
3. How much are you aware of a cycle in activity level throughout the day? (scale from 1 - 10)
4. How often do you experience any signs of negative emotions during work, including but not limited to stress, anxiety, frustration and depression)? (scale from 1 - 10)
5. When you experience negative emotions at work, how do you usually cope with them?
6. How effective is your coping mechanism?
7. What is your ideal status at work?
8. How would you rate your current status? (scale from 1 - 10)
9. How much awareness are you towards your current body and body status? (scale from 1 - 10)
10. Use a few words to describe your current mood/emotion.

Appendix D: Post-study Questionnaire

Appendix D: Post-study Questionnaire

The survey will be hosted on SurveyMonkey or on paper and be completed individually.

1. How would you rate your current awareness of body and health status (scale from 1 - 10)?
2. Rate your experience with the wearable glove (scale from 1 - 10).
3. Rate your experience with the MR environment and headset (scale from 1 - 10).
4. Use a few words to describe your current mood/emotion.
5. Is there any noticeable difference compared to your previous status (pre-user testing)?
6. Can you share some quick thoughts on the overall experience.

Appendix E: Post-study Semi-structured Interview

Appendix E: Post-study Semi-structured Interview

This 30 minute semi-structured interview takes place *after* the user testing to capture reflections from the experience:

1. Tell us about your experience
2. Which part of the experience do you enjoy the most and which part do you dislike the most?
3. Tell us about your experience with the wearable device?
4. Tell us about your Mixed Reality experience?
5. Is there any inconvenience or difficulty in using the tools?
   a. At what points were the tools hard to use?
6. How did the wearable tools feel to use?
   a. What is one thing you wish was different in these tools and which would have made your experience better?
7. How would you describe your current status after the user testing?
   a. Are you more, or less aware about your body status?
   b. Are the intervening mechanisms working for you? If so, in what way?
   c. Are the intervening mechanisms disturbing for you? If so, in what way?
   d. Is there anything you would like to change that would provide a better experience or be more effective?
8. What, if anything, will you take from this experience?

Appendix F: Arduino Source Code

```
/*Sensors*/
const int GSR = A2;
const int Temp = A3;
const int HeartRate = A0;
const int trigPin = 9; //Proximity trig
const int echoPin = 10; //Proximity echo

/*Interval time for serial reads*/
const unsigned long intervalTime_GSR = 500;
const unsigned long intervalTime_HR = 100;
const unsigned long intervalTime_US = 1000;

unsigned long previousTime_GSR = 0;
unsigned long previousTime_HR = 0;
unsigned long previousTime_US = 0;

/*others*/
long duration;
int distance;
int counter = 0;
int hThreshold = 853;
int gThreshold = 30;
int gSensorValue, hSensorValue;
int currentTemp = 36.8;

void setup() {
  long sum = 0;
  pinMode(trigPin, OUTPUT); // Sets the trigPin as an output
  pinMode(echoPin, INPUT); // Sets the echoPin as an input
  Serial.begin(115200);//115200 bits per second

  for (int i = 0; i < 1000; i++)
  {
    gSensorValue = analogRead(GSR);
    sum += gSensorValue;
    delay(5);
  }
  gThreshold = sum / 1000;//Takes the average as GSR threshold
}

void loop() {

  unsigned long currentTime = millis();//update current time

  int gsr;
  hSensorValue = analogRead(HeartRate);
  gSensorValue = analogRead(GSR);
  gsr = gThreshold - gSensorValue;
```

```
/*prep for temperature read*/
int reading = analogRead(Temp);
float voltage = reading * 5.0;
voltage /= 1024.0;
float temperature = (voltage - 0.5) * 100;

/*prep for ultrasonic*/
// Clears the trigPin
digitalWrite(trigPin, LOW);
delayMicroseconds(2);
// Sets the trigPin on HIGH state for 10 micro seconds
digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin, LOW);
// Reads the echoPin, returns the sound wave travel time in microseconds
duration = pulseIn(echoPin, HIGH);
// Calculating the distance
distance = duration * 0.034 / 2;


/*GSR & Temperature*/
if (currentTime - previousTime_GSR >= intervalTime_GSR)
{
  if (abs(gsr) > gThreshold)
  {
    Serial.write(3);
    Serial.flush();
  }

  else if (abs(gsr) <= gThreshold)
  {
    Serial.write(4);
    Serial.flush();
  }
  //If body temperature exceeds 37.2 celsius
  if (temperature > currentTemp + 0.4)
  {
    Serial.write(5);
    Serial.flush();
  }
  //If body temperature ranges from 36.4 to 37.2 celsius
  else if (temperature > currentTemp -0.4 && temperature <= currentTemp + 0.4)
  {
    Serial.write(6);
    Serial.flush();
    }
    //If body temperature below 36.4 celsius
    else if (temperature <= currentTemp - 0.4)
    {
    Serial.write(7);
    Serial.flush();
      }
```

```
    previousTime_GSR = currentTime;
  }


  /*HeartRate*/
  if (currentTime - previousTime_HR >= intervalTime_HR) {
    if (hSensorValue >= hThreshold) {
      Serial.write(1);
      Serial.flush();
    }
    else if (hSensorValue < hThreshold) {
      Serial.write(2);
      Serial.flush();
    }
    previousTime_HR = currentTime;
  }


 /*Ultrasonic*/
  if (distance > 1 && distance < 50)
    {
      counter = counter + 1;
    }
    // restore to normal state - after a stretch or exercise
    else if (distance > 100) //leaving the seat
    {
      counter = 0;
      Serial.write(9);
      Serial.flush();
    }

  if (currentTime - previousTime_US >= intervalTime_US) {

    //alert for need of physical exercise - sitting too long
    if (counter >= 200000)
    {
      Serial.write(8);
      Serial.flush();
    }
    previousTime_US = currentTime;
  }
}
```

Appendix G: Unity Source Code

Script 1: Reading signal from Arduino

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System.IO.Ports;

public class PedalScale : MonoBehaviour
{

       SerialPort sp   new SerialPort("COM3", 115200); // set port of your arduino
connected to computer

       Vector3 scaleChange   new Vector3(0.5f, 0.5f, 0.5f);

       public int serialRead;
       public AudioSource audio;
       public AudioClip bell;
       private GameObject pedal;
       //public AudioSource2 source2;
       //public AudioClip bird;

       void Start()
       {
              sp.Open();
              sp.ReadTimeout   1;
       }

       void Update()
       {
              if (sp.IsOpen)
              {
                     try
                     {
               serialRead   sp.ReadByte();
               Debug.Log(serialRead);
                     }
                     catch (System.Exception)
                     {
                     }
              }
       }
}
```

Script 2: Table lamp responding to body temperature

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class Lightbulb : MonoBehaviour
{
    private PedalScale script;
    public AudioSource audio;
    public AudioClip bell;
    public MeshRenderer BlubMaterial;
    public Light BlubLigther;
    private float timer   0.0f;
    private int seconds;
    public int totalTime;
    public List<Color> ColorList   new List<Color>();
    void Start()
    {
        script   GameObject.FindObjectOfType<PedalScale>();
        setLighting(1);
    }

    // Update is called once per frame
    void Update()
    {
        timer += Time.deltaTime;
        seconds   (int)(timer % 60);
        if (seconds >= totalTime) {
            seconds   0;
            timer   0;

            if (script.serialRead    7)
            {
                setLighting(0);
            }
            else if (script.serialRead    6)
            {
                setLighting(1);
            }
            else if (script.serialRead    5)
            {
                setLighting(2);
            }
            if (script.serialRead    8)
            {
                BlubLigther.enabled   false;
                BlubMaterial.materials[0].SetColor("_EmissionColor", Color.white);
                BlubLigther.color   Color.white;
                audio.PlayOneShot(bell);
            }
        }
```

```
    }

    void setLighting(int indeer)
    {
        BlubLigther.enabled   true;
        BlubMaterial.materials[0].SetColor("_EmissionColor", ColorList[indeer]);
        BlubLigther.color   ColorList[indeer];
    }
}
```

Script 3: Table fan responding to GSR arousal

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class Rotation : MonoBehaviour
{
    private PedalScale script;
    private float speed   1000;
    private float timer   0.0f;
    private int seconds;
    public int totalTime;
    public List<int> speeds   new List<int>();
    void Start()
    {
        script   GameObject.FindObjectOfType<PedalScale>();
        speed   speeds[0];
    }
    // 30 second of rotation then listen to the next signal - 3 or 4
    void Update()
    {
        transform.eulerAngles += new Vector3(0,0, speed * Time.deltaTime);
        timer += Time.deltaTime;
        seconds   (int)(timer % 60);
        if (seconds > totalTime)
        {
            seconds   0;
            timer   0;

            if (script.serialRead    3)
            {
                speed   speeds[1];
            }
            else if (script.serialRead    4)
            {
                speed   speeds[0];
            }
        }
```

```
    }
}
```

Script 4: Plant scaling responding to heart status

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class PlantGrowth : MonoBehaviour
{
    private PedalScale script;
    public float maxSize;
    private float timer   0.0f;
    private int seconds;
    public int totalTime;
    public List<float> numbeats   new List<float>();
    [SerializeField]int calculationnum   0;
    public float currentbeat;

    void Start()
    {
        script   GameObject.FindObjectOfType<PedalScale>();
        calculationnum   0;
        StartCoroutine(Scale(numbeats[0]));
    }

    void Update()
    {
        timer += Time.deltaTime;
        seconds   (int)(timer % 60);
        if (seconds >= totalTime)
        {
            calculationnum   0;
            seconds   0;
            timer   0;
            if (script.serialRead    1)
            {
                StopAllCoroutines();
                StartCoroutine(Scale(numbeats[0]));
            }
            else if (script.serialRead    2)
            {
                StopAllCoroutines();
                StartCoroutine(Scale(numbeats[1]));
            }
            else
            {
                StopAllCoroutines();
                transform.localScale   new Vector3(1, 1, 1);
```

```
            }
        }
    }

    IEnumerator Scale(float growFactor)
    {
        float timer   0;
        currentbeat   growFactor;
        while (calculationnum < 1 )
         {
            // Scale all axis to get the same value
            while(maxSize > transform.localScale.x)
             {
                timer += Time.deltaTime;
                transform.localScale += new Vector3(1, 1, 1) * Time.deltaTime * growFactor;
                yield return null;
            }
            // reset timer
            yield return null;

            timer   0;
            while(1 < transform.localScale.x)
             {
                timer += Time.deltaTime;
                transform.localScale    new Vector3(1, 1, 1) * Time.deltaTime * growFactor;
                yield return null;
            }
            timer   0;
            yield return null;
            calculationnum    1;
        }
    }
}
```