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Beyond Functionality: Exploring Interaction, Sensation, and Experience in Assistive Technology Design

A dissertation submitted in partial satisfaction
of the requirements for the degree

Doctor of Philosophy
in
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by

Atieh Taheri

Committee in charge:

Professor Misha Sra, Chair
Professor Nina Miolane
Professor B.S. Manjunath
Professor Tobias Höllerer

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The Dissertation of Atieh Taheri is approved.

Professor Nina Miolane

Professor B.S. Manjunath

Professor Tobias Höllerer

Professor Misha Sra, Committee Chair

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Atieh Taheri

To my family, who loved me unconditionally, supported me tirelessly, and believed in me even when I could not believe in myself.

Acknowledgements

Ten years of of doubt, triumph, and everything in between. A decade of "what ifs" transformed into "eureka!" moments. As I stand at the summit of this PhD journey, I am struck by how the view from here differs from what I had imagined at the start. This journey has been a rollercoaster ride through the corridors of UCSB, punctuated by hospital visits and late-night coding sessions. And yet, here I am, standing at the finish line, marveling at the incredible souls who have been my North Star.

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As I close this chapter, I am acutely aware that this PhD is not just a personal achievement. It is a mosaic of support, a tapestry woven from countless acts of kindness, a symphony of voices that said “yes, you can” when the world seemed to be saying “no, you can’t.” To anyone reading this who is standing at the base of their own mountain, questioning if they have what it takes to climb: take it from someone who has been there - the view from the top is worth every struggle, and the climb itself will transform you in ways you never imagined. Thank you to everyone who has been part of this wild, wonderful, sometimes terrifying, and always inspiring journey. We did it.

Curriculum Vitæ

Atieh Taheri

Education

2024	Ph.D. in Electrical and Computer Engineering (Expected) *University of California, Santa Barbara*
2019	M.Sc. in Electrical and Computer Engineering *University of California, Santa Barbara*
2011	B.Sc. in Computer Engineering *Sharif University of Technology, Tehran*

Work Experience

2022	Ph.D. Student Researcher *Google, Mountain View (Remote)*
2016	Associate *Apple, Cupertino*
2017	Associate *Apple, Cupertino*
2015	Intern *Magic Leap, Mountain View*

Publications

- **Atieh Taheri**[1], Arthur Caetano[1], Misha Sra. "Virtual Steps: The Experience of Walking for a Lifelong Wheelchair User in Virtual Reality." *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR), Orlando, FL, USA, 2024, pp. 168-178,* DOI: 10.1109/VR58804.2024.00040.

- **Atieh Taheri**[2], Carlos Gilberto Gomez-Monroy[2], Vicente Borja, and Misha Sra. "MouseClicker: Exploring Tactile Feedback and Physical Agency for People with Hand Motor Impairments." *ACM Transactions on Accessible Computing (2024), Volume 17, Issue 1, Article No.: 5, pp 1-31,* DOI: 10.1145/3648685.

[1] Joint first-authorship
[2] Joint first-authorship

- **Atieh Taheri**, Purav Bhardwaj, Arthur Caetano, Alice Zhong, Misha Sra. "Virtual Buddy: Redefining Conversational AI Interactions for Individuals with Hand Motor Disabilities." *UIST '23 Adjunct: Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology, Article No.: 23, pp. 1–3, 2023, San Francisco, CA, USA,* DOI: 10.1145/3586182.3616680.

- **Atieh Taheri**, Mohammad Izadi, Gururaj Shriram, Negar Rostamzadeh, Shaun Kane. "Breaking Barriers to Creative Expression: Co-Designing and Implementing an Accessible Text-to-Image Interface." *Machine Learning for Creativity and Design, NeurIPS 2023 Workshop. arXiv preprint,* DOI: 10.48550/arXiv.2309.02402.

- **Atieh Taheri**, Ziv Weissman, Misha Sra. "Design and Evaluation of a Hands-Free Video Game Controller for Individuals with Motor Impairments." *Frontiers in Computer Science 3 (2021), Volume 3, Article 751455, pp 1-15. Frontiers Media SA, 2021,* DOI: 10.3389/fcomp.2021.751455.

- **Atieh Taheri**, Ziv Weissman. "Designing a First Person Shooter Game for Quadriplegics." *CHI EA '21: Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems, Article No.: 493, pp. 1–6, 2021, Yokohama, Japan,* DOI: 10.1145/3411763.3451850.

- **Atieh Taheri**, Ziv Weissman, Misha Sra. "Exploratory Design of a Hands-Free Video Game Controller for a Quadriplegic Individual." *AHs '21: Proceedings of the Augmented Humans International Conference 2021 pp. 131–140, 2021, Rovaniemi, Finland,* DOI: 10.1145/3458709.3458946.

Awards

2024	Presidential Postdoctoral Fellowship
2023	People's Choice Best Poster at UIST '23
2023	UCSB Doctoral Student Travel Grant
2021	First-place Winner of Student Game Competition, Category of Innovative Interfaces at CHI '21
2021	GHC Student Scholarship for Virtual Grace Hopper Celebration
2021	Fellowship for Outstanding Academics at UC Santa Barbara's Electrical and Computer Engineering Department
2014	Graduate Fellowship at UC Santa Barbara's Electrical and Computer Engineering Department
2011	Fellowship of Exceptional Talents at Sharif University of Technology

Abstract

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by

Atieh Taheri

The design of assistive technology has traditionally focused on addressing the functional limitations associated with physical disabilities, often overlooking the holistic experience of using an object, tool, or application. This dissertation introduces a novel conceptual design space for accessible human-computer interaction that expands beyond this utilitarian approach. By integrating interaction, sensation, and user experience, each influenced by the dynamic relationship between user goals and context, this design space offers a comprehensive perspective for creating more inclusive and empowering technologies for people with disabilities, especially motor impairments.

My research contributes to this multidimensional design space through a series of interconnected studies, each contributing to different dimensions while showcasing their interdependencies: 1) On the interaction component, I present a hands-free video game controller based on facial expressions that allows individuals with motor impairments to play independently. This system not only provides users with severe motor impairments a novel input method that accommodates their current level of physical constraint but also enhances the overall gaming experience and social connectivity. I further explore AI-generated virtual companions and text-to-image generation tools, developing accessible interfaces for people with motor impairments through leveraging large language models. I demonstrate how advanced AI can be utilized to create more natural and engaging interfaces, ultimately empowering individuals with motor impairments to express their

creativity in a more natural and effortless manner. 2) For the sensation component, I present a system that provides haptic feedback to simulate clicking a computer mouse for users with severe hand motor impairments. This study demonstrates how sensory feedback can be provided through alternative means, emphasizing the tight coupling between input actions and output responses in creating a sense of agency and control. In fact, this study shows the fundamental reason why holistic inclusion is critical in technology design. Importantly, this research study highlights the fundamental need for holistic inclusion in technology design. 3) The user experience component is exemplified by our study on simulating walking in virtual reality for a lifelong wheelchair user. This work provides crucial insights into designing immersive experiences that align with the mental models and emotional needs of users who have never walked, catering to unfulfilled desires for exploration and freedom of movement. Methodologically, my research is anchored in the domains of human-computer interaction and accessibility studies. I employ an iterative and participatory design process that actively engages diverse stakeholders, including end users with motor impairments and technology designers. My evaluation methods include user experiments, in-depth interviews, and diary studies each tailored to the specific requirements of individual projects.

My holistic design space reveals important synergies and trade-offs across the three components. For example, the choice of interaction method affects the type of experience that can be created, which in turn influences the appropriate sensory feedback. Similarly, focusing on the desired user experience guides decisions about the interaction modality and corresponding sensation design. This dissertation contributes to a more comprehensive understanding of accessible interaction design. By considering interaction, sensation, and user experience as part of an integrated whole, my goal is to open new possibilities for creating technologies that not only overcome physical limitations but also enhance independence, creativity, and quality of life for people with motor impairments.

Contents

Chapter 1

Introduction

In the 21st century, we are experiencing a digital upheaval that has fundamentally transformed the fabric of society. Technology has become ubiquitous, reshaping almost every aspect of our life - from how we acquire information to how we work, how we interact with others, learn and sense our surroundings [1, 2]. From smartphones that serve as pocket-sized computers to the rise of smart home devices that anticipate our needs, digital innovations have penetrated every component and field of our daily life [3].

This technological paradigm shift has brought unprecedented opportunities to many. It has democratized access to information, revolutionized global communication, and opened new avenues for education, employment, and social interaction. The ability to connect instantly with anyone across the globe, access vast repositories of knowledge with a click of a button, or control one's environment through voice commands was once the stuff of science fiction. Today, it is our reality.

However, this rapid digital transformation has also created new challenges and exacerbated existing inequalities. As our world becomes increasingly dependent on digital interfaces and interactions, those who struggle to use standard technologies risk being left behind. This digital divide is particularly pronounced for individuals with disabilities, who may face substantial barriers in accessing and using technologies that many take for granted [4]. The gap between the capabilities of modern technology and the needs of users with diverse abilities has highlighted the critical importance of accessible design and assistive technologies. It raises fundamental questions about inclusivity, equity, and the role of technology in promoting or hindering full participation in society for all individuals [5].

This context sets the stage for my investigation and development of assistive technologies for individuals with motor impairments. As we delve into this field, we must consider not just the functional aspects of technology use, but also its broader implications for quality of life, social inclusion, and personal empowerment.

1.1 Concept of Disability

To address the challenges faced by individuals with disabilities in our technology-driven world, it is essential to understand the evolving concept of disability According to the World Health Organization (WHO)[1], "disability results from the interaction between individuals with a health condition, such as cerebral palsy, Down syndrome and depression, with personal and environmental factors including negative attitudes, inaccessible transportation and public buildings, and limited social support." This definition highlights that disability extends beyond a mere health condition, encompassing a multifaceted interaction between an individual's physical traits and the societal context they inhabit.

Throughout history, the conceptualization of disability has undergone significant shifts. The *Medical Model*, which prevailed for most of the 20th century, conceptualizes disability as an issue inherent to the person, stemming from factors like illness or injury.

[1] http://www.who.int/topics/disabilities/en/

This approach emphasizes the individual's bodily or cognitive restrictions and seeks to "cure" or "fix" these impairments. While this perspective has undoubtedly spurred significant medical progress, it has also drawn criticism for overlooking societal obstacles and potentially marginalizing individuals with disabilities [6, 7, 8], as it clearly views people who have disability as abnormal and it asserts that the skills of medical professionals are necessary to minimize or potentially eliminate this abnormality [9, 10].

In response to the limitations of the medical model, the *Social Model* of disability during the 1970s and 1980s, driven by the disability rights movement [11, 12]. This perspective posits that societal barriers, rather than individual impairments, are the primary cause of disability. It conceptualizes disability as a form of social oppression, involving restrictions on activity and undermining of psycho-emotional well-being for people with impairments [13]. The social model distinguishes between "impairment" as a physical or mental condition and "disability" as the cultural stigma and societal barriers associated with being impaired [14]. It advocates for the removal of these barriers to enhance life choices for people with disabilities and addresses broader societal issues such as poverty, employment, and social exclusion. The social model has played a crucial role in advancing disability rights and inclusive design, though it has faced criticism for potentially minimizing the impact of impairments on individuals' experiences and overlooking the complex interplay between impairment and societal factors.

More recently, the *Biopsychosocial Model* has gained prominence, adopted by the WHO in its International Classification of Functioning, Disability and Health (ICF) [2]. This model combines aspects of both the medical and social models, recognizing disability as an interaction between health conditions and contextual factors, both personal and environmental [15, 16]. By providing a more comprehensive view of disability, the

[2] `https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health`

biopsychosocial model acknowledges the complex interplay of individual and societal factors.

In the context of this dissertation, I align with the biopsychosocial model. This perspective allows us to consider the complex interplay between an individual's physical or cognitive conditions, their personal experiences and attitudes, and the societal and technological environments in which they operate. It emphasizes that our goal in designing assistive technologies is not just to address physical limitations, but to create solutions that enable full participation in all aspects of life, considering the multifaceted nature of disability.

1.2 The History and Evolution of Assistive Technology Design

> "For people without disabilities, technology makes things easier. For people with disabilities, technology makes things possible." - Mary Pat Radabaugh

Mary Pat Radabaugh, who once part of the IBM National Support Center for Persons with Disabilities, stated technology holds significant value in empowering individuals with disabilities (National Council on Disability 1993) [17].

Assistive technology (AT) has a rich history that mirrors the broader narrative of human ingenuity and the quest for improved quality of life. The Technology Related Assistance to Individuals with Disabilities Acts of 1988 (Tech Act) [3] defines an assistive technology device as "any item, piece of equipment, or product system, whether acquired commercially, modified, or customized, that is used to increase, maintain, or improve functional capabilities of individuals with disabilities". The history of AT is as old as hu-

[3] https://www.congress.gov/bill/105th-congress/senate-bill/2432/text

man ingenuity itself, with early examples including prosthetic limbs in ancient Egypt [18] and eyeglasses in medieval Europe [19]. However, the field has seen exponential growth and sophistication in recent decades, paralleling advances in technology at large.

While these technologies have undoubtedly improved the lives of many individuals with motor impairments, the traditional approach to AT design has often been characterized by several limitations. One significant issue is the focus on functionality, where emphasis has often been placed on enabling basic task completion, sometimes at the expense of user experience or efficiency. Designs often prioritize function over form, resulting in devices that look and feel “medical” rather than mainstream [20, 21, 22]. Another drawback is the tendency towards one-size-fits-all solutions. Development has typically involved general-purpose tools that may not adequately address the diverse and specific needs of individuals [23, 24]. Limited integration presents a further challenge, as AT solutions have tended to operate in isolation rather than seamlessly integrate with mainstream technologies.

In recent years, however, there has been a notable shift in AT design philosophy, influenced by broader trends in technology and design thinking. The field of Human-Computer Interaction (HCI) offers valuable insights and methodologies to overcome traditional AT design limitations [25]. HCI is an interdisciplinary area dedicated to the creation, assessment, and deployment of interactive computer systems for human utilization. It emphasizes user-centered design, understanding user needs, abilities, and contexts through methods like ethnographic research, participatory design, and usability testing [26, 27, 28].

HCI’s focus on the entire user experience, considering user satisfaction, emotional engagement, and social acceptability, aligns well with a holistic approach to AT design [29, 30]. Additionally, HCI explores new interaction paradigms like gesture-based interfaces, voice control, and brain-computer interfaces, offering promising, natural interaction methods for individuals with motor impairments.

By integrating HCI principles and methodologies, I created assistive technologies that are functional, intuitive, engaging, and empowering. This integration formed the foundation for the three-dimensional design space proposed in this dissertation, aiming to address traditional AT design limitations and create more effective, satisfying, and inclusive technologies for individuals with disabilities, specifically those with motor impairments.

1.3 Focus on Motor Impairments

Within the extensive spectrum of disabilities, this dissertation focuses on motor impairments. Motor impairments encompass various physical disabilities that hinder an individual's capacity to control and coordinate physical movements [31]. These impairments manifest in various types, severities and origins, including neuromuscular disorders like muscular dystrophy and spinal muscular atrophy, neurological conditions such as cerebral palsy, multiple sclerosis, and Parkinson's disease, as well as spinal cord injuries, strokes, amputations, arthritis, and other joint conditions.

Focusing on motor impairments comes from several crucial considerations:

- Prevalence: Motor impairments affect a significant portion of the global population. According to the WHO, approximately 1.3 billion people, about 16% of the global population, live with some form of severe disability, with a notable percentage experiencing motor impairments. In the United States alone, the Centers for Disease Control and Prevention (CDC) estimates that about 12.1% of adults have mobility disabilities, making it the most common type of disability [4]. This high prevalence highlights the potential impact of advancements in this field, as

[4] https://www.cdc.gov/ncbddd/disabilityandhealth/infographic-disability-impacts-all.html

improvements in assistive technologies could benefit millions of people worldwide. Technological Challenges: Traditional input methods for computers and mobile devices rely heavily on fine motor control, posing substantial barriers to technology use for individuals with motor impairments [32]. Keyboards, mice, touchscreens, and game controllers typically require precise hand and finger movements. These standard interfaces can be inaccessible and frustrating for those with limited motor control, necessitating the development of alternative input methods.

- Potential for Innovation: Assistive technology in the context of motor impairments and digital technology use has focused on several key areas and offers significant opportunities for innovative solutions. Advances in areas such as brain-computer interfaces (BCIs), eye-tracking technology, facial expression recognition, and adaptive input devices hold promise for creating more accessible and intuitive input methods. For instance, BCIs have shown potential in enabling people with significant motor impairments to operate computers and various devices through only their thoughts [33, 34, 35]. Eye-tracking technology has evolved to provide precise cursor control and text input for those who cannot use traditional pointing devices [36, 37, 38]. Advances in machine learning and computer vision are enabling more sophisticated facial expression and gesture recognition systems, opening up new possibilities for hands-free device control [39, 40, 41, 42].

- Diverse Needs: The diversity of needs among individuals with motor impairments necessitates a broad spectrum of solutions. Challenges range from difficulties with fine motor tasks to complete loss of voluntary movement, offering a rich space for exploring various assistive technology designs [43, 44, 45].

- Personal Experience: As a researcher with motor impairments, I bring unique insights and motivations to this work. This personal connection has driven my commitment to advancing the field and improving the lives of others facing similar challenges. It also provides a valuable perspective in understanding the real-world implications of the technologies being developed. My lived experience navigates the gap between theoretical research and practical application, informing the design of more user-centric and effective assistive technologies.

1.4 Personal Motivation: A Journey from Limitation to Innovation

My journey into the field of accessible HCI is deeply personal, rooted in my lived experience as an individual with Spinal Muscular Atrophy (SMA) type 2. Born with this severe genetic motor neuron disease, I have never had the ability to stand or walk. My mobility has always been dependent on wheelchairs, both mechanical and power-operated, with the latter requiring assistance even to place my hand on the joystick.

As a graduate engineering student, my interactions with technology have been both a lifeline and a persistent challenge. With voluntary control limited to my right thumb, I rely on a trackpad for all my computer interactions. This limitation has made tasks that many take for granted - like right-clicking, scrolling, or combining keyboard and mouse inputs - either impossible or dependent on caregiver assistance. Even a simple left-click can become challenging and error-prone when I am tired or my hands are cold.

These daily struggles with technology have been the main motivator for my research. I have experienced firsthand the frustration of being unable to work independently due to interface limitations, the lag in assistive software that slows down my workflow, and the lack of sensory feedback that comes with using adaptive devices. Each of these challenges has fueled my desire to create better solutions not just for myself but for all individuals facing similar barriers.

My experience with virtual reality (VR) development has been particularly informative. While fascinated by its potential, I have been largely unable to engage with VR due to the inaccessibility of its controllers and the fact that 3D development tools like Unity often require the use of both hands. This has given me a unique perspective on VR interaction, highlighting the urgent need for more inclusive design in emerging technologies. Perhaps most poignantly, as someone who has never stood or walked, I have always wondered about these experiences that so many others take for granted. This curiosity has led me to explore how VR might provide new forms of embodiment and mobility for individuals with physical disabilities.

Throughout my research, I have served not only as an investigator, but also as a participant and co-designer. This dual role has allowed me to bring a deeply personal perspective to the work, ensuring that the solutions we develop are grounded in the real needs and experiences of a user with motor impairments and potentially generalizable. By maintaining detailed diaries of my experiences with prototype systems, I have been able to provide rich, nuanced feedback that goes beyond traditional usability metrics to capture the emotional and psychological impacts of assistive technologies.

My journey from a user struggling with technological barriers to a researcher designing solutions has given me a unique vantage point. It has shown me that the most effective assistive technologies are those that consider not just functionality but the entire spectrum of user needs - physical, emotional, and social. This holistic view forms the foundation of the three-dimensional design space proposed in this dissertation.

Ultimately, my goal is to leverage my dual perspective as both researcher and user to bridge the gap between the technical possibilities of assistive technology and the lived realities of users with motor impairments. Through this work, I hope to contribute to the development of technologies that not only overcome physical limitations but also enhance

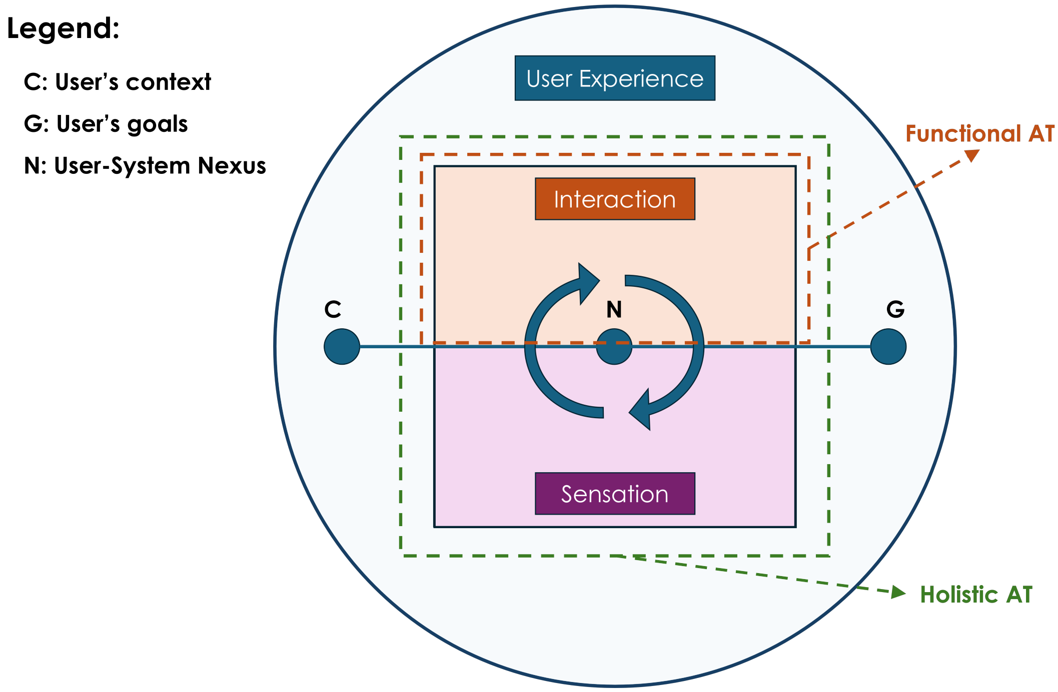


Figure 1.1: The proposed conceptual design space illustrating the dynamic interplay between interaction, sensation, and user experience, all influenced by the user's goals (G) and context (C). The User-System Nexus (N) is central to this model, representing the critical point of interaction where the user and the system meet.

quality of life, promote independence, and empower individuals with motor impairments to fully participate in our digital world.

1.5 A Novel Conceptual Design Space

Building upon the insights from HCI, the limitations of traditional assistive technology design, and my personal experiences, this dissertation proposes a novel conceptual design space for accessible human-computer interaction (Figure 1.1). This design space aims to provide a comprehensive perspective for creating more inclusive and empowering technologies for people with motor impairments. A design space, in the context of HCI, is a conceptual tool that maps out the possible design choices and their implications for a given problem or domain [46]. The proposed design space is structured around three core components - *interaction*, *sensation*, and *user experience* - that are influenced by the user's *goals* (G) and the *context* (C). These components converge at, what I term, the *user-system nexus* (N), a critical point where the user and the system interact. This model recognizes that these components are deeply interconnected and influence one another in complex and dynamic ways. The resulting design space expands our understanding of how users engage with interactive systems, accounting for the nuanced interplay between different aspects of the user experience.

1.5.1 Core Components: Interaction, Sensation, and User Experience

The conceptual design space is built around three core components:

- **Interaction**: Interaction represents the processes by which users engage with technology, including the input methods they use. It is a dynamic, bidirectional process that is constantly informed by the user's sensations and influenced by their goals and context.

- **Sensation**: This component addresses the ways in which users perceive and processes information from their environment and the technology they are interacting with. Sensation is fundamental to interaction, providing the raw data that the user must interpret and respond to.

- **User Experience**: User experience encompasses the emotional, cognitive, and social aspects of technology use. It reflects how the user feels during and after the interaction, including aspects of satisfaction, frustration, engagement, and the sense of agency and control.

1.5.2 The User-System Nexus (N)

At the heart of the proposed conceptual design space lies the user-system nexus (N), which represents the critical interaction point between the user and the system. This nexus is where all the elements of the design space - interaction, sensation, and user experience - converge and influence one another.

The user-system nexus is not just a physical point of interaction, such as a button press or a voice command; it is a dynamic and fluid interface where the user's goals and context come into direct contact with the system's capabilities. The quality of this interaction is crucial, as it determines how effectively the system can respond to the user's needs, how seamlessly it can integrate into the user's context, and how satisfying the overall experience will be. For instance, in a hands-free video game controller, the user-system nexus might be represented by the interface where the user's facial expressions are translated into game controls. The effectiveness of this nexus depends on how accurately and responsively the system can interpret these expressions and how well this interaction aligns with the user's goals and context.

In this dissertation, the user-system nexus serves as a focal point for evaluating and improving the effectiveness, efficiency, and satisfaction of assistive technologies. By understanding and optimizing this nexus, designers and researchers can create more intuitive, responsive, and empowering user experiences.

1.5.3 Situational Factors: Goals and Context

The core components of the design space are framed within two crucial contextual factors:

- **Context (C)**: Context refers to the user's physical, cognitive, and environmental circumstances, including their abilities, limitations, and the surrounding environment. Context shapes how users perceive sensations, interact with technology, and experience the outcomes.

- **Goals (G)**: Goals represent the user's intentions, desires, and objectives when interacting with technology. These can range from basic functional tasks to more complex aspirations like creative expression or social interaction.

In addition to these components, it is important to consider *scale* and *temporality* as two additional elements that significantly influence the design and effectiveness of assistive technologies.

By scale, I refer to the complexity and scope of the interaction that is employed in AT. This element spans a wide range, from simple, discrete actions like button clicks to complex, multi-modal interactions such as facial expressions for input or gesture-based controls. By explicitly considering the scale of interaction, we can ensure that our design space accommodates the full spectrum of potential interaction methods, allowing for more tailored and effective solutions for users with varying degrees of motor impairments. For instance, while a simple click might be appropriate for users with some motor limitations, more complex interaction methods like eye-tracking or brain-computer interfaces could offer enhanced capabilities for users with severe motor limitations or needs. By incorporating scale into our design considerations, we can better match the interaction method to the user's abilities, preferences, and the task at hand.

Temporality, or the time element, is another essential aspect that influences the design and use of ATs. This element considers how interactions and sensations unfold over time, ranging from instantaneous feedback to extended usage, or even long-term adoption and adaptation. Short-term temporality might focus on the immediate feedback and responsiveness of a system, necessary for maintaining user engagement and providing a sense of agency. Long-term temporality, on the other hand, could involve considerations for learning curves, fatigue, and the evolution of user proficiency over multiple sessions. It might address aspects such as the adaptability of the system to changing user needs over time, the integration of the technology into daily life, and the potential for personalization and customization based on extended usage patterns. By considering temporality in our design space, we can create ATs that not only meet immediate user needs but also support sustained, enjoyable, and effective use over time. This approach allows us to design for both immediate usability and long-term user satisfaction and empowerment.

These elements influence how we approach the design of interactions, the choice of sensory feedback mechanisms, and the overall user experience. For example, when designing interaction methods, we must consider both the scale of interaction (from simple to complex) and the temporal aspects (from immediate response to long-term adaptation). Similarly, in designing sensory feedback, we need to account for both the complexity of the sensation and how it evolves over time. The user experience component is particularly directly influenced by temporality, as it encompasses not just immediate satisfaction but also long-term engagement and empowerment. By taking into account scale and temporality as part of our holistic approach, we can create a more comprehensive understanding of AT design. This enhanced approach allows us to better address the diverse and evolving needs of users with motor impairments, leading to more effective, adaptable, and satisfying assistive technologies.

While the ideal goal is to create a holistic experience that combines all design elements, there may be trade-offs between different aspects of design elements. For instance, a quick button click for a one-time task may not necessitate the need for haptic feedback, prioritizing simplicity and speed of execution, whereas the same button click for prolonged use may benefit from enhanced feedback with haptic sensation as its absence may lead to reduced engagement or even user fatigue over time. Here, the trade-off lies in balancing the immediate efficiency of the interaction against the potential benefits of enhanced sensory feedback, which could improve the long-term user experience.

These trade-offs can also go beyond individual elements, affecting how they interact with each other. For example, incorporating complex sensory feedback mechanisms might enhance the user's sensation and overall experience, but it could also increase cognitive load or the time required to perform an interaction. In scenarios where users need to make quick decisions or perform rapid actions, such as in a gaming context, the trade-off might involve simplifying interactions at the expense of rich sensory feedback to maintain responsiveness and flow.

1.5.4 Holistic Approach to Assistive Technology Design

The proposed design space advocates for a holistic approach to assistive technology design, one that considers the intricate relationships between interaction, sensation, and user experience, and their dynamic interplay within the scope of the user's goals and context. This approach moves beyond merely functional assistive technologies towards solutions that are deeply satisfying, empowering, and inclusive.

By addressing these three core components and their interdependencies, this conceptual design space encourages designers and researchers to consider not just how a user will interact with technology, but how the entire experience will be perceived, including the emotional and psychological impacts. This holistic perspective is crucial for creating assistive technologies that truly meet the needs of users with motor impairments, enhancing their quality of life and enabling full participation in society.

1.6 Research Objectives and Questions

The primary objective of this research is to explore and validate the proposed conceptual design space for accessible human-computer interaction. Through a series of interconnected studies and prototype systems, this dissertation aims to demonstrate how this holistic approach can lead to more effective, engaging, and empowering assistive technologies for individuals with motor impairments.

My exploration begins with investigating the core components of the design space, i.e., interaction, sensation, and user experience, and how they dynamically interact within the broader scope of user's goals and user's context. This approach seeks to understand the nuances of each component and their interdependencies, paving the way for more sophisticated and user-centered design strategies.

Beyond mere functionality, I strive to craft user experiences that are both impactful and pleasant. This means understanding the emotional and social dimensions of technology use for individuals with motor impairments. By incorporating these insights into our designs, we can transform assistive technologies into gateways for connection, expression, and fulfillment.

My journey continues with the exploration of innovative output modalities. My aim has been to enhance user agency using digital devices through carefully designed feedback mechanisms and information presentation. By tailoring these elements to support individual goals, we can empower users to confidently and independently navigate the digital world.

Finally, the intricate dance between input methods, user experience, and output modalities will be examined. Recognizing that these dimensions are interconnected, it is important to understand how choices in one area can ripple through the others, ultimately shaping the overall effectiveness of assistive technology. This holistic perspective will be a guide towards a future where technology smoothly integrates into the lives of individuals with motor impairments, enriching their experiences and expanding their horizons.

To guide this research and address these objectives, several key questions will be raised:

1. How can we design interactions that are both accessible and engaging for users with severe motor impairments? This question explores the balance between functionality and the richness of interaction, considering factors such as ease of use, customizability, adaptability, and the potential for conveying different levels of intent or expression even with limited motor control.

2. How can we enhance the user's perception and sensation when using assistive technologies? This question explores the role of sensation and feedback in shaping user experience, investigating how different sensory modalities can support user's goals and improve their sense of agency.

3. What design principles can guide the creation of engaging and meaningful user experiences that are both functional and fulfilling for individuals with motor impairments? This question delves into the emotional and social aspects of technology use, seeking to understand what makes an interaction not just functionally effective, but also truly satisfying and empowering for this group of users.

4. What are the synergies and trade-offs between interaction, sensation, user experience in assistive technology design? This question examines the interconnections between the core components of our design space, seeking to understand how decisions in one area influence the others and the overall effectiveness of the technology.

By addressing these questions, this research aims to contribute to a more comprehensive understanding of accessible interaction design and provide practical guidelines for creating more inclusive and empowering technologies. The answers we uncover will not only validate the proposed design space but also offer valuable insights for researchers, designers, and developers working in the field of assistive technology.

1.7 Methodological Overview

The research presented in this dissertation employs a mixed-method approach that combines qualitative and quantitative techniques to explore and validate the proposed conceptual design space for accessible human-computer interaction. The methodology is grounded in the principles of user-centered design and participatory research, recognizing the crucial importance of involving individuals with motor impairments throughout the research process [47, 48, 49].

Each study within this dissertation follows an iterative design cycle:

- **Exploratory Studies**: Initial research to understand user needs and contexts, heavily informed by my personal experiences as a user and researcher with motor impairments.

- **Ideation and Prototyping**: Development of early design concepts and low-fidelity prototypes, where I could directly test and provide feedback on early designs.

- **User Testing**: Rigorous testing by involving other users, in some cases individuals with motor impairments, to evaluate usability and satisfaction.

- **Refinement and Development**: Iterative improvement of prototypes based on user feedback, focusing on both functionality and user experience.

- **Longitudinal Studies**: Assessment of the long-term impact and integration of the developed assistive technologies in the daily lives of users.

By maintaining a reflexive stance and adhering to ethical standards, this comprehensive approach ensures that the findings are robust, reliable, and practically applicable.

This methodology aims to generate insights that advance the field of accessible technology design, which can ultimately lead to more effective, satisfying, and empowering assistive technologies.

1.8 Dissertation Overview

The journey through this dissertation explores the intricate landscape of accessible human-computer interaction, guided by the proposed conceptual design space. This dissertation aims to bridge the gap between the technical possibilities of assistive technology and the lived experiences of individuals with motor impairments. By integrating insights from HCI and accessibility studies, this work seeks to advance the design of more effective, engaging, and empowering assistive technologies.

This dissertation is structured to systematically explore and validate the proposed conceptual design space for accessible HCI. Each chapter builds upon the previous ones, collectively demonstrating the value and potential of this holistic approach to assistive technology design.

Chapter 1: Introduction This current chapter sets the stage for the dissertation. It provides context for the research, defines key concepts, outlines the research objectives and questions, and describes the methodological overview. It introduces the novel conceptual design space and explains its potential significance for the field of assistive technology.

Chapter 2: The Conceptual Design Space Here, I present a detailed explanation of the proposed design space, its theoretical foundations, and how it extends beyond traditional approaches to assistive technology design. Each component - interaction, sensation, and user experience - will be introduced, along with discussions of their individual roles and their interrelationships within the broader scope of user goals and user context. This chapter serves as the conceptual core of the dissertation and provides guidelines for the subsequent empirical chapters.

Chapter 3: Interaction This chapter focuses on the Interaction component of the proposed design space, exemplified through the implementation of three projects: 1) a hands-free video game controller using facial expression recognition (2021), 2) a Virtual Buddy (2023) that is a redefined conversational AI interactions tool, and 3) PromptAssist (2023) that is an accessible text-to-image interface.

Chapter 4: Sensation This chapter explores new ways of providing feedback and conveying information to users with motor impairments. The chapter features a detailed discussion of MouseClicker (2024), which provides haptic feedback to simulate mouse clicks for users with severe hand motor impairments who cannot use the conventional computer mouse. This case study illustrates how augmenting output modalities can enhance users' sense of agency and the overall user experience.

Chapter 5: User Experience Addressing the user experience component, this chapter explores how emotional, cognitive, and social factors influence the interaction with assistive technologies. It includes Virtual Steps (2024), a case study of a virtual reality walking simulation designed for lifelong wheelchair users. Through this example, I demonstrate how thoughtful design can address unfulfilled desires of individuals with motor impairments for exploration and freedom of movement through virtual reality.

Chapter 6: Conclusion This chapter synthesizes the findings from the previous chapters, discussing the implications of my research for assistive technology design. Finally, some final thoughts conclude the chapter.

Through this structure, I aim to provide a comprehensive exploration of the proposed conceptual design space, demonstrating its potential to revolutionize the design of assistive technologies for individuals with motor impairments.

1.9 Key Contributions

This dissertation makes several significant contributions to the field of accessible HCI and assistive technology design. These contributions span theoretical, methodological, and practical domains, collectively advancing our understanding of how to design more effective, engaging, and empowering technologies for individuals with motor impairments.

My primary contribution is the development and validation of a novel conceptual design space for accessible HCI. This holistic framework, integrating interaction, sensation, and user experience, and their relationship to the user's context and user's goals, provides a comprehensive approach to creating more inclusive and empowering technologies. By encouraging designers and researchers to consider these components simultaneously, a new paradigm for assistive technology design is offered that goes beyond mere functionality to address the full spectrum of user needs and experiences.

This research, in the first step, introduces innovative interaction techniques for individuals with severe motor impairments. The facial expression recognition system enabling hands-free video game control, the conversational AI system, and the text-to-image interface based on LLM (large language models) discussed in Chapter 3 illustrate how the spectrum of interaction methods can be broadened for users unable to utilize conventional input devices. This contribution not only demonstrates technical innovation but also showcases how novel input methods can enhance user agency and engagement. My work also highlights the importance of the sensation component, such as the haptic feedback augmentation system presented in Chapter 4. It contributes by demonstrating how innovative feedback mechanisms, including haptic feedback systems, can enhance user's perception and sensation of agency in digital environments and ultimately can significantly impact user experience. My work continues to design engaging user experiences, as illustrated by the virtual reality walking simulation for lifelong wheelchair users in Chapter 5, demonstrates how assistive technologies can address deeper needs for exploration and embodiment. This contribution highlights the potential for assistive technologies to not only overcome physical limitations but also to provide meaningful, emotionally resonant experiences that enhance quality of life.

Lastly, through rigorous evaluation of multiple prototype systems, this research contributes valuable empirical data on the effectiveness and user acceptance of novel assistive technologies. These findings not only validate my proposed design space but also offer substantial data resources to future researchers and designers in the field.

Collectively, these contributions advance our understanding of how to design more effective, engaging, and empowering technologies for individuals with motor impairments. By demonstrating the value of a holistic, multidimensional approach to assistive technology design, this research lays the groundwork for future innovations in this critical field. My work aims to inspire a new generation of assistive technologies that not only overcome physical limitations but also enhance independence, creativity, and quality of life for individuals with motor impairments.

Chapter 2

The Conceptual Design Space

This chapter presents the theoretical foundations and detailed exploration of the proposed conceptual design space for accessible human-computer interaction. The design space includes three key components: interaction, sensation, and user experience. Each component is discussed in terms of its relevance, existing technologies, and the theoretical underpinnings that inform our approach. Central to this design space is the user-system Nexus, where the user's goals and context dynamically interact with the system's capabilities.

2.1 Introduction to the Design Space

The conceptual design space proposed in this dissertation aims to provide a comprehensive tool for creating more inclusive and empowering technologies for individuals with motor impairments. This design space encompasses three critical components: 1) interaction, 2) sensation, and 3) user experience. Each of these components is crucial for comprehending and enhancing the interactions between users and technology, particularly for those with motor impairments. The effective integration of these components at the user-system Nexus is vital for delivering a seamless and empowering experience tailored to the user's goals and context.

2.1.1 Conceptual Foundation

The conceptual foundation of this design space draws from various fields, including HCI, assistive technology, and cognitive psychology. By integrating insights from these disciplines, and by deeply considering the user's goals and context, we can develop a holistic understanding of how to design technologies that not only meet functional needs but also enhance user satisfaction, emotional engagement, and social inclusion. The point where these interdisciplinary insights converge ensures that the technology aligns with the user's intentions and circumstances.

2.1.2 Relevance to Assistive Technology

In the context of assistive technology, the proposed design space provides a structured way to explore, analyze, and compare different design alternatives. It encourages designers and researchers to consider the full spectrum of user needs and experiences, from physical interactions to emotional and social aspects. This approach is particularly relevant for individuals with motor impairments, who often face significant barriers in using conventional technologies.

2.2 Interaction Component

The first component of the proposed design space focuses on innovative interaction methods. In this dissertation, these methods are exemplified in three main projects: a hands-free video game input controller using facial expression recognition, conversational

AI systems based on LLMs, and a text-to-image interface also based on LLMs.

2.2.1 Hands-free Video Game Controller

For people with severe motor impairments, various methods can facilitate unassisted video game play. Assistive devices for users with motor impairments encompass a variety of systems, including eye-tracking systems [50], camera-based interaction systems [51, 52], speech and sound recognition systems [53, 54, 55], tongue and breath-based systems [56, 57], mouth controllers [58], switch-based systems [59], and EEG/EMG-based systems [60, 61], trackballs and joysticks [62]. Among these assistive technologies, several have also been utilized for the purpose of controlling video games. Many of these technologies rely on signals from body parts like the tongue, brain, or muscles that the user can voluntarily control. Each has its own advantages and limitations.

Growing up with a passion for video games, I often found myself frustrated by the limitations imposed by my motor impairment. Traditional controllers were simply not an option, and while many assistive technologies existed, they often felt cumbersome or inadequate for the fast-paced nature of gaming. This personal struggle inspired me to seek out a better solution, one that would offer the same excitement and fluidity that others experienced.

Our proposed webcam-based input method addresses some of these limitations by enabling fast and easy gameplay, allowing complex macros (e.g., jump + turn left) to be mapped to a single facial expression, and offering customizable mapping of expressions to game actions. This system utilizes a webcam and eliminates the need for users to wear any sensors, trackers, or devices.

Prior to this project, there had been no investigation or evaluation of facial expression recognition using both quantitative and subjective data specifically in the context of game interaction for individuals with motor impairments. This lack of research underscored the importance of our work and motivated us to conduct a thorough evaluation, combining performance metrics with user feedback to refine and enhance the system further.

Through this project, we demonstrated that facial expression recognition could be a powerful tool for creating more inclusive gaming experiences. By leveraging the unique capabilities of modern computer vision technologies, we provided a new avenue for individuals with motor impairments to engage in activities they love, promoting both independence and enjoyment. The interaction component in this context plays a crucial role in optimizing the nexus, where the user's inputs are effectively translated into game actions, aligned with their goals and gaming context.

2.2.2 Conversational AI Systems

Conversational AI systems, including virtual assistants and chatbots, have evolved significantly [63, 64, 65]. These systems can interact with users through natural language, providing assistance with various tasks. Our development of the Virtual Buddy (V-Buddy) system represents a significant leap forward in making conversational AI more accessible for individuals with motor impairments. V-Buddy allows users to create multiple agent personas based on their hobbies and interests, supporting topic-based conversations. This approach contrasts with existing systems like Replika [66], which offer a one-to-one relationship with a virtual agent.

The motivation for focusing on this aspect originates from my own experiences as an individual living with SMA. Operation with digital systems, including conversational AI platforms, with limited hand-motor control has always been challenging for me. The need for constant data input made existing systems quickly unusable. This inspired the creation of Virtual Buddy, which minimizes user input by allowing the creation of multiple personas through pre-filled templates with easy-to-select options. This system employs LLMs such as GPT-4 [67] to simulate intelligent and human-like conversations. The system allows users to create several virtual personas, each with distinct roles and personalities, facilitating one-to-many interactions. For example, a user can have different virtual buddies for various purposes, such as a tutor for learning a new language or a companion for casual conversation.

In this interaction component, the focus is on aligning the system's conversational capabilities with the user's goals and context, ensuring that the user-system connection is both intuitive and responsive.

2.2.3 Accessible Text-to-Image Interface

The third innovative interaction method in my proposed design space is an LLM-based interface, known as PromptAssist. Recent breakthroughs in text-to-image (T2I) models have empowered users to generate high-quality and stylistically varied images from textual inputs [68, 69, 70, 71]. PromptAssist is a web-based application enabling users to create T2I prompts using a combination of keyboard and mouse input. PromptAssist uses a LLM to suggest prompts based on whatever the user has input.

Creating PromptAssist was a deeply personal endeavor. As someone who has struggled with traditional methods of art creation, the ability to generate images through text opened up new possibilities for self-expression. Seeing others benefit from this technology reinforced my commitment to developing inclusive tools that empower individuals with disabilities. Through this project, it was demonstrated that text-to-image interfaces could bridge significant gaps in accessibility. By leveraging the capabilities of LLMs, a powerful tool was provided that enables users to create and share visual art, fostering a sense of achievement and connection.

In the context of the interaction component, PromptAssist enhances the connection between the user and the system by providing a platform where the user's creative goals can be realized, adapting to their context and abilities.

2.3 Sensation Component

The second component of the proposed design space focuses on innovative sensation methods, with a particular emphasis on enhancing user perception and sense of agency for users with motor impairments. This component includes various methods for conveying information and feedback to users in a way that is both intuitive and immersive. Here, the sensation component is crucial in enhancing the connection between the user and the system by making sure that the feedback aligns with the user's goals and situational context.

2.3.1 MouseClicker with Haptic Feedback

One of the key projects in this component is the development of a MouseClicker that offers haptic feedback to recreate the experience of using a conventional mouse for individuals who cannot use these types of computer mice. This device grants physical agency over a computer mouse and mimics the tactile feeling of clicking on it. The preliminary approach to recreating the experience of the computer mouse relied on previous methods that highlight the significance of direct interaction in the design phase [72, 73, 74]. These methods propose that direct interaction is typically valuable as it facilitates more efficient and comfortable usage.

Having to use assistive technologies for computer interaction, creating MouseClicker was very significant to me. I personally know the challenges of a standard mouse and the aggravation of insufficient feedback from almost all adaptive devices that are usable for me. The success of the MouseClicker project highlighted the necessity of integrating sensory feedback in assistive technology design.

The tactile feedback feature, illustrated by MouseClicker, augments the user-system nexus, thereby boosting the user's perception of control and immersion, which are crucial for efficient interaction.

2.4 User Experience Component

The third component of the proposed design space focuses on creating engaging and meaningful user experiences. I particularly discuss it through the use of a VR application. This component emphasizes the emotional, cognitive, and social aspects of the use of technology, with the aim of improving the quality of life for people with motor impairments.

2.4.1 The Experience of Walking for Lifelong Wheelchair Users

Walking is not just a way to get around; it enables freedom, adventure, and autonomy. However, some conditions, such as SMA (which I have), can make it impossible for people to walk from birth. This lifelong experience of immobility has fueled my curiosity and desire to explore what walking might feel like, even if only in a virtual environment.

Walking produces a range of sensory stimuli [75, 76, 77, 78]. Emulating these sensations is a complex task that has been the target of extensive research, especially using virtual reality [79, 80, 81, 82].

However, earlier, VR walking experiences predominantly aimed at replicating the experience of individuals who could walk or who had been able to walk at some stages in their lives. This emphasis does not always match the preferences of users who have never had the ability to stand or walk. The VR Steps project was born out of this gap, driven by my personal motivation and the recognition that many individuals with congenital mobility impairments share similar unfulfilled desires for exploration and movement.

This project illustrates how the user experience component can enhance the user-system interaction by aligning technology use with the user's goals and context, providing immersive experiences that resonate deeply on an emotional and cognitive level.

2.5 The User-System Nexus in Practice

The user-system nexus, as the critical interaction point between the user and the system, plays a vital role in shaping the effectiveness of our assistive technologies. In the context of my design space, the nexus serves as a focal point for evaluating and refining the interaction between core components. For example, in the hands-free video game controller, the nexus informs how we balance the complexity of facial expression recognition with the need for responsive game control. For the Virtual Buddy system, the nexus guides the design of conversational flows, ensuring that the AI's responses align closely with user intentions and context. In the MouseClicker project, the nexus helps us fine-tune the relationship between physical action, digital input, and haptic feedback to create a cohesive experience.

2.6 Situational Factors: Informing Design Decisions

The user's goals and context serve as guiding principles in my proposed design process. Context, in particular, plays a significant role in shaping design decisions, referring to the various external and internal factors that influence how users interact with a system. These factors include environmental conditions, the user's immediate goals, physical and cognitive states, and the specific tasks they are engaged in. In fact, it acts as a modulating factor that can shift the emphasis within the design space. By treating it as an important aspect of the design space, we can make more informed decisions about when and how to emphasize different components, be it interaction, sensation, or user experience.

Recognizing the dynamic role of context in shaping design decisions is essential. It influences priorities, constraints, and opportunities in design. Context can prioritize certain aspects of the design, such as in a gaming environment, the user's immediate need may prioritize interaction for real-time responsiveness, whereas in a virtual reality experience focused on sensation, user experience may take precedence. The constraints imposed by context guide design choices as well. Environmental factors such as lighting conditions or noise levels, for example, can significantly impact the effectiveness of interaction methods. Similarly, the physical and emotional state of the user can influence how sensory feedback is perceived or how user experiences are designed. By acknowledging these constraints, designers can create solutions that are not only innovative but also grounded in the practical realities of everyday use. At the same time, context presents unique opportunities to enhance the user experience. For instance, a virtual reality system could adjust its feedback mechanisms based on the user's level of immersion, or a conversational AI could tailor its responses based on the user's mood. These examples illustrate how context can be leveraged to create more engaging, effective, and satisfying interactions.

2.7 Scale and Temporality: Additional Elements of Design Space

In addition to the core components and situational factors discussed above, my conceptual design space incorporates two essential elements that further enhance our understanding and approach to AT design: scale and temporality.

Scale in my design space refers to the complexity and scope of interactions, sensations, and experiences. It allows us to create a spectrum of solutions that can adapt to various user needs and preferences. On the simpler end of the scale, we have basic, discrete interactions, such as clicking a mouse. On the more complex end, we encounter sophisticated, multi-modal interactions, exemplified by the facial expression-based input system, Virtual Buddy, or the PromptAssist project. Considering scale allows us to design technologies that can grow with the user, adapting to changing needs and abilities over time.

Temporality adds a time dimension to my design space, encouraging us to consider how interactions and experiences evolve. In the short-term, it emphasizes the importance of immediate feedback and responsiveness, which are crucial for maintaining engagement and user agency. Over the medium-term, the focus shifts to managing learning curves and fatigue, as well as accommodating the evolution of user proficiency over multiple sessions. In the long-term, temporality involves designing for system adaptability, integration into daily life, and personalization based on extended usage. By incorporating temporality, we ensure that our assistive technologies remain effective and satisfying not just in the moment, but over extended periods of use.

2.8 Integration and Synergies

These additional elements - the user-system nexus, situational factors, scale, and temporality - create new connections within our design space. The nexus point can adapt based on the scale of interaction and temporal context, ensuring that the user-system connection remains optimal regardless of complexity or duration of use. Situational factors inform how we approach scale and temporality, allowing us to create technologies that are responsive to both immediate needs and long-term goals. Scale and temporality together allow for the design of adaptive systems that can grow and change with the user over time, always aligned with their evolving goals and contexts.

By combining these elements, we create a more dynamic and responsive approach to assistive technology design, capable of addressing the diverse and changing needs of users with motor impairments.

2.9 Conclusion

The conceptual design space presented in this chapter provides a comprehensive framework for creating more inclusive and empowering technologies for individuals with motor impairments. This holistic approach recognizes that effective assistive technology must address the full spectrum of user needs, from physical interaction to emotional engagement and sensory feedback.

At the core of this design space are the three primary components: interaction, sensation, and user experience. These components form the foundation on which we build our understanding of how users engage with assistive technologies. By simultaneously considering these components, designers and researchers can develop assistive technologies that go beyond basic functionality.

Interaction methods such as facial expression recognition, conversational AI, and accessible text-to-image interfaces offer new avenues for users to engage with digital environments, tailoring experiences to their unique capabilities and preferences. These techniques enable users to engage with technology in a way that feels comfortable and instinctive, reducing physical obstacles and improving accessibility. The sensation component as exemplified by MouseClicker with haptic feedback underscores the critical role of sensory feedback in user interaction. Tactile sensations provide users with important cues and a sense of physical agency, making digital interactions more engaging and effective. This component ensures that users receive the necessary feedback to navigate and control their digital environments confidently, bridging the gap between physical and virtual experiences. The emphasis on user experience highlights the importance of creating technologies that are both practical and pleasurable, as well as having a sense of purpose. Projects like Virtual Steps demonstrate how immersive experiences can provide users with new forms of exploration and movement, addressing unfulfilled desires and enhancing quality of life. By focusing on the emotional and cognitive aspects of technology use, we can create experiences that resonate deeply with users, offering them a sense of agency and satisfaction.

The integrated approach of the conceptual design space fosters innovation by encouraging the exploration of synergies between these components. For example, combining facial expression recognition with haptic feedback can create a more immersive and responsive gaming experience, while integrating conversational AI with personalized user experiences can enhance the relevance and effectiveness of assistive technologies. This cross-dimensional perspective promotes the development of technologies that are adaptable, customizable, and deeply attuned to the needs of users with motor impairments.

Building upon these core components, I introduced the concept of the user-system nexus, which represents the critical point of interaction between the user and the system. This nexus serves as a focal point for evaluating and refining the effectiveness of ATs, ensuring that user needs and system capabilities are optimally aligned.

Furthermore, I explored the role of situational factors - specifically, the user's goals and context - in shaping the design and implementation of assistive technologies. Taking these aspects into account allows us to develop solutions that are both effective and highly pertinent to the user's conditions, goals, and surrounding environment.

The introduction of scale and temporality as additional dimensions of our design space adds further depth to the approach to AT design. Scale allows us to consider the complexity and scope of interactions, enabling the development of technologies that can adapt to varying user abilities and preferences. Temporality, on the other hand, encourages us to design for both immediate usability and long-term engagement, ensuring that our technologies remain effective and satisfying over extended periods of use.

By integrating all these elements - core components, user-system nexus, situational factors, scale, and temporality - we create a robust and flexible approach for AT design. This holistic approach allows us to address the diverse and evolving needs of users with motor impairments more effectively than ever before. By adopting this holistic method, we can develop technologies that enable individuals with motor impairments. These technologies will enable users to engage with the digital world on their terms, offering them the tools they need to live fuller, more autonomous lives. Through this comprehensive design space, my aim is to inspire a new generation of ATs that not only overcome physical limitations but also improve independence, creativity, and quality of life. The research presented in this dissertation demonstrates the potential of the conceptual design space to transform the landscape of accessible human-computer interaction, providing a robust foundation for future innovations.

As we move forward, it is essential to continue refining and expanding this design space, incorporating emerging technologies and insights to ensure that assistive technologies remain at the forefront of accessibility and user-centered design.

Chapter 3

Interaction

In this chapter, I delve into the first component of my proposed conceptual design space: interaction. Interaction is fundamental to the way users engage with digital systems. Particularly in the context of accessibility for individuals with motor impairments it is crucial for the interaction methods to cater to their diverse needs to create accessible technologies. In this chapter, I explore three distinct interaction methods developed during my research: a hands-free video game controller using facial expression recognition, conversational AI systems based on LLMs, and a text-to-image interface also based on LLMs. Each section provides an in-depth analysis of the development process, user evaluation, and the implications of these technologies.

3.1 Introduction

Interaction methods are the core mechanisms by which users communicate their intentions to digital systems. Traditionally, these methods include devices like keyboards, mice, and touchscreens, which allow users to enter text, select items, and navigate interfaces. These conventional approaches are designed for individuals with typical motor abilities, offering precise control and responsiveness. However, as technology evolves and diversifies, so too do the ways in which it is utilized. The advent of new input technologies is expanding the possibilities that a person can interact with technology. These advances are not only improving user experience, but also increasing the accessibility of digital systems for a wider audience. By exploring and developing alternative input methods, we can create more inclusive technologies that accommodate the diverse abilities and requirements of all users.

The motivation for exploring these input methods is rooted in the recognition that traditional approaches are insufficient for many users with severe motor impairments. By leveraging advancements in computer vision, natural language processing, and machine learning, we can develop systems that accommodate diverse abilities and preferences. These technologies not only facilitate basic interactions, but also enrich the overall user experience by providing intuitive and engaging ways to control and communicate with digital environments.

3.2 Related Work

In recent years, AT researchers have explored computer input devices extensively, to help individuals with mobility impairment due to diseases including spinal muscular atrophy (SMA), quadriplegia, muscular dystrophy (MD), locked-in syndrome, amyotrophic lateral sclerosis (ALS), multiple sclerosis (MS), cerebral palsy (CP), and spinal cord injuries [83]. The main challenge to design and build assistive computer-human interfaces is that the proposed devices need to accommodate the special needs of the target individual. The design of an AT device necessitates maximizing information flow while simultaneously minimizing the physical and mental effort of the end user [84]. Consequently, the majority of current AT techniques for people with motor impairments rely on the collection of signals from different parts of the body, such as the tongue, brain, or muscles which are often under the individual's voluntary control.

3.2.1 Assistive Input Techniques for Individuals with Motor Impairments

There is a need for hands-free input devices for users with severe hand motor impairments. Brain-Computer Interfaces (BCIs), eye tracking, tongue-based interfaces, and voice input have been explored in prior work. BCIs have been used for brain-to-text communication [85] and hands-free wheelchair control [86] have enabled interaction with computers and movement without assistance, empowering individuals with paralysis or motor impairments. There are two main types of BCI systems: 1) non-invasive approaches that predominantly use electroencephalography (EEG) data, which is analyzed and deciphered using signal processing and machine learning methods [87, 88, 89, 90], and 2) invasive methods that involve brain surgery to implant an electronic port physically connected to the brain anatomy. However, invasive BCI techniques are usually inaccessible outside of research labs [91]. Recent research has shown significant advances in BCI. For example, a novel hybrid EEG-based BCI system that merges motor imagery with P300 signals has been developed for efficient 2D cursor movement and target selection [92]. Another framework utilizes EEG signals to control operating system functionalities [93]. Performance comparison of a non-invasive P300-based BCI mouse to a head-mouse for people with spinal cord injuries revealed that the P300-BCI mouse offered a promising alternative for users with severe motor impairments, showing potential for everyday use [93]. There is also a growing number of EEG-enabled BCI devices for consumers. Emotiv[1], Advanced Brain Monitoring[2], and Muse[3] are some commercial devices that allow integration of various brain signals into a single headset for use in daily life, even though the limitations preclude continuous wearing for extended periods of time necessary for interaction with computers. Despite extensive research in BCIs for over four decades, most BCI devices are limited in their use because of challenges related to EEG signals being highly susceptible to noise both from the user and their environment.

Voice input has been the subject of considerable research and development as a hands-free input technique. For voice-based interaction, sounds are converted into digital instructions [94, 95, 54, 96, 97], whether they are speech or non-speech sounds (e.g., such as whistling, humming, or hissing) [98, 99]. Most speech-based methods have been trained on speech by native speakers of a language, making it challenging for the system to recognize accented speech [100, 101]. Notable advancements include the Voice Controlled Mouse Pointer (VCMP), which uses voice commands for cursor movement and operating system functions, offering accessibility for people with disabilities without requiring a user's voice database [102]. Another innovation is a voice-controlled cursor for point-and-click tasks using non-verbal sounds, demonstrating higher accuracy and user preference over traditional spoken digit recognition methods [103]. A recent technique combining eye tracking and voice recognition enables laptop operation for those with physical challenges, using cameras for eye movement tracking and converting speech into commands [104]. These developments illustrate the ongoing progress in voice-based input technologies, enhancing the interaction experience for users with various needs. However, in order for either of these voice-based methods to be effective, a relatively quiet environment is often necessary, since ambient noise can have an undesired impact on their performance, though that is improving with ambient noise canceling methods. In individuals with neu-

[1] Emotiv: `https://www.emotiv.com/`.
[2] Advanced Brain Monitoring: `https://www.advancedbrainmonitoring.com/`.
[3] Muse: `https://choosemuse.com/`.

romuscular diseases, speech clarity can be significantly affected by compromised tongue muscle function, influencing the usage of voice-based systems [105]. Additionally, these systems may struggle to reliably recognize varying accents, potentially leading to user frustration.

Eye gaze tracking has been extensively explored as an input modality. An eye gaze tracking system works by detecting, tracing, and mapping the movements of the user's eyes to the controls on a computer screen, first demonstrated by Jacob et al. [106] in 1991. Following their work, AT experts have studied eye gaze tracking in more detail to minimize the errors associated with this kind of method and increase performance [107, 108, 109, 110]. It has been noted that using this type of interaction method over a prolonged period of time can cause headaches [111]. The slower speed of input, lower accuracy, and the need to wear a device, all make it challenging for prolonged use as a primary input method.

Another area of exploration has been Tongue-Computer Interfaces (TCIs). TCIs use sensors mounted on the tongue to measure movement and pressure [112]. These types of systems have been used to help perform various tasks. For instance, the Tongue-Drive System (TDS), capable of generating 9 distinct signals [113], has been used for operating computers [114], managing a hand exoskeleton with one degree of movement control [115], and controlling a power wheelchair [116]. The Inductive Tongue-Computer Interface (ITCI), which Struijk initially introduced [117], offers 18 command signals [118]. It has been employed as a control interface for multiple applications. The Itongue®[4], a commercial variant of the ITCI, enables users to operate personal computers and power wheelchairs. ITCI's performance has been tested on the individuals with and without disabilities through various tasks such as typing [119, 120] cursor control on a computer [120, 121], and managing an assistive robotic arm [118, 122]. A significant drawback

[4]Itongue®: https://tks-technology.dk/produkter/#itongue

of these sensors is their placement in the mouth which can cause fatigue and discomfort from extended use.

In addition to these technologies, another area that complements the spectrum of hands-free input methods is the development of head-controlled systems and Camera Mouse technology. These innovations specifically target individuals who, while capable of head movement, face challenges with hand-based interactions, thereby broadening the range of ATs available for diverse motor impairments. Head-controlled systems generally use a piece of equipment, like a transmitter or reflector, attached to the user's head, designed to interpret the user's head movements and map them into the cursor's movements on a computer screen [123, 124]. An additional switch often substitutes for the mouse button. The Camera Mouse uses a front-facing camera without the need for head attachments [51, 125]. It tracks head movements via computer vision, translating them into on-screen cursor movements. Mouse clicks are enabled through a dwell-time-based customizable process. As stated earlier, these systems require users to have full control over their head's movements, thus, those who are unable to stabilize and control head movements may find it challenging or impossible to effectively use these systems [126].

The diverse range of hands-free input technologies, from BCIs to head-controlled systems, have expanded interaction options, including alternatives to computer mice, for individuals with severe motor impairments. However, there remains a need for more conventional yet adapted input devices. These devices can cater to individuals whose hand impairments may not be severe enough to require entirely hands-free solutions but who still face challenges with standard input methods. For example, trackballs as an alternative to computer mice offer ease of use for those who have difficulty with wrist movements or grasping. They can be operated using fingers, palms, or even the side of the hand, providing flexibility in control methods. However, research has shown that the use of trackballs decreases the strain on shoulder muscles, but increases the strain on the wrist [127]. Another tool that can be used as an alternative to pointing devices is the joystick. Joysticks are typically used to assist individuals with mobility impairments operate their power wheelchairs, while in other contexts, they are commonly utilized as game controllers. However, operating a joystick requires a certain level of fine motor control and coordination. Some individuals may find it difficult to grasp, move, or manipulate the joystick with the precision required due to limited motor strength, dexterity, or coordination [128, 129]. In addition, typically an extra button is necessary for clicking, requiring users to alternate hand movements between the button and the knob. Touchpads or trackpads, commonly built into laptops, require minimal wrist movement and no need for grasping. They support basic gestures like tapping for clicks. However, multi-gesture actions often needed for double-clicks, grabbing screen elements, etc., may not be feasible for individuals with hand motor impairments who are unable to use more than one finger.

While all these techniques enable interaction with computers, they have their limitations of cost, efficiency, feedback, discomfort, and speed.

3.2.2 Game Input Methods for Players with Quadriplegia

Assistive devices for users with quadriplegia include trackballs and joysticks [62], speech and sound recognition systems [53, 54, 55], camera-based interaction systems [51, 52], gaze-based interaction using EOG [130] or eye tracking systems [50], switch-based systems [59], tongue and breath-based systems [56, 57], mouth controllers [58], and EEG/EMG based systems [60, 61]. Of these assistive technologies, we discuss below specific systems that have been used for controlling video games.

Most devices for gameplay collect signals from the tongue, brain, or muscles that the individual may have voluntary control over. There are several Tongue Machine Interfaces

(TMIs) such as tongue-operated switch arrays ([117]) or permanent magnet tongue piercings that are detected by magnetic field sensors ([131, 132]) to enable interaction with a computer. [133] created a radio frequency transmitting device shaped like an orthodontic retainer containing Braille keys that could be activated by raising the tongue tip to the mouth superior palate. [134] presented a theoretical framework for using a multi-camera system for facial gesture recognition for children with severe spastic quadriplegic cerebral palsy. [135] mapped eye and lip movements to a computer mouse for a face-based input method.

Assistive devices based on BCI directly tap into the source of volitional control, the central nervous system. BCIs can use non-invasive or invasive techniques for recording the brain signals that convey the user's commands. BCIs can provide non-muscular control to people with severe motor impairments. While non-invasive BCIs are based on scalp-recorded electroencephalograms (EEGs) created using adaptive algorithms have been researched since the early 1970s ([87, 89, 88, 90]), they have not yet become popular among users due to limitations, such as bandwidth and noise ([136]).

Motor impaired users can play video games with a few consumer products. One [59] is a non-profit dedicated to arcade style games that can be played with one switch. [58] enables three-way communication with computers and video games using a mouth-controlled device and to engage in social interaction through streaming on Twitch [5]. It includes sip/puff pressure sensors, a lip position sensor, and a joystick with customizable input and output mapping.

All these systems and devices have their unique affordances and limitations. For example, [58] is the most popular video game controller for quadriplegics, though it is expensive and needs updating with each new console release. There are several games

[5] https://www.washingtonpost.com/video-games/2019/10/14/its-my-escape-how-video-games-help-people-cope-with-disabilities/

where it is not possible to map a physical option on the Quadstick to a game action because of the large number of game actions possible. Our proposed software based input method overcomes some of the limitations of prior devices by enabling fast and easy gameplay, design of macros for complex input (e.g. jump + turn left) can be mapped to a single facial expression, and customizable mapping of expressions to game actions. Hands-free interfaces like BCI require the user to wear a headset which may be difficult to wear and use for extended periods of time for playing games ([137]). Our system is webcam-based and does not require the user to wear any sensors, trackers or devices. To our knowledge, facial expression recognition has not yet been investigated and evaluated based on quantitative and subjective data in the context of game interaction for quadriplegic individuals.

3.2.3 Accessibility in Consumer Video Games

More consumer games are starting to include accessibility options. For example, The Last of Us: Part II released in June 2020 offers around 60 accessibility options like directional subtitles and awareness indicators for deaf players or auto-target and auto-pickup for those with motor disabilities [6]. The accessibility options in Naughty Dog's 2016 release Uncharted 4: A Thief's End [7], support features like auto-locking the aiming reticle onto enemies, changing colors for colorblind users, or adding help to highlight enemies. Sony has included a number of accessibility functions in the PS4 system [8], including text-to-speech, button remapping, and larger font for players with visual and auditory impairments.

In addition to adding accessibility options in commercial games, many special pur-

[6] https://www.playstation.com/en-us/games/the-last-of-us-part-ii-ps4/accessibility/

[7] https://dagersystem.com/disability-review-uncharted-4/

[8] https://support.playstation.com/s/article/PS4-Accessibility-Settings?language=en_US

pose games have also been developed for blind players [138, 139, 140], with a large list of games available on the Audio Games website [9]. Canetroller [141] is device that enables visually impaired individuals to navigate a virtual reality environment with haptic feedback through a programmable braking mechanism and vibrations supported by 3D auditory feedback. Virtual Showdown [142] is a virtual reality game designed for youth with visual impairments that teaches them to play the game using verbal and vibrotactile feedback. Players of Animal Crossing: New Horizons, released in March 2020, are using the game's customization options to make the game more accessible. For example, a blind player demonstrated how they modified the game in ways that do not rely on sight while another player low-vision player covered their island in grass and flowers to force fossils and rocks to spawn in specific spots [10]. Not all commercial games are customizable which leaves some players with disabilities are to rule out those games or seek help of a friend or assistant to "play" the game.

The leading example of an accessible game controller is Microsoft's Xbox Adaptive game controller that allows people with physical disabilities who retain hand/finger movement and control, to be able to interact and play games [143]. By connecting the adaptive controller to external buttons, joysticks, switches and mounts, gamers with a broad range of disabilities can customize their setup. The device can be used to play Xbox One and Windows 10 PC games and supports Xbox Wireless Controller features such as button remapping [144].

The solutions presented here, while accessible, are not usable by those with severe motor disabilities as most of these solutions rely on hand-based control.

[9] `https://audiogames.net/`

[10] `https://kotaku.com/how-animal-crossing-new-horizons-players-use-the-game-1844843087`

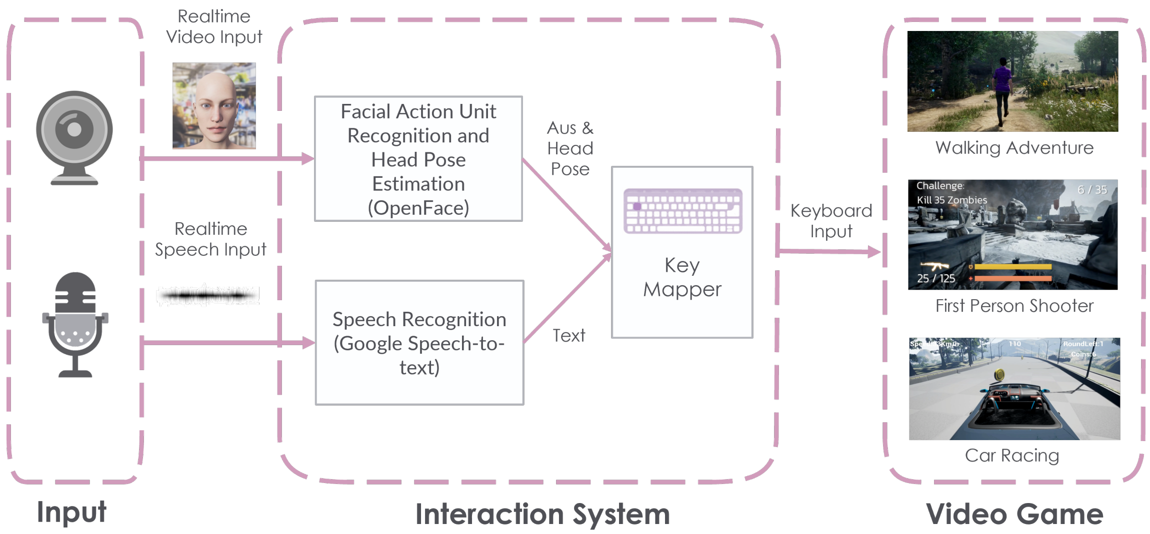


Figure 3.1: The system pipeline showing input of video and speech data that is processed and converted to keyboard bindings for controlling actions in each game.

3.3 Hands-free Video Game Controller (2021)[11]

For many people, video games are about experiencing great adventures and visiting new places that are often not possible in real life. People also build social and emotional connections through gaming [147]. Yet, as prolific as gaming is, it is largely inaccessible to a significant number of people with disabilities. Video games are increasingly being used for purposes other than entertainment, such as education [148], rehabilitation [149, 150] or health [151, 152]. These new uses make game accessibility increasingly critical, and even more so for players with disabilities who stand to benefit greatly from the new opportunities video games offer.

Gaming is usually far more demanding than other entertainment media “in terms of motor and sensory skills needed for interaction control, due to special-purpose input devices, complicated interaction techniques, and the primary emphasis on visual con-

[11]The content of this section is part of the papers previously published in **Frontiers in Computer Science (2021)**, Volume 3, Article 751455, pp 1-15. Frontiers Media SA, 2021 [145] and in **Proceedings of the Augmented Humans International Conference 2021**, pp. 131–140, 2021, Rovaniemi, Finland [146].

trol and attention" [153]. For individuals with degenerative neurological diseases such as muscular dystrophy or spinal muscular atrophy, grasping, holding, moving, clicking, or doing pushing and pulling actions, often needed for using console game controllers, is challenging and may present an insurmountable hurdle to playing. PC mouse and keyboard input is also not suitable for many of these users due to the need for bi-manual control necessary to control game camera and movement [32]. The suitability of a device (AT or not AT) depends on an individual's requirements as determined by the degree and type of muscle function available and targeted by that device.

Players may be restricted to playing greatly simplified games compared to games created for those with full muscle control. While gaming software has started to include more options for different types of disabled players, there is still a great need for the design of new gaming input methods. Newer input types can give disabled players similar amounts of agency and control as non-disabled players, especially when software accessibility features are not helpful, as is the case for players with severe motor disabilities where using hands to control an input device is not an option.

In order to facilitate this, in this work, we propose a novel hands-free input system, which translates facial expressions, recognized in a webcam video stream, into game input controls. The system is designed through my dual role as both the researcher and the tester, leveraging my experience as a player with severe motor impairment. The system includes speech recognition to serve as a secondary hands-free input modality. Our system contribution specifically pertains to the design of a hands-free interaction system. While built using the known technique of facial expression recognition, put together with keyboard mapping, speech input and custom test games, the system holistically accomplishes novel functionality, which has not been explored in prior work. Specifically, our system provides a new hands-free method of playing video games which individuals with severe motor impairments or quadriplegia are otherwise unable to play with traditional input methods like a keyboard plus mouse, or a joystick, or a gamepad. Unlike BCIs and other input technologies designed for motor-impaired users, our system is inexpensive, easy to learn, flexible and works without encumbering the user with sensors and devices.

The main contributions of this work are:

- A fully functional prototype of facial expression recognition based video game control.
- Design of three games that demonstrate the mapping of facial expressions to game actions with focus on user agency, user comfort, ease of use, memorability, and reliability of recognition along with some design reflection.
- Results of an evaluation with individuals with quadriplegia because of neuromuscular diseases.

3.3.1 System Design

Interaction design strives to create solutions that are generalizable to a large group of people. By contrast, AT are usually tailored to the individual. In prior research, it has been shown that the best effects of an AT are seen when it is developed with and tested by potential end users [137]. The work presented here uses the AT design method to develop a camera-based game input system, and test games with the help of me. Our co-design process is similar to that of [154] who designed a game controller and a mouse for a quadriplegic teen.

Our design goal was to make the use of any small muscle movements available to people with severe mobility impairments to the fullest extent possible. My prior experience with mouth-based and gaze-based systems was not so positive, so those input modalities were discarded. Since I had voluntary control over only one finger, hand-based systems

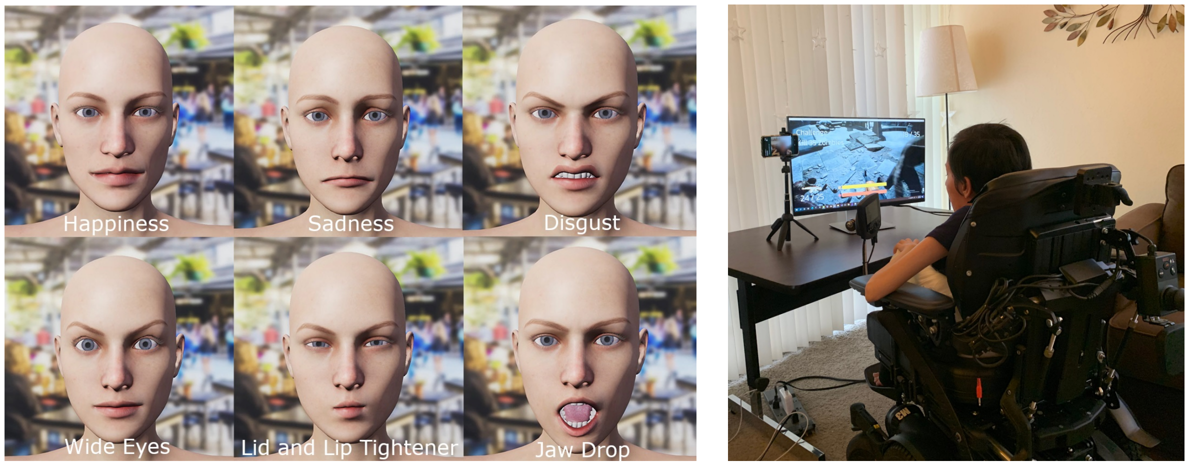


Figure 3.2: Left: Six facial expressions used for playing the games. Top row left to right: Happy face, Sad face, Disgust. Bottom row left to right: Wide open eyes, Pucker, Jaw drop. Right: I am playtesting the FPS game at home using a smartphone camera as the input device.

were also impractical. In contrast with other methods that require users to wear external hardware such as Earfieldsensing [155] or Interferi [156], we converged on a camera-based system that could use facial muscle control, which I possessed, as input and support functionality using webcams or other camera devices that most users already own or can afford.

Pipeline

There are four main components to our system: 1) facial expression recognition (FER) or facial action unit (AU) recognition along with head pose estimation, 2) speech recognition, 3) interaction design (AU and head movement to keyboard mapping), and 4) game design and gameplay. Figure 3.1 illustrates the system pipeline. Through the two recognition systems (one for facial expressions and head pose and the other for voice), webcam and microphone input are sent to the keyboard mapper (Section 3.3.1), which converts them into keyboard input for each game. For creating the Temple Looter and First Person Shooter (FPS) games, we used Unreal Engine (UE) version 4.25.1.

Facial AUs Combinations or Facial Expression			Keyboard Key
AU6 + AU12	Cheek Raiser + Lip Corner Puller	Happiness	1
AU1 + AU4 + AU15	Inner Brow Raiser + Brow Lowerer + Lip Corner Depressor	Sadness	2
AU9 + AU10	Nose Wrinkler + Upper Lip Raiser	Disgust	3
AU1 + AU2 + AU5	Inner Brow Raiser + Outer Brow Raiser + Upper Lid Raiser	Wide Eyes	4
AU7 + AU23	Lid Tightener + Lip Tightener	Contempt	5
AU4 + AU25 + AU26	Brow Lowerer + Lips Part + Jaw Drop	Jaw Drop	6

Table 3.1: Facial AU combinations with their descriptions and their approximate equivalent facial expressions mapped to keyboard keys.

Video Input

Ekman et al. [157] categorized facial muscle movements into Facial Action Units (FAUs) to develop the Facial Action Coding System (FACS). There have been two major types of methods used for recognizing FAU over the years - those that use texture information and those that use geometrical information [158]. Our system uses the OpenFace 2.0 toolkit developed by Baltrusaitis et al. [159] that is based on capturing facial texture information, for facial expression recognition (FER) and head pose estimation, hereafter referred to as OpenFace.

Facial Input - Action units (AUs) in our pipeline are detected in two ways: 1) AU presence - a binary value that shows whether an AU is present in the captured frame, and 2) AU intensity - a real value between 0 and 5 that shows the intensity of the extracted AUs in the frame. OpenFace can detect AUs 1, 2, 4, 5, 6, 7, 9, 10, 12, 14, 15, 17, 20, 23, 25, 26, 28, and 45. In testing, we eliminated AUs 14, 17, 20, since they were similar to other AUs. Also AU45, which corresponds to blinking, could not serve as an input. As soon as the player starts, the system begins to estimate AU presence and intensity values for all 18 AUs within each frame in the input video stream. The keyboard mapper then converts these values into game input. Figure 3.2: *Left* shows the six FEs the player makes for taking actions in the games. These FEs are obtained by combining two or three facial AUs (Table 3.1). Figure 3.2: *Right* shows when I am playtesting the FPS game at home. I determined the game's AU combinations experimentally, favoring those with higher detection reliability. Table 3.1 shows the AU combinations used in the games.

Head Pose Input - Head gestures were included to augment the system since not all AU combinations are expected to work equally well for all users. We use head nodding instead of turning the head sideways which has greater potential for being falsely detected as input. In each frame, the 6-dimensional head pose is estimated. If the player chooses to use head nodding as input in the customization interface, we track the vertical movement through rotation angle around the x-axis to detect a nod.

Speech Input

We used a Python speech recognition library [160] to communicate with Google Cloud Speech API [161] for converting spoken commands to text. The text data was scanned for specific keywords like "Walk" or "Yes" and converted into keyboard input using Pynput [162] and mapped to keys previously programmed in Unreal Engine for each action in each game. Speech interaction served as a backup modality to AU recognition and for interactions with the system such as pausing a game or choosing a game to play.

Key Mapping

Facial expressions, head nods and text keywords are mapped to keyboard input through the keyboard mapper. During testing, it became evident that AU recognition

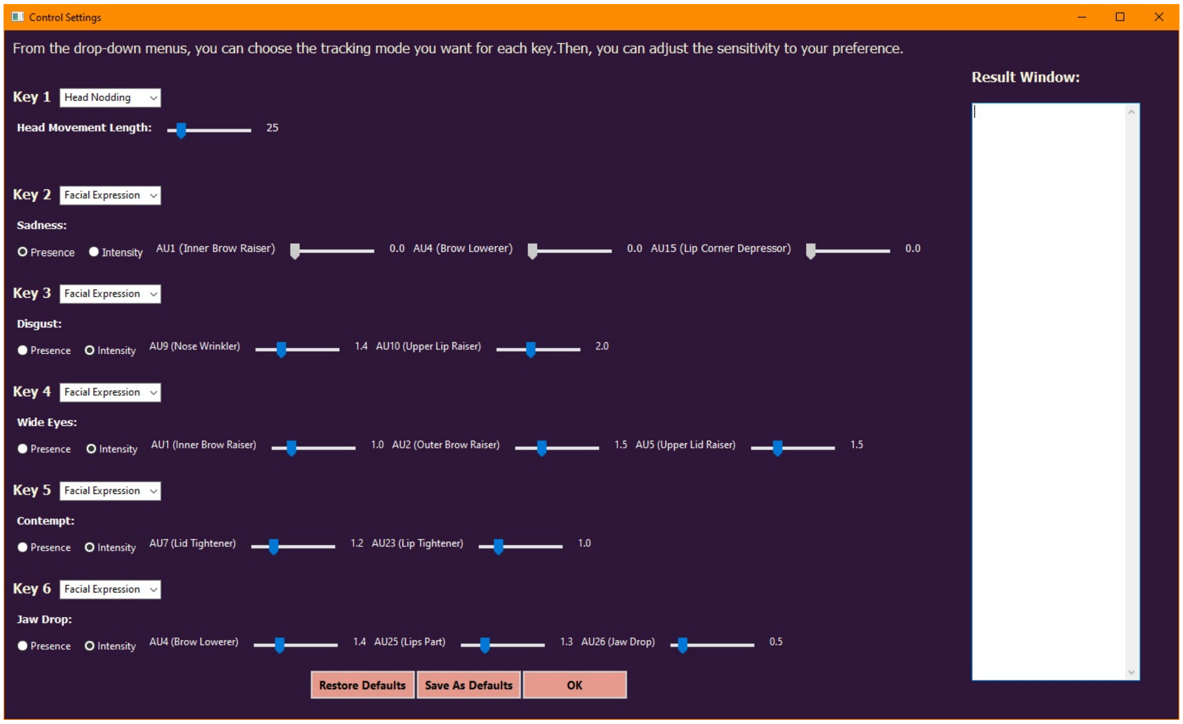


Figure 3.3: We built a custom interface to enable users to change AU detection thresholds and head nod distance.

and mapping per input frame was frustrating to the user due to the system making multiple keyboard mappings per second leading to the midas-touch problem. To resolve the issue, we set a threshold for the number of consecutive frames an AU combination needed to be visible in before getting mapped to the keyboard. This helped provide more control to the user and improved reliability. After testing with me, I set all AU combinations to a five-frame threshold as it struck the right balance between responsiveness and accuracy for me.

Customization

While the setup and all adjustments presented in this work are best suited for me as one of the target users and the thresholds configured to my specific facial expression abilities, we created an interface (Figure 3.3) to support personalization for all users. It gives the user the flexibility necessary for personalizing the system to their own needs. Users also have this ability to choose head nodding to activate a game action, therefore, replacing the default input of a facial expression. When picking head nodding, the vertical range of movement is configurable, and the user is encouraged to test and determine the values that work best for them. When choosing facial expressions, users can set the type and threshold of the AUs, again based on testing during the setup process. Figure 3.3 depicts the customization interface. As seen, head nodding has replaced the default facial expression of happiness for key 1.

3.3.2 Game Design and Gameplay

Over 91 different video game genres are available [163]. We implemented three different ones to implement. I did tested all 3 of them through using our input prototype, but two games were selected for the final user evaluation. Temple Looter as part of Walking Adventure was used as a tutorial and the FPS was used for the study task. Table 3.1 shows the mapping of AU combinations to keyboard keys.

Walking Adventure

I had not played any video games due to being severely affected by SMA for years. Hence, the game controls and genres were introduced to me step by step, going from fewer to more interactions and from slower to faster paced games. Walking Adventure has three levels: Nature Walk, Cave Explorer and Temple Looter. The keyboard to game action mapping is presented in Table 3.2: Left. Each level is visually different, designed to immerse the player in a different environment with its own set of tasks and goals. The game character is created in Adobe Fuse [164] and rigged and animated using Mixamo [165]. All three levels use ambient and task related sounds. Each time a

Keyboard Key	Game Action	Input Type
1	Start Walking	AU
2	Stop Walking	AU
3	Pick up	AU
4	Sprint	AU
5	Turn Yes	AU or Speech
6	Turn No	AU or Speech

Keyboard Key	Game Action	Input Type
1	Start/Stop Walking Fwd	AU
2	Aim and Shoot	AU
3	Start/Stop Turning Left	AU
4	Start/Stop Turning Right	AU
5	Jump	AU
6	Pause	AU or Speech

Table 3.2: Left: Mappings of the keyboard keys to the actions defined in the Walking Adventure game. Right: Mappings of keyboard keys to the actions defined in the FPS game.

facial expression is correctly detected, the system provides audio feedback to the player. Thus, the player always feels in control of the game character's actions with multimodal feedback from the visual and the audio channels.

Nature Walk. It is the first level in the Walking Adventure game. The goal is to enjoy walking and exploring the level and interacting with the environment. Nature Walk is a nature scene with realistic water, trees, and flowers that are organically scattered throughout the map built with assets from the Meadow Environment [12]. The level design consists of tree lined walking trails with branching paths. The level uses a modular spline path for the character to follow at a fixed walking speed. The player can stop to interact with the flowers that use an emissive texture to make them stand out from the rest of the vegetation. Interaction with the flower (Figure 3.4: Left) proceeds as follows:

1. If the player is in the walking state, stop the player.

[12] `https://www.unrealengine.com/marketplace/en-US/product/meadow-environment-set`

2. Over a maximum of 2 seconds, turn the player to face the flower.

3. Over another second move the player up to 90% of the distance from its current position towards the rose, such that when the character bends over to pick up the flower, their hand intersects with the flower's stem giving it a more natural appearance.

4. Play the pickup animation and partway through the animation sequence, delete the flower on the ground, and spawn an identical flower attached to the player's hand.

5. Wait for the animation to end, then let the player go idle with the flower in the character's hand for 3-4 seconds.

6. When the idle time ends, play the put-down animation.

7. When the player is bent half-way, destroy the rose that is in the character's hand to make it look like the rose was actually was put back down on the ground.

8. Wait for the put-down animation sequence to end.

9. Find a spot on the spline that is 100 steps ahead of where the player was before they chose to interact with the flower.

10. Make the character face and walk towards that spot.

11. Finally, make the character face forward and continue walking along the trail.

At path branches, we added a decision making option to enable the player to choose if they want to turn or continue walking along the main path (Figure 3.4: Right). In keeping with the lighthearted mood of the level, there were no timers or tasks.

Figure 3.4: Left: The player bending over to pick up a flower in Nature Walk with the requisite facial expression shown as inset. Right: Two different facial expressions or speech input allow the player to make the decision to turn left or not in Nature Walk.

Cave Explorer. For designing the Cave Explorer level, we downloaded free 3D assets from Quixel's Limestone Quarry [13] collection. The downloaded assets were assembled to create a complex cave environment as shown in Figure 3.5: Left. The player explores a dimly lit cave bearing a torch in hand. Their task is to collect crystals and safely exit the cave. The crystal collection mechanic was added not only to mimic a task commonly found in commercial video games but also to make the level more interactive and goal oriented. The game character from Nature Walk is reused with different clothing and animations. To add an element of surprise, we implement a "jump scare" mechanic by hanging zombie skeletons from the cave roof that would abruptly drop down with appropriate animations and sound effects to scare the player at opportune moments.

Temple Looter. The last level in the Walking Adventure game is built by modifying a map in the free Infinity Blade: Fire Lands asset [14]. We created an ancient temple scene, similar to what one might see in an Indiana Jones movie. We again used the character from Nature Walk with an adventurer's clothing and different animations. The player is tasked with looting hidden treasure in the temple and escaping. We added a stamina bar that the player needed to fill up by not spending too much energy before

[13] https://quixel.com/megascans/collections?category=environment&category=natural&category=limestone-quarry

[14] https://www.unrealengine.com/marketplace/en-US/product/infinity-blade-fire-lands?lang=en-US

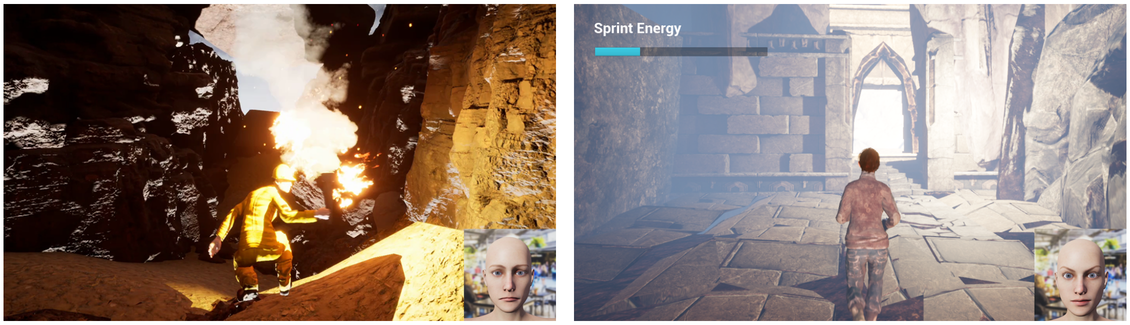


Figure 3.5: Left: Player pauses to look around for crystals in Cave Explorer using the facial expression shown in the inset. Right: Player sprinting in Temple Looter with facial expression input shown in the inset.

sprinting out of the temple (Figure 3.5: Right). Running is a new action added to this level, something I expressed a strong desire to be able to do. We selected this game level for the tutorial stage in the final user evaluation to introduce the player to our proposed input mechanism.

Following the Walking Adventure gameplay, I noted in my notebook, where I was keeping my reflections after playtesting each game:

> "The three levels of Walking Adventure have nice environments. I loved taking actions in the game world like jumping, picking up, walking around on it. I'd like the game better if there was a story behind, but I realize it's only an exploratory design."

First Person Shooter

The second type of the game we created is a FPS. The user study test game was conducted playing this game, a popular video game genre. As opposed to Walking Adventure, which was a third-person game, FPS allowed users to see through the eyes of the character. The FPS character and 40 animation sequences for covering typical movements in an FPS game were downloaded from Mixamo [166]. A blendspace was created to manage the animation logic playback with actions like walking, turning, jumping, aiming and shooting, reloading, and crouching. A single weapon option was added with sound effects and gunfire animation which showed as a flash at the tip of the gun (Figure 3.6: Left). The zombies from Cave Explorer were re-used with different animations to walk, attack, and die. Pathfinding logic was created for the zombies to move towards the player, when the player was within a certain distance range. A horde system was implemented to spawn new zombies based on the player's heading. We added trigger boxes on some paths in the environment to spawn a horde of zombies in a plausible location. This created the effect of there being more zombies than there actually were, which helped with performance and made the game feel higher action. The FPS map was created using elements from a free asset on the Unreal Engine Marketplace called Infinity Blade: Ice Lands[15].

In my initial playtest, FPS proved difficult due to fast pacing for facial expressions and speech input. To improve gameplay and reduce frustration, we added an auto-aim feature and limited the number of zombies to 15. With auto-aim, the player character is turned by a defined amount per frame before the scoped gun is pointed at the nearest zombie that is within a predetermined range. Toggling a key for character movement replaced holding down a key continuously as in traditional FPS games. This way, the player could control the character by using their facial expressions, such as to walk forward or turn left or right. Due to latency in cloud speech processing, speech input did not work as well for FPS gameplay as it did for the slower paced Walking Adventure games. Thus, it was only used for pausing the game and not for the main actions.

The mapping of facial expressions to FPS actions is presented in Table 3.2: Right.

Once playtesting the FPS game for a while, I stated,

> "[I]t is smooth and it did not frustrate me playing whereas most of the time

[15] `https://www.unrealengine.com/marketplace/en-US/product/infinity-blade-ice-lands`

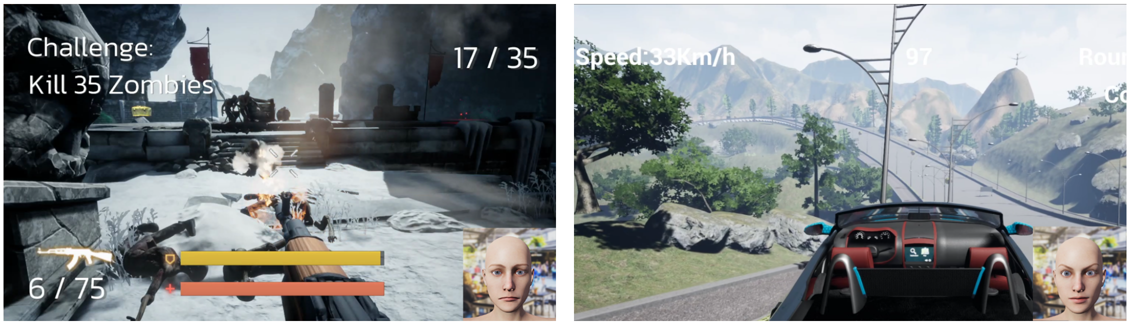


Figure 3.6: Left: Player shooting zombies in the FPS game using a facial expression shown as inset. Right: Player turning the car right using the facial expression shown as inset.

any assistive tool that comes out for people with disability, would somehow need the person an exhausting effort. If you notice, for example when the character shoots the zombies, it is only a matter of lowering your lips and your eyebrows which is very simple. For me, it is a fun experience...I just wish it was a multi-level game."

Car Racing

The game is based on the Car Game template from Unreal to which 3D assets consisting of hills and trees were added from CSDN[16], a community of game developers. The player competes against a clock on a closed loop track. To make the game more engaging, the player collects coins along the track, an idea inspired by the popular Nintendo car racing game, Mario Kart. The coins are created using simple cylinders with yellow material and spin animation attached. Other than coins, there are obstacles on the road that the player needs to maneuver around as bumping into them reduces the car's speed. During playtesting, I found the default car speed to be too high to easily control with facial expressions. That made the car difficult to maneuver around obsta-

[16] `https://www.csdn.net/`

Keyboard Key	Game Action	Input Type
1	Start/Stop Driving Forward	AU
2	Start/Stop Driving Backward	AU
3	Start/Stop Turning Left	AU
4	Start/Stop Turning Right	AU

Table 3.3: Mappings of the keyboard keys to the actions defined in the Car Racing game.

cles which required many iterations of complex manipulations in a fast sequence. To help make the game more fun, the maximum car speed was lowered, the obstacle physics was simplified to enable turning the car easily with a facial expression toggle, similar to turning in the FPS game (Figure 3.6: Right). The mapping of facial expressions to car motions is presented in Table 3.3.

After playing the Car Racing game, this is what I noted:

> "In the past, when I could still play with my hands and regular controllers, I loved playing racing games. However, losing my ability to use my hands, playing this genre of game became impossible. I could never have imagined that I would be able to play my favorite game genre again without putting in too much effort. When the idea of incorporating facial expressions in this genre first came up, I thought well, if we could make the game so customized, we could probably make it possible. Though surprisingly, after only the second attempt that lowered the vehicle speed, the game resembled what I used to play years ago and became very entertaining."

3.3.3 Evaluation

To evaluate whether a facial expression-based input system is usable for playing video games by other individuals with neuromuscular diseases, especially those who have challenges playing with conventional PC game input (keyboard + mouse), we conducted a study with eight remotely located participants (in-person study was not allowed due to COVID-19 restrictions).

Method

Participants. Twelve individuals were recruited from relevant Facebook groups created by and for people with MD and SMA. Of those twelve, we conducted a pilot study with one individual. From the remaining eleven participants, we had to discard study data from three of them because of slow computers and non-working webcams that made it difficult to complete the study. Eight participants (5 females, age range 18 - 45, 2 with MD and 6 with SMA) were able to participate in the remote study. This sample size falls within the range of most prior research with quadriplegics [167, 168, 169], and in many cases, it is higher [170, 171, 172]. For instance, Ammar and Taileb [167] explored EEG-based mobile phone control and while they conducted an HCI requirement study with eleven quadriplegic participants based on the work by Dias et al.[173], they conducted their final usability study with five healthy participants. In contrast, our system was co-designed iteratively with my participation as an individual with SMA and the full system usability and experience study was conducted with eight participants with quadriplegia.

Procedure. We conducted the study over Zoom videoconferencing and split the procedure into two separate sessions to minimize user fatigue, a regular response to physical exertion resulting from prolonged sitting, using the computer, or head nodding [174]. The study took each participant about three hours. A 1.5-hour first session began with participants providing informed consent (study approved by the UCSB Human Subjects Committee), completing a pre-study questionnaire with demographic questions and information about their background playing video games. Following the questionnaire, participants were walked through the installation of our system. Depending on their ability and hand muscle control as well as their computer setup (e.g., virtual keyboard, placement of webcam, number of applications running on the computer), this step took the longest time, especially for those who did not have assistance or had assistants with little or no experience working with computers.. After installation, participants were shown how to customize the system and tailor the settings to their facial muscle movement abilities. A tutorial game (Temple Looter (described in Section 3.3.2) was used to familiarize participants with FER-based gameplay.

While the gameplay was different from the FPS (study task) game, the tutorial allowed participants to get comfortable with making facial expressions in front of their webcam, understand how long each expression needs to last, and control their expression speed when playing. In order to avoid exhausting the participants after 1.5 hours of setup time, they played the FPS game in the second session, scheduled for a different day. Following the FPS gameplay, participants were asked to fill out a post-study questionnaire which was split into three parts: 1) system usability, 2) user experience, and 3) game experience. We also included an open-ended feedback question at the end of the post-study questionnaire asking about their overall experience.

Interaction Framework

For the first two parts of our post-study questionnaire, we used McNamara and Kirakowski's theoretical framework of interaction [175] in order to assess our input system's usage. The framework focuses on functionality, usability and user experience. It explores functionality by investigating how the controller supports the available game commands. The interaction method and how input is translated into game actions is presented in Section 3.3.1.

Iso 1998 [176] describes usability as having three components: 1) *Efficiency*, 2) *Effectiveness*, and 3) *Satisfaction*. The purpose of our study is not to compare our input

Component	Question Item	Minimum	Maximum
Efficiency	Overall, playing the FPS game was.	Very Difficult	Very Easy
Satisfaction	How satisfied are you with using facial expressions as input for playing video games?	Very Unsatisfied	Very Satisfied

Open-ended Question
What did you not like about the system?
What did you like most about the system?

Table 3.4: The first part of the post-study questionnaire. The first two questions were rated on a 7-point Likert scale and the second two questions are open-ended questions.

system with other input methods, but to determine if a system such as ours can offer a viable option to those with limited choices in gaming input. We measured input *Effectiveness* based on game completion set to a maximum of 25 minutes based on a pilot study with one participant (not me). *Efficiency* is measured by mental effort expended by the participants, and *Satisfaction* by fulfillment of a mental desire. The first part of our post-study questionnaire measured *Efficiency* and *Satisfaction* as part of the overall usability measurement. There were four related questions, two evaluated with a 7-point Likert scale and two other open-ended questions asking participants what they liked and disliked most about the input system (shown in Table 3.4). The Likert scale for *Efficiency* is (1 = Very Difficult, 7 = Very Easy) and for *Satisfaction* is (1 = Very Unsatisfied, 7 = Very Satisfied).

The last element of interaction design is user experience. Experience is the psychological and social impact of technology on users. This means impact beyond completing game tasks and is affected by external factors like design, marketing, social influence, and mood [178]. The second part of the post-study questionnaire asked participants for feedback on their experience (Table 3.5). We collected data for this element using the

Category	Component	Question Item
FER-based input-related	Sensitivity	Overall, the system is sensitive enough to detect my facial expressions while playing.
	Learnable	I could learn how the system works in a short time.
Game-related	Ease of Use	I found it easy to take actions in the FPS game using my facial expressions.
	Comfort	Overall, using facial expressions to interact in the FPS game did not tire me.

Table 3.5: The second part of the post-study questionnaire. The questions here were rated on a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree). For each component we also asked the participants to provide open-ended feedback on that component.

Component	Statement
Sensory and Imaginative Immersion	S1: I was interested in the game's story.
	S2: It felt like a rich experience.
Tension	S1: I felt frustrated playing the FPS game.
	S2: I felt irritable.
Competence	S1: I felt successful.
	S2: I felt skillful.
Flow	S1: I forgot everything around me.
	S2: I was fully occupied with the game.
Negative Affect	S1: I felt bored.
	S2: I found it tiresome.
Positive Affect	S1: I enjoyed it.
	S2: I felt good.
Challenges	S1: I felt challenged.
	S2: I had to put a lot of effort into it.

Table 3.6: The third part of post-study questionnaire (GEQ) [177]. All questions were rated on a Likert scale (1 = Strongly Disagree, 7 = Strongly Agree).

Critical Incident Technique (CIT) [179]. The questions fell into two categories:

- FER-based input-related questions: We asked participants four questions (two evaluated on a 7-point Likert scale with 1= Strongly Disagree, 7= Strongly Agree and two open-ended) regarding how sensitive the input system was and how quickly they learned to use it.

- Game-related questions: These centered around the FPS video game played with our input system. Four questions (two evaluated on a 7-point Likert scale with 1= Strongly Disagree, 7= Strongly Agree and two open-ended) asked about the ease of use and how comfortable it was to use FER for playing the FPS game.

The third part of the questionnaire used questions from the Game Experience Questionnaire (GEQ) by IJsselsteijn et al. [177]. As many of the questions were not relevant to our task and game, we chose 14 out of 33 questions in the original questionnaire. GEQ categorizes all questions into seven factors. We picked two questions from each factor that were most relevant to our study (Table 3.6).

Results

Findings from the Usability Questionnaire. Results of *Efficiency* and *Satisfaction* as part of the usability of FER-based input system for playing the FPS game are shown in Figure 3.7:A. As can be seen, the ratings are positive. Responses to open-ended questions about *Efficiency* and *Satisfaction* were also very positive.

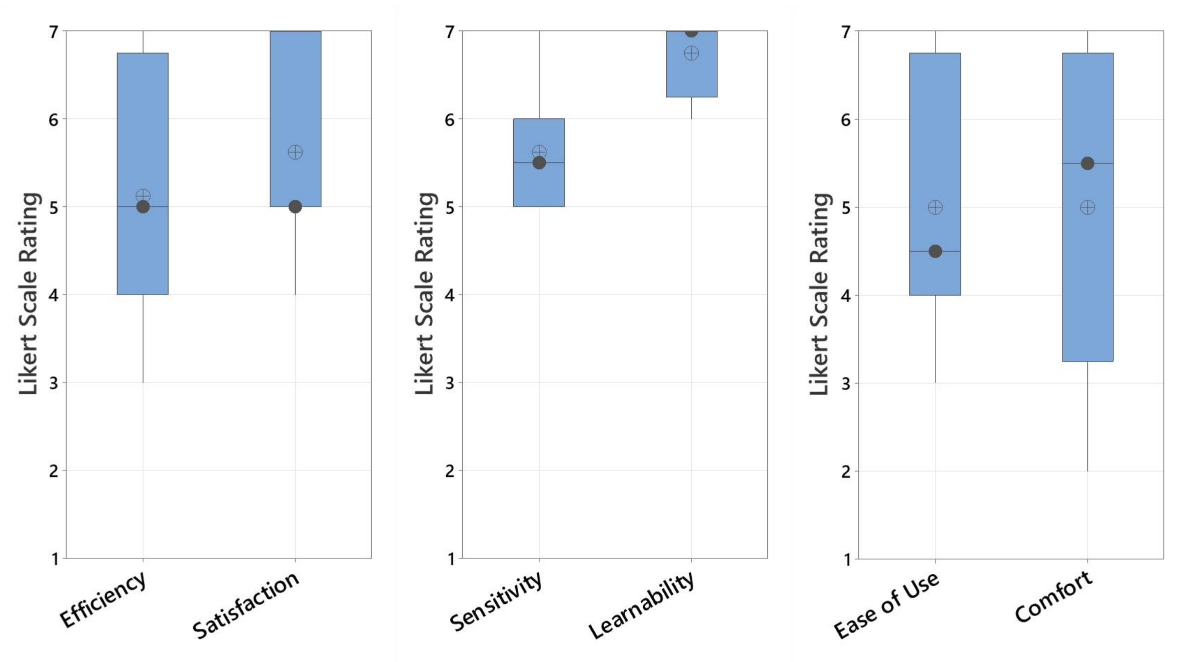
The fact that participants were able to play without using their hands and that the system offers an easy to use alternative were two of the most appealing features of the system. P2 said, "[I]t was very intuitive and easy to learn how to use. Just the fact that I can have potentially one extra mode of input would be huge." P3 agreed saying, "[B]eing able to toggle certain movements with just a facial expression was a interesting idea."

P4, P5, P6, and P7 also said the feature they liked most was being able to play without using their hands. P1's favorite feature was that it is "Easy to navigate."

In response to what they did not like about the FER-based input, participants expressed a desire to change all the mappings, although they appreciated the FER sensitivity customization that the system already provides. P4 said, "[I] wish you could swap facial expressions as inputs." For some players, as also revealed in our testing, making some facial expressions was not easy. We expected this since each individual with neuromuscular diseases has different levels of facial muscle control. P5's comment reflected that: "[I]t can be difficult to get the expressions right." Interestingly, the *sadness* expression (AU1 + AU4 + AU15 or Inner Brow Raiser + Brow Lowerer + Lip Corner Depressor) was the most challenging for almost everyone). P7 said there was "Nothing" they did not like and P6 said, "I like it a lot" which helps validate our fundamental design idea of using FER as a hands-free input method.

Findings from the User Experience Questionnaire. We collected data for 'user experience' using the Critical Incident Technique (CIT) [179]. Table 3.5 summarizes the categorization and the components for each category that we developed: FER-based input-related ={*Sensitivity*, *Learnable*}, and Game-related = {*Ease of Use*, *Comfort*}. Each component has one question reporting the answer on a 7-point scale, depicted in Table 3.5 and one open-ended question asking the participants for additional feedback.

As shown in Figure 3.7:B, we see high ratings for both the *Sensitivity* and *Learnability* components of the first category - FER-based input. Several user comments for *Sensitivity* also provided positive feedback. While P7 found the system to be fairly sensitive, P3 found it much too sensitive and P8 was mixed. The high sensitivity can lead to the midas-touch problem that we mitigated for when I playtested the games (see Section 3.3.1) by increasing the number of frames in between detections. However, this element was not customizable for the user study experience. P7 offered design feedback



(A) (B) (C)

Figure 3.7: Usability and User Experience ratings for our input system when playing the FPS game. (A) Efficiency and Satisfaction ratings as part of the Usability of our input system for playing the FPS game. (B) Sensitivity and Learnability ratings for our input system as part of User Experience. (C) Ease of Use and Comfort ratings when playing the FPS game with our input system as part of User Experience.

on the customization interface: "I would like there to be some tooltips when you hover over the sensitivity sliders that tell you exactly what they govern and what they do. Some are obvious but others not much." There were also comments regarding *Learnability* such as: "As someone who uses computers a lot, it didn't take me long to figure out how it all works and what the sliders did.", P2 said. P7 remarked: "Learning process was pretty straightforward. I quickly figured out how to use it." P6 even found the learning process entertaining and said, "It was fun." While many of the comments indicated that the learning process was short, P3 said, "It was usable but learning how to adjust the settings could be difficult for some users. It would certainly take some time."

The results for the *Ease of Use* and *Comfort*, the two components of the Game-related category are shown in Figure 3.7:C. In these two categories, the distribution of response ratings is wider, but it still resides on the higher side of the scale. The responses to open-ended questions were very varied. For the *Ease of Use* category, for example, P3 commented: "The overall system did take a lot of adjustments to get working with my facial expressions but worked decently when it was calibrated." P7 said: "Once I learned which facial expression is connected to a specific action, it became very exciting." On the other hand, P2 said: "Once I was able to figure out exactly how to do action number two, it became fairly easy. The facial expression required was not what I imagined when I was told to make a sad face. It required a lot more tension than I initially thought, but eventually it worked."

Responses to the *Comfort* category were also diverse. "It could become tiring if playing for extended period.", said P5 and "Since I cannot play this type of game anymore, it was quite rewarding to be able to play without any difficulty in game control." stated P7. With a fast-paced game like FPS, we expected some exhaustion, similar to traditional input systems. Consequently, we put these last two categories under the Game-related since gameplay affects the overall player's experience, which does not depend solely on the controller. A criticism of the sad face expression from P2 showed the mapping of a facial expression to frequent game actions should be customizable along with game settings themselves (e.g, number and speed of zombies in the FPS game). P2 said, "Making a sad face to shoot zombies made my cheeks get a bit tired."

Findings from the Game Experience Questionnaire (GEQ). Table 3.7 reports these values, along with the mean and standard deviation for each item. To measure the internal consistency between the two items in each component, Cronbach's alpha was calculated. Except for *Flow* and *Challenges*, all components have satisfactory internal consistency. These results indicate that the participants' responses to the first question did not match their responses to the second question in these categories. For example, for

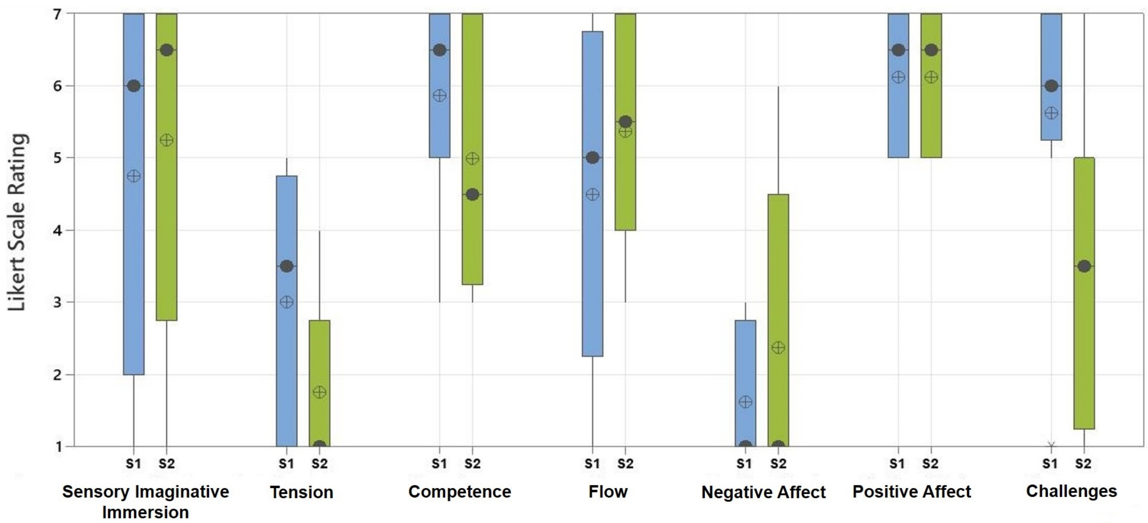


Figure 3.8: Participants' ratings of each statements in every component of the GEQ post-study as part of post-study questionnaire. The statements for each component are shown in Table 3.6.

Flow, while most of the participants were fully occupied in the game, it did not make them forget everything around them. Based on their ratings for *Challenges*, it appears that although they felt challenged, the effort required to play was variable across participants leading to a wider distribution with a low mean (Figure 3.8). The visualization of the participants' scores for each category are shown in Figure 3.9.

Overall Opinions About the System. At the end of the study, we asked participants for their overall feedback on the whole experience, which was very positive. A good number of comments mentioned that participants "loved it", or that "it was fantastic", or "way too fun" or "Overall my experience today was easy and very straightforward. I had no issues getting anything to work the way it should." One participant said they are "eagerly awaiting its availability" so that they can play games again and use it for other input. One participant mentioned that they would like to reduce the number of markers (AUs) required for facial expressions to one. As much as we value user input, we have to point out that limiting the number of AUs to one may potentially cause facial expressions to overlap leading to difficulty in accurate detection. When we were

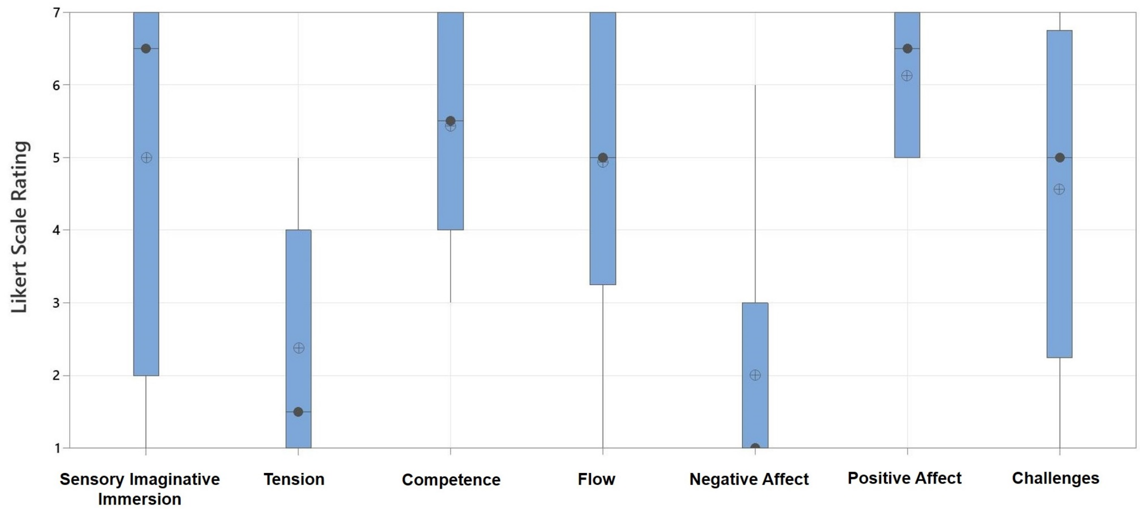


Figure 3.9: Participants' ratings of each component of the GEQ questionnaire as part of the post-study questionnaire.

iteratively developing our system we realized that facial muscles are unconsciously linked together and when you move one muscle on your face it will inadvertently move one or two other muscles also, making them unusable for other controls. Another participant found the input system intriguing and said they would likely use it in combination with other input devices validating our inclusion of speech-based input as an added modality. Not only could additional modalities help with potential fatigue, they could also make the mappings more natural (e.g., saying "pause" vs making a facial expression for pausing the game as used in the FPS game).

3.3.4 Discussion

System Usability

As presented in Section 3.3.3, *Efficiency* and *Satisfaction* represent two components of system usability. The two related questions were rated moderately high and open-ended questions received very positive responses. Almost all of the participants were amazed that our system did not require hands to play video games and yet offered

Component	Statement Numb.	Mean	Standard Deviation	Cronbach's alpha
Sensory and Imaginative Immersion	S1	4.75	2.49	.95
	S2	5.25	2.28	
Tension	S1	3	1.66	.77
	S2	1.75	1.09	
Competence	S1	4.75	1.36	.9
	S2	5.88	1.66	
Flow	S1	4.5	2.12	.52
	S2	5.38	1.49	
Negative Affect	S1	1.63	.87	.77
	S2	2.38	1.93	
Positive Affect	S1	6.13	.93	1
	S2	6.13	.93	
Challenges	S1	5.63	1.87	.48
	S2	3.5	2	

Table 3.7: Report of Mean and Standard Deviation for each question item in GEQ along with Cronbach's alpha for each component.

the ability to play a fast-paced and popular game like an FPS. Their feedback also indicates that changing the game mapping to suit different needs is strongly appealing. For example, making a sad face was very easy for me so I customized it for myself to map to a repetitive and perhaps critical action in the game. However, after conducting the study, we found that most participants found it difficult or tedious to make a sad face expression, which suggests that providing the option to change the mappings might be a way to accommodate the variable user abilities. Since most neuromuscular diseases affect facial muscle control over time, making all expressions might not be possible for everyone and even for one user that ability may evolve depending on physical therapy and disease progression.

User Experience

We evaluated user experience based on *Sensitivity*, *Learnability*, *Ease of Use*, and *Comfort*. Participants rated the system's *Sensitivity* and *Learnability* very high. This was also reflected that in their answers to the open-ended questions. While most participants felt the system was sufficiently sensitive, two said it was too sensitive. As discussed in Section 3.3.1, midas-touch is a problem that we resolved for me by setting a higher threshold for the number of consecutive frames in which an AU combination must be visible before registering it as detected input to map to the keyboard. However, based on the study and feedback, this threshold may vary across users and thus needs to be customizable for each input expression during an initial system setup phase.

Participants rated *Ease of Use* and *Comfort* moderately high. Their comments also implied that the system is learnable and easy to use. Despite the fact that we had tried to map positive expressions to positive game actions, the comment about sad face being hard to make and the desire to change the mappings demonstrates the personal nature of expression-to-action associations and the ability to customize the input for each individual would be ideal.

Game Experience

Even though our aim was to study and explore how users experienced our input system for video game playing, we had to find out how the players felt about the design of the game itself after they tested the input system. To do so we utilized all seven factors from the GEQ that cover multiple aspects of game design. Four factors - *Tension*, *Competence*, *Negative Affect*, and *Positive Affect* - scored satisfactory.

We received a wide range of scores for *Sensory and Imaginative Immersion*. Cronbach's alpha and some analysis revealed why the distributions of scores for *Flow* and *Challenges* were wide - a low alpha value indicates inconsistency among questions in these factors and for these two factors we got low alpha values (Table 3.7). While the majority of the participants did not strongly agree that they forgot everything around them, they did agree that they were fully occupied in the game which resulted in inconsistency in the *Flow* factor. Or, for the *Challenges*, the participants all strongly agreed they were challenged by the game. However, not all of them agreed that the challenge required a lot of effort. This is another affirmation that the game mechanism and input system were not overly complex and cumbersome.

3.3.5 Design Considerations

Here we articulate three design considerations that future developers of hands-free input systems for individuals with neuromuscular diseases may want to consider. These are based on our experience of co-designing our system, feedback from the users and the process of conducting the remote user study.

Design Input to Support Player Ability

While obvious, understanding the capabilities of the target users, especially in this community where each user's situation and needs are unique based on their disease progression, is the first step in determining the appropriate input method for them. In our design, we predominantly rely on facial muscle movements since those were the muscles me had most voluntary control over. During the co-design process, we discovered that the number of muscles employed in each facial expression was an additional factor that needed to be considered for 1) the player's comfort level, 2) the system's ability to detect the expression reliably, and 3) the potential mapping to a game action. As I tried several facial expressions, we found out that those with 2 or 3 AUs were most effective because they were easy to make repeatedly when needed, and were most reliably detected without false positives.

Design for Personalization and Flexibility

The frequency of taking certain actions varies across games. For example, start/stop walking in Temple Looter or turning and shooting in the FPS are most frequently used. The facial expressions selected for these actions need to be fast and easy to make while actions less often used can be relegated to either a secondary input method (e.g., speech input) or a more complex expression. During the study, user feedback pointed to a greater need for customization than our system currently supports, from mapping expressions to game actions to choosing whether or not to use expressions at all. The four FEs (happiness, sadness, disgust, and contempt) were relatively easy for me to make, but the study showed that making the sadness expression was particularly challenging for some users. Additionally, we had attempted to map positive expressions to positive game actions (e.g., smiling to moving forward) and negative expressions to negative actions (e.g., sadness to shooting) in order to assist the user in remembering the mapping. However, the study showed that mappings are more personal. Thus, in order to accommodate each player, enabling a change in mappings is another type of customization that should be supported. Lastly, given the limited set of facial expressions that are easy to make and detect reliably, and the need to map them to a much larger set of game actions, combining game action sequences into 'macros' is another customization possibility that would make the system broadly usable in a large variety of games.

Consider Fatigue and Disease Progression

The target audience is particularly prone to fatigue from muscle use and thus repeated actions like facial expressions to play a game can be exhausting, especially if a large number of muscles are involved in making those expressions. Reducing the number of muscles can lead to false positives. Hence, it is a fine balance between the number of AUs, the type of expression and the game action and this balance is best achieved by involving the individual in the design process. A characteristic of neuromuscular diseases is the progression and change in voluntary muscle control over time. A system that integrates multimodal input (e.g., facial expressions and speech in our case), can help provide the player access for a longer duration as their disease progresses. Similarly, providing multimodal output through visuals, text and sound data can help the player stay in control by letting them know that their facial expression or speech input was detected by the system, and allowing them to make informed decisions about next steps.

3.3.6 Adoption in Other Video Games

We were curious to test our system with some commercial games to explore how it would perform outside our designed games. We were surprised to find that games that do not require a mouse or games where the mouse movements can be replaced with keyboard input, worked well with our system without requiring any modifications. We tested four atmospheric single player puzzles games on Steam like GRIS[17] and Inside[18], Limbo[19], and Little Nightmares[20]. For all these games, we created macros for game actions that required rapid key presses in a particular sequence to accomplish the game task. With that small change, the games were fully playable without requiring me to make multiple

[17] https://store.steampowered.com/app/683320/GRIS/
[18] https://store.steampowered.com/app/304430/INSIDE/
[19] https://store.steampowered.com/app/48000/LIMBO/
[20] https://store.steampowered.com/app/424840/Little_Nightmares/

facial expressions in quick succession. To switch to the macro mode and back, an FE was used. Based on this experiment, I was excited about the potential of our system to work with other commercial games. We believe that the set of games that work with our system will grow as more developers enable mapping game controls to a keyboard.

3.3.7 Assumptions and Challenges

COVID-19-induced restrictions prevented in-person evaluation and therefore we conducted a remote study. This was incredibly challenging considering our participants' degenerative neurological conditions. The ability to participate remotely required the ability to participate independently, even if assistance was available to install our application and setup the webcam. Despite being easy to install on any Windows 10 x64 machine (a prerequisite for participating), our participants' respective unique situations brought new challenges to each study session. The participant was presumed to be sitting in a wheelchair like me, facing a monitor and webcam. However, one participant was unable to sit up and carried out the study lying down. Assuming everyone could hear over Zoom was another assumption (though we also shared instructions for installing and using Google Docs). Our best efforts failed to continue with one deaf participant. Furthermore, we assumed that having a PC meant having a functional GPU. One participant's system had so many apps running that our application could not manage the realtime frame rate. Our goal was not to make our participants change their PC environment since they might have spent hours setting it up exactly how they needed it. As a result, this study had to be terminated prematurely. Our study attracted many people, but attempting to set up the input system on a PC with different specs can be challenging.

3.3.8 Summary

In this work, we have presented a novel hands-free video game control system that translates facial expressions into game input actions, specifically designed for individuals with severe motor impairments. This system provides an accessible, affordable, and user-friendly alternative to traditional game controllers and other assistive technologies. To further support this goal, we have made the code for our facial expression-based input controller open source [21], allowing other researchers and developers to build upon and improve this technology.

The main contributions include the development of a fully functional prototype that utilizes facial expression recognition, speech recognition, and customizable interaction design, enabling users to map facial expressions and head movements to game actions. We demonstrated the effectiveness of our system through the creation and evaluation of three games: a walking adventure, a FPS, and a car racing game. Each game was designed to highlight different aspects of our input system, from basic navigation and interaction to fast-paced action and precise control.

Our evaluation with eight participants, all of whom had quadriplegia due to neuromuscular diseases, revealed positive responses regarding the system's usability and user experience. Participants found the system intuitive, sensitive enough to detect facial expressions, and easy to learn and use. While some users experienced challenges with specific facial expressions, the overall feedback highlighted the potential of this hands-free control system to enhance the gaming experience for individuals with severe motor impairments.

The study also provided valuable insights into the design considerations necessary for developing effective assistive technologies, such as the importance of customization

[21] https://github.com/atiehtaheri/Facial-Expression-based-Input-Controller.git

and flexibility to accommodate individual needs and preferences, as well as the need to address user fatigue and the progressive nature of neuromuscular diseases.

Overall, our work contributes to the field of accessible gaming by offering a practical solution that can significantly improve the quality of life for individuals with disabilities, enabling them to engage in and enjoy video games just like their non-disabled peers.

3.4 Virtual Buddy (2023)[22]

Conversational AI is fast proving to be a valuable tool in our day-to-day lives, providing support, companionship, and stress relief [181, 182, 183, 184]. It is now plausible to consider the use of this technology as a means of mitigating social isolation [185, 186, 187, 188]. However, current conversational AI technologies have largely catered to the general audience. The unique needs of people with mobility disabilities, who may not be able to leave home to engage in social interactions, or those who have motor impairments, that make it challenging to interact with computers, have not been the primary focus of their design, despite clear benefits. Our work focuses on people with motor challenges, addressing the physical barriers that impact interactions with conversational AI as a socialization aid.

The motivation and design decisions for this work originate from my firsthand experience of living with SMA. Although AI-powered real-time conversations and question-answering offer substantial potential, their accessibility is limited. For instance, I have a deep interest in learning a new language. Attending in-person Italian lessons is difficult for me. Interacting with a conversational AI could provide a dynamic and real-time experience similar to talking and learning from a language tutor but one that tirelessly

[22]The content of this section is part of the paper previously published in **Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology**, Article No.: 23, pp. 1–3, 2023, San Francisco, CA, USA [180].

provides explanations and practice, is available any time of day, is not impacted by my personal circumstances and moods, and in general adjusts to my needs. However, existing conversational AI systems constantly require manual information input to make the agent act in a desired role, making them quickly unusable for me, as input with one thumb is time consuming and exhausting. This inspired us to focus on the potential of conversational AI for me and for individuals in similar situations, by smoothing out the onboarding process of engaging with chatbots by minimizing user input.

In this work, we aim to pinpoint the limitations of available conversational AI agent in assisting users with hand-motor disabilities. Replika [66], designed as a general companion, provides emotional support and companionship to its users. It has the distinct ability to adapt to a user's personality and preferences, carving a unique relationship with each user. However, it is only accessible via mobile devices, which is inaccessible to me and potentially to others with hand-motor impairments. Caryn AI [189], still in beta, allows users to converse with a virtual influencer. Although its unique training method using GPT-4 [67] and Forever Voices [190] suggests potential, its performance is still being evaluated. These systems and others like them primarily foster a one-to-one relationship with the user, useful for entertainment and skill building. To allow the agent to adopt a different persona, complete with unique behaviors and attitudes, the user must provide the necessary information repeatedly. This requires a significant amount of input effort, difficult for someone who is unable to type. Our proposed system aims to overcome this limitation with pre-created personas to facilitate building one-to-many relationships with different AI agents.

In this project, we introduce a prototype called Virtual Buddy, also referred to as V-Buddy, that focuses on reducing friction in the onboarding process of interaction with conversational agents. V-Buddy offers the ability to create multiple personas, optionally via pre-filled templates with easy-to-select options, each giving the AI agent a different

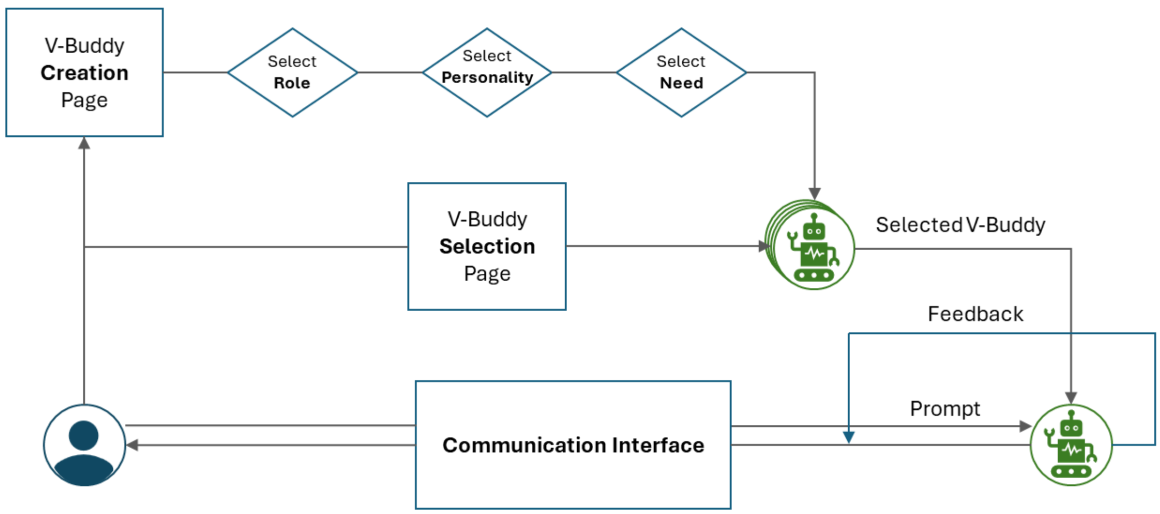


Figure 3.10: V-Buddy's interaction flow. Users start by visiting the V-Buddy Creation Page, where they can select the role, personality, and specific needs for their virtual buddy. These choices guide the creation of a customized V-Buddy, which is then available for selection on the V-Buddy Selection Page. The selected V-Buddy interacts with the user through the Communication Interface, providing responses and receiving feedback to refine interactions. This design ensures a seamless and accessible onboarding process, particularly beneficial for users with hand-motor disabilities.

role and personality, to assist focused or topic-relevant conversations. The personas created on V-Buddy remain usable across interaction sessions without requiring repeated or further information from the user over time. However, if the user so chooses, they are editable allowing the user to modify the persona as needed. With multiple available personas, V-Buddy also enables supporting one-to-many relationships (e.g., one user can have many different AI buddies in the same app) as opposed to the one-to-one relationship the current conversational AI systems offer.

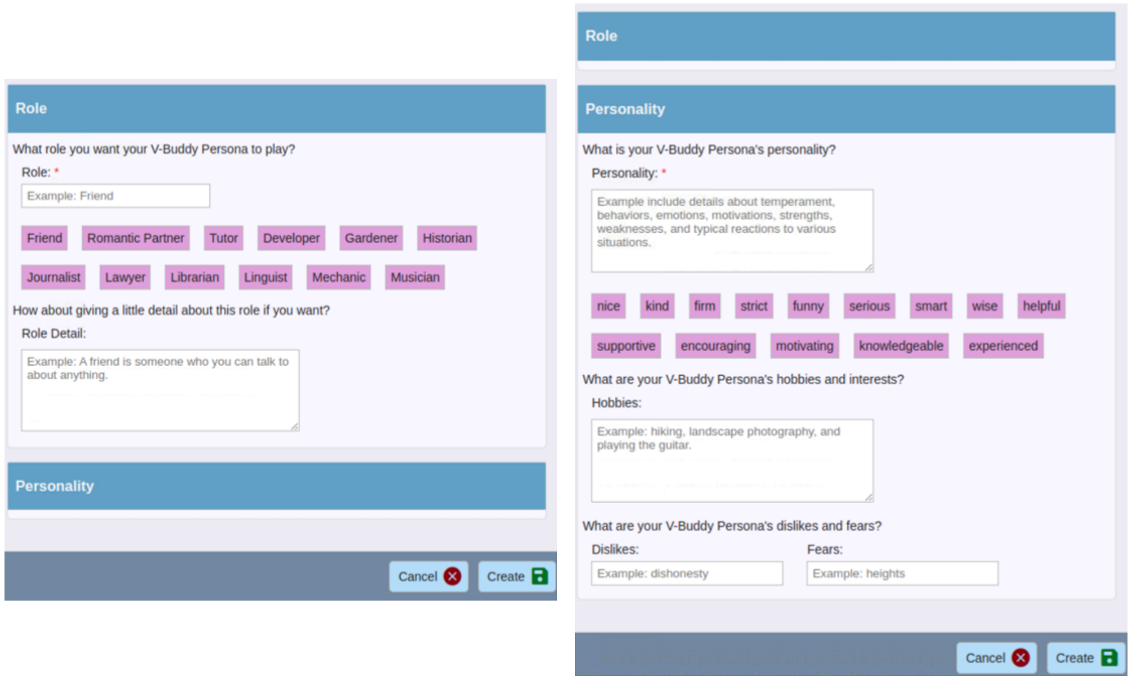


Figure 3.11: Screenshots of the interface, showing easy-to-select personality (e.g., kind, strict) and role (e.g., Gardener, Musician) options to generate a V-Buddy; customizable as needed.

3.4.1 System Design

V-Buddy is a web-based system that enables users to create several virtual personas facilitating one-to-many interactions focusing on specific hobbies and personality types of agents. The digram in Figure 3.10 shows the interaction flow within V-Buddy. The *User* component of V-Buddy collects basic details like the user's name, pronouns, and optionally, their general needs, including disability-related ones. The *V-Buddy Personas* component lets users "create" a new persona or "select" from their previously created ones. Users can customize their persona based on three attributes: Role, Personality, and Needs, each offering pre-filled options for ease. For example, Role can be a friend or tutor, Personality can be kind or witty, and Needs might incorporate disability accommodations. Figure 3.4 shows the interface for setting the role and personality. Once set, these preferences are stored in a MongoDB-based [191] database. Through the *Converse* component, users can begin to interact with their created persona, with responses powered by GPT-4 [67]. V-Buddy's GUI adheres to WCAG's operability principles, offering tailored options for users with limited hand-motor control. It directs GPT-4 with specific prompts to align responses with user-selected roles and personalities, such as guiding a "friend" role with a "witty" personality to elicit friendly and humorous conversations.

V-Buddy is an early proof-of-concept, designed with the goal of adapting conversational AI to be accessible to me and potentially, people in a similar situation, where typing is challenging or not possible due to temporary injury or long term disability. While speech-based input is an option, it may not always work due to varying accents, levels of speech clarity, and tongue muscle control and hence not considered in our current prototype. Including specific needs for both the user and the virtual buddy in the design process can lead to more empathic and understanding interactions, which can potentially strengthen the bond between the user and the virtual buddy [192, 193]. V-Buddy offers easy-to-select options, generated using a GPT-4 model inspired by Valencia et al.'s work [194], which showcased the utility of LLMs to expand short text snippets into longer output aiding augmentative and alternative communication (AAC) for non-verbal individuals. The options provided are contextually appropriate to the ongoing conversation, aiming to improve user experience and reduce physical strain.

3.5 PromptAssist (2023)[23]

Recent advances in T2I models [68, 69, 70, 196, 71] have enabled users to create high-quality, stylistically diverse images of nearly any subject with little or no artistic

[23]The content of this section has been previously submitted as a preprint to arXiv (2023) [195], available at: https://arxiv.org/abs/2309.02402

training [197]. Models such as DALL-E 2 [24], Midjourney [25] and Stable Diffusion [26] allow users to enter a text or text+image prompt, which the system interprets to generate images that themselves are not contained within the training set.

T2I models have gained attention in part because they enable non-artists to create images that may be of a similar quality to those created by professional artists. However, these models also have potential to help would-be artists who encounter accessibility issues during their artistic work. Specifically, we see potential for T2I models to serve as an accessible image creation method for those with motor disabilities, as it sidesteps the need for fine motor control that might occur when using a paintbrush to paint on canvas or using a mouse to edit pixels in a digital image [198]. Most current T2I models generate images based on a text prompt (*e.g.*, "photograph of an orange cat riding on a skateboard"), which is ideal for accessibility as text can be entered in many ways, including traditional keyboards, alternative input devices, eye or head movements, or voice [199].

While text input can accommodate users with a range of abilities, text entry may still be challenging for users with motor disabilities [200, 201, 202]. Thus, it is important that accessible T2I tools be designed to support user interaction that best suits their abilities [198], while maintaining the sophistication needed to support users' creative goals.

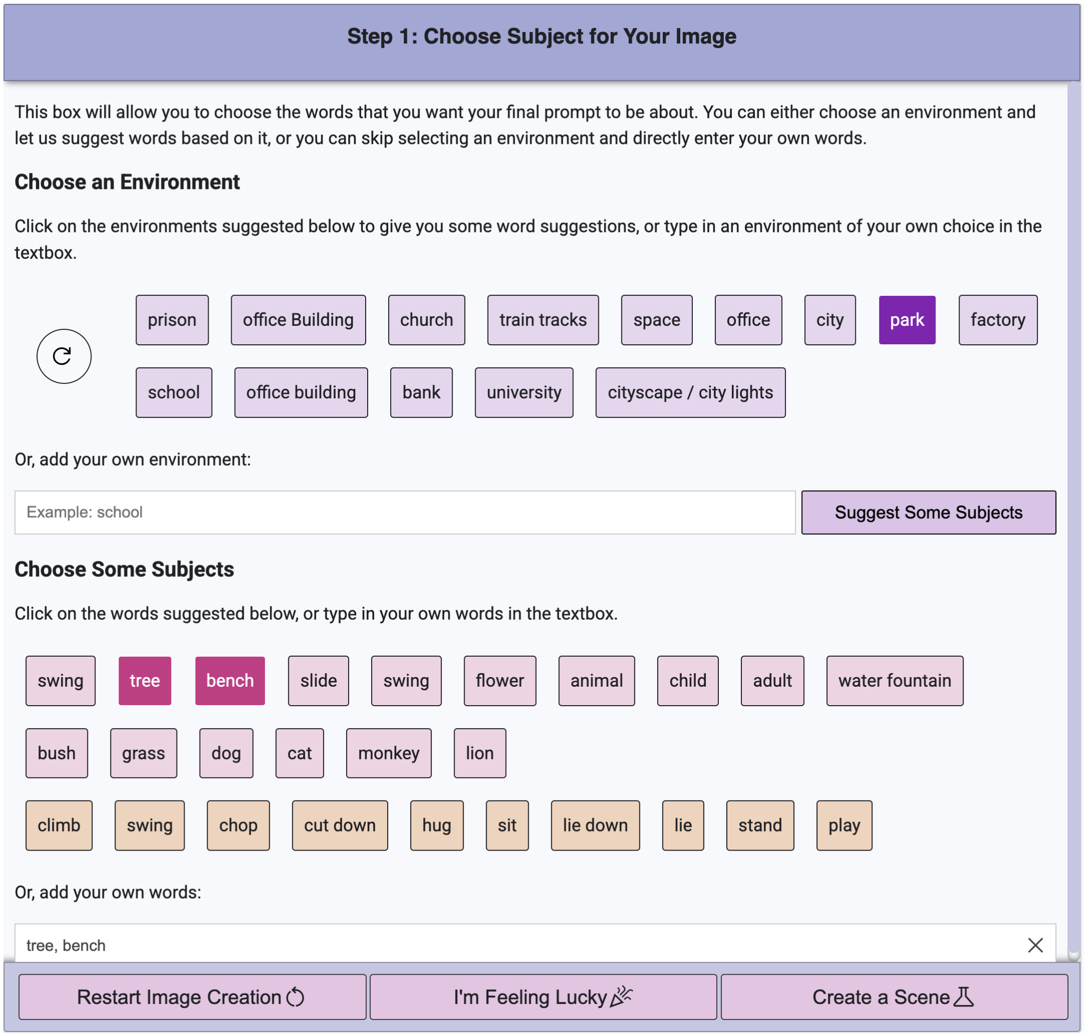
In this work, we discuss the design and development of *PromptAssist*, a prototype, accessible interface for creating T2I prompts. PromptAssist is a web-based application that allows users to create T2I prompts using a combination of keyboard and mouse input. PromptAssist uses an LLM to suggest prompts based on whatever the user has input. PromptAssist offers three primary features for creating prompts:

[24] `https://openai.com/dall-e-2`
[25] `https://www.midjourney.com`
[26] `https://stability.ai`

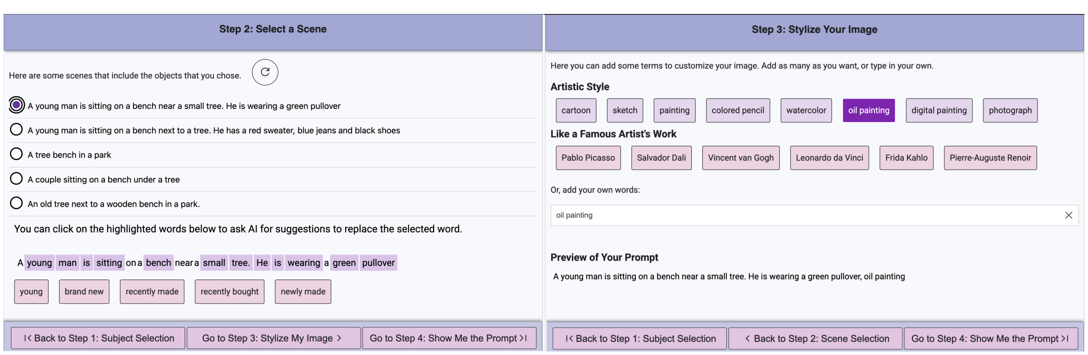
1. Automatically-generated suggestions for creating prompts or adding details to prompts;
2. An accessible text entry interface that supports both text entry and pointer-based interaction;
3. A wizard-based workflow that guides the user in creating prompts.

PronptAssist was created by a diverse team that primarily includes individuals with motor disabilities (4 of 5 authors identify as having a motor disability); its design is motivated by our personal experiences interacting with inaccessible user interfaces and solving our own accessibility problems. We developed PromptAssist as a way to explore accessibility challenges inherent in T2I tools, and potential ways to mitigate those challenges. The initial project idea was after several weeks of testing existing T2I models and user interfaces. After brainstorming various ideas for more accessible T2I tools, the team settled on the goal of enabling *easier composition of text-to-image prompts* for users who experience difficulty in typing long texts.

The PromptAssist prototype focuses on enabling users to write usable T2I prompts with minimal input. PromptAssist was partially inspired by existing tools like Promptomania's Prompt Builder [203], which helps users come up with creative ideas for prompts by suggesting image attributes that can be included in a prompt, such as style (*e.g.,* pencil drawing or photograph), color palette (*e.g.,* monochrome), or artist style (*e.g.,* Frida Kahlo). Promptomania provides lists of these attributes, usually with thumbnails that show example output; users can include specific attributes by selecting them from menus. While Promptomania was designed to address creative challenges, its design may solve some accessibility challenges as well. With PromptAssist, our team attempted to build on this menu-based prompt creation workflow, with a specific focus on 1) enabling users to create prompts using a variety of input methods, and 2) enabling users to create prompts with minimal input.



(A)



(B)

Figure 3.12: (A) Step 1 of PromptAssist allows users to select an environment and choose subjects and optionally actions within that environment. (B) In Step 2, PromptAssist enables users to choose from a variety of prompts (left image), and in Step 3, it provides the facility to incorporate artistic style data (right image).

3.5.1 PromptAssist Workflow

To support the design goals we identified, PromptAssist uses generative *text* models (*e.g.*, large language models) to aid users in creating prompts for a text-to-image model. Recent accessibility research has explored how LLMs can help users compose text [204, 205, 206] and create interactive prototypes [207]; with PromptMaker, we extend that approach to creating text-to-image prompts. Instead of offering a preset list of prompt ideas, as Promptomania does, PromptAssist can extend whatever input the user provides. For example, a user might begin a prompt by typing the word “beach”, and the system could add stylistic and other details (*e.g.*, ”watercolor painting of a beach at sunset”). The PromptAssist prototype was built using an internal transformer-based large language model [208] comparable to models such as GPT-3 [209].

PromptAssist uses a wizard-based workflow to walk users through creating a prompt. At each step, the user can input their own text, request assistance from the model, or skip that step. PromptAssist breaks down prompt creation into four components:

1. *Environment*. Choose an environment in which the image takes place;
2. *Subjects*. Identify particular objects to be included in the prompt;
3. *Actions*. Describe actions taking place within the scene;
4. *Scene*. Select a scene relevant to the chosen subjects and actions. Editing the scene may involve typing modifications directly or replacing selected words with suggested alternatives;
5. *Style*. Describe a medium (*e.g.*, photograph) or other style characteristics.

To support accessibility, information can be typed in at each step, or users can choose from suggestions using the mouse. At each step, the user can edit the suggested text or generate new suggestions. Figure 3.12 demonstrates an example interaction with PromptAssist. In the first step as depicted in Figure 3.12:A, the user chooses an environment from a list of environments - in this case a *park*. They then add some objects to the scene - a *tree* and a *bench*. Moving on to step 2, as illustrated in Figure 3.12:B-left, the user selects a contextual scene from suggested ones - in this example *"A young man is sitting on a bench near a small tree. He is wearing a green pullover"*. Lastly, as shown in Figure 3.12:B-right, the user adds an artistic style - here *oil painting* to the scene. The resulting prompt was copied from PromptAssist into DALL-E and the resulting images are shown in Figure 3.13.

3.5.2 Research and Co-Design of PromptAssist

PromptAssist has been developed through iterative development over the course of several months. The PromptAssist team contains multiple researchers with motor disabilities who themselves are users of the system.

Research Team and Process

Our multidisciplinary research team, led by primary investigators including myself, Rostamzadeh, and Kane, comprised experts from computer science, human-computer

Figure 3.13: DALL-E 2 output for prompt "A young man is sitting on a bench near a small tree. He is wearing a green pullover, oil painting." This prompt was created by the authors using suggestions from PromptAssist.

interaction, accessibility, and computer vision. As someone living with SMA, I spearheaded the development of PromptAssist and led the paper writing process. Our team members contributed to research sessions, feedback, and project outputs. We utilized Google Chat and Google Meet for real-time discussions and Google Docs for collective note-taking and resource exchange to maintain efficient communication.

Iterative Development of PromptAssist

Rostamzadeh, Kane, and I conceived the initial concept for PromptAssist and developed its early iterations. We refined this prototype through testing and recurring group discussions. Both Kane and I used our personal accessibility tools during testing. Once the PromptAssist prototype matured and could be more easily tested, we recruited Izadi and Shriram via an internal disability interest group within our organization. Although Izadi and Shriram did not have a background in research, they joined the project because of their interest in shaping the development of more accessible T2I technologies and to gain experience in accessibility research.

Izadi, Shriram, Kane, and I were present at every test session, and I generally served as the session facilitator. Our research team tested the prototype of PromptAssist on our own devices, but we primarily tested our prompts using an internal version of Parti [210], an autoregressive text-to-image model that produces images comparable to models such as DALL-E. It is worth noting that prompts generated by PromptAssist can be copied and pasted into any T2I model.

Test Session 1: Collaborative Planning and Discussion

This session functioned as an informative gathering. I detailed the research goals and future plans, particularly guiding less experienced members, Izadi and Shriram, about their roles in iterative testing and feedback. We created a group chat room for the research duration to facilitate questions and image sharing among the team.

Test Session 2: Experimenting with Existing Text-to-Image Tools

In this session, I familiarized the team with existing T2I tools, encouraging them to experiment with the current Parti user interface, which consisted of only a text box and submit button. We explored the tools' potential and boundaries by generating images based on varying concepts, styles, and detail levels. Izadi, for example, focused on an idea of a bird with a corgi's face flying over San Francisco. Shriram experimented with multiple prompts to understand the safety filter's operation. Kane used different color terms to observe their impact on cat portrait images. The team members communicated their experiences throughout the session in a "think-aloud" format, and Kane and I documented the proceedings.

Feedback on Current T2I Systems. The team members, particularly those new to T2I systems, were impressed by the output quality but agreed on the need for usability and accessibility improvements. Issues identified included the absence of access keys or keyboard shortcuts, the inability to cancel the slow image generation process, and the lack of autocomplete or grammar correction. The possibility of benefiting from pre-made prompt categories or ideas was also discussed. One theme that arose during testing was difficulty in generating longer prompts or iterating on prompts. Shriram, in particular, found it difficult to type longer or more prompts. The team discussed how to refine prompts using natural language instructions like "make this more descriptive." Izadi expressed interest in using natural language to edit or merge images generated by the model.

Test Session 3: Experimenting with PromptAssist

In this collaborative session that I led, the team tested the PromptAssist prototype. I explained how PromptAssist addressed the usability and accessibility issues identified in the previous T2I systems session. Team members worked together and shared feedback via a "think-aloud."

This version of PromptAssist, while similar to the one described above, required users to compose their prompt in a specific order, without skipping steps.

Feedback from the session. Shriram spent much of his time generating images related to the ocean. He was particularly interested in what subjects were added to the image, noting that requesting ocean images tended to include plants but not animals. Izadi noted that the user interface did not quite match their goals; while they appreciated that PromptAssist offered suggestions, they wanted to be able to start with their own specific prompt and build upon it. While Izadi noted that selecting parts of prompts using the mouse reduces the need for typing, they desired the ability to do both.

The team suggested a variety of user interface changes, including: reducing white space in the interface; increasing color contrast; and making it easier to go back or restart a prompt. This early version usually provided 3-5 suggestions in each category; participants requested that ten or more suggestions would be useful, especially when coming up with their initial idea for the prompt. As discussed in the first session, adding autocomplete would be helpful so that users could enter a partial prompt and let the model finish it.

Test Session 4: Revised PromptAssist

Following the previous session, I updated PromptAssist based on user feedback. Enhancements included adding a multi-page layout, improving color contrast, writing human-readable error messages, increasing the number of suggestions, allowing users to generate additional suggestions, adding the option to skip steps like artistic style, and enabling keyboard-only navigation of all buttons and menus.

As in the previous session, I walked the team through the updates made in response to their feedback. The team members tested the enhanced PromptAssist and shared their thoughts. They all found that the changes made it easier to navigate through the process and follow their own creative ideas. The revised prototype's notable advancement was its flexibility in allowing user-defined creative processes over prescribed sequences. Unlike the prior version, which enforced a specific prompt format, this version allowed users to enter their own prompts, accessing assistance only when needed.

3.5.3 Discussion

Improving Usability and Accessibility of T2I Tools

This paper documents the co-design and evolution of an accessible prompt creation tool for T2I systems, which was designed in response to feedback from disabled team members who found typing prompts, particularly longer ones, challenging in the existing text-based interface, which was essentially just an HTML text input control.

The creation of PromptAssist provides ways to enhance T2I interface accessibility. It facilitates prompt creation through typing, pointing, clicking, or a combination, adhering to the WCAG's concept of *operability*—allowing any input device to perform all actions. Unlike existing tools that limit input to predefined categories, PromptAssist uses an LLM to offer contextual suggestions, allowing users to expand their own ideas, rather than choosing from a preset list of image ideas. In addition to enabling more accessible forms of input, these contextual suggestions could be beneficial for all users regardless of their abilities.

Unleashing Creativity with T2I Tools

It is clear that T2I models can enhance the creative abilities of people, enabling them to create images that they would be unable to create by other means. T2I systems may be especially empowering to individuals who are unable to effectively use other image creation tools because of accessibility barriers. The focus on text input in current T2I models is beneficial in some ways, as many people with disabilities have already found accessible ways to input text. However, as shown in this work, there remains the opportunity to increase accessibility and ease of use of these systems.

Creativity *vs.* Ease of Use

One tension that arose in designing PromptAssist's user interface was balancing creative flexibility and ease of use. While pre-generated contextual prompt ideas can help users who find typing challenging, it risks limiting creativity and user autonomy. Interviews with experienced T2I users revealed that prompt crafting is viewed as part of their creative work [197]. Over-reliance on language generation could also diminish the perceived independence of a user with disability, giving the impression that the system, rather than the user, is doing the work [205].

To mitigate concerns about creativity and autonomy, PromptAssist enables users to view system suggestions, which they can then accept, modify, or reject. This approach amplifies their original ideas without making creative choices for them, an aspect that remains crucial in the development of accessible creative tools.

3.5.4 Summary

In this work, we introduced PromptAssist, a prototype designed to enhance the accessibility and usability of T2I models for individuals with motor disabilities. PromptAssist leverages LLMs to generate contextual suggestions, making it easier for users to create detailed and creative prompts with minimal input. Our iterative development process, informed by feedback from a diverse team that includes individuals with motor disabilities, highlights the potential of PromptAssist to bridge accessibility gaps in current T2I tools.

The findings from our research emphasize the importance of designing accessible interfaces that support various input methods and creative workflows. By integrating user-centered design principles and participatory research methods, PromptAssist demonstrates how technology can be adapted to meet the diverse needs of users, empowering them to engage in creative endeavors regardless of physical limitations.

PromptAssist not only addresses the usability challenges inherent in existing T2I systems but also opens up new avenues for creativity and expression. The balance between providing useful suggestions and maintaining user autonomy ensures that individuals with disabilities can fully participate in the creative process, fostering a more inclusive and accessible digital art landscape.

Future work will focus on further refining PromptAssist based on user feedback, exploring additional input modalities, and expanding its applicability to a broader range of T2I models. The development of accessible T2I tools like PromptAssist is a step toward a more inclusive future where technology empowers everyone to unleash their creativity.

3.6 Conclusion

In this chapter, I presented the development and evaluation of innovative input methods and interaction approaches designed to enhance accessibility for individuals with motor impairments. Through detailed analysis of three distinct input systems—a hands-free video game controller using facial expression recognition, an LLM-based conversational

AI system called Virtual Buddy, and an accessible text-to-image interface also grounded in LLMs called PromptAssist—I highlighted the potential of these technologies to transform the interaction experience for users with diverse abilities.

The hands-free video game controller demonstrated the viability of using facial expressions as a primary input method for gaming, providing an inclusive and engaging experience for individuals with severe motor impairments. We conducted a user study with eight participants with neuromuscular diseases to evaluate the system's usability and gameplay experience. The system's ability to map facial expressions to game actions effectively and the positive feedback from user evaluations underscore its potential to offer a fun and accessible gaming alternative. Given the unique needs of each motor-impaired person, our software solution can be easily customized to suit their abilities and needs, assuming they can control their facial muscles. With more game developers including accessibility features, we are hopeful facial expression recognition will soon be available, opening up new gaming possibilities for people with severe mobility issues.

Conversational AI systems have shown promise in reducing barriers to social interaction and learning for users with hand motor disabilities. By enabling the creation of multiple personas with customizable roles and personalities, V-Buddy offers a flexible and empathetic approach to conversational AI, fostering meaningful connections and tailored support for users.

The development of PromptAssist as an accessible interface for text-to-image generation illustrates the importance of user-centered design in creating tools that accommodate various input methods and creative workflows. By leveraging LLMs to generate contextual suggestions and providing an intuitive, wizard-based workflow, PromptAssist empowers users with motor disabilities to engage in digital art creation with minimal effort, expanding the possibilities for creative expression.

The findings from the evaluation of these input methods highlight the critical need for customization and flexibility to address the unique needs of each user. Personalization options, multimodal input, and considerations for user fatigue are essential components in designing effective input technologies.

In conclusion, this chapter reaffirms the critical role of interaction methods in accessible technology design. By leveraging advancements in computer vision, natural language processing, and machine learning, we can create systems that empower individuals with disabilities, enhancing their ability to interact with digital environments seamlessly. The insights and lessons learned from this research provide a strong foundation for future work, guiding the development of even more sophisticated and user-centric assistive technologies, and ultimately enhancing the quality of life for individuals with disabilities and promoting greater inclusivity in digital environments.

Chapter 4

Sensation

In this chapter, I delve into the second component of my proposed conceptual design space: sensation. Sensation refers to the various ways in which a system communicates information back to the user, encompassing a range of sensory feedback mechanisms [211, 212], including visual, auditory, and tactile outputs. The focus on sensation is crucial in the domain of accessibility, as it ensures that the system's feedback is tailored to the diverse needs and preferences of users, particularly those with disabilities [213, 214].

4.1 Introduction

Accessible output modalities play an essential role in creating an inclusive user experience. By integrating multiple forms of feedback, we can cater to a wider audience, including individuals with sensory impairments or motor disabilities. The effectiveness of sensation is not only a matter of technological sophistication but also of understanding the user's sensory and cognitive processing. For individuals with disabilities, the traditional forms of feedback might not suffice, necessitating innovative approaches that consider their unique requirements. This chapter highlights the interplay between different feedback mechanisms and their impact on usability and user satisfaction. One of the primary projects I will discuss in this chapter is the MouseClicker system. This system exemplifies the integration of tactile feedback to provide physical agency and enhance the interaction experience for users with severe hand motor impairments. By simulating the tactile sensation of clicking a mouse, MouseClicker showcases how sensory modalities can bridge the gap between digital interactions and physical sensations, offering a more holistic and inclusive approach to assistive technology design.

In chapter 3, I discussed in detail the technologies and devices developed for people with motor impairments to interact with computers. While all those interaction modalities enable input functionality, none provide haptic feedback inherent in physical tools, such as a computer mouse or keyboard.

Studies with users have revealed that thinking and creativity are facilitated by the tools we use, from the versatile pencil and paper to the more purpose-oriented computer keyboards. Psychologist Vygotsky proposed the idea that tools enhance a person's problem-solving abilities by expanding their Zone of Proximal Development (ZPD) [215]. According to him, tools play a crucial role in shaping and extending human cognitive abilities. That work laid the foundation for understanding how tools and external aids contribute to problem-solving and higher-order thinking processes. To further expand upon the idea, sociologist Sherry Turkle highlighted the significance of objects in providing a sense of materiality, embodiment, and connection to the physical world [216]. She further suggested that physical objects, such as pencils, can engage our senses and enable deep thinking, reflection, and imaginative exploration, offering sensory richness and a tangible presence that digital technologies often lack. Continuing the discourse on the importance of tangibility, designer Don Norman contended that physical objects can shape and influence human cognition and problem-solving [217]. His work, particularly the book *The Design of Everyday Things*, showcased the impact of physical object design on the way we think and interact with the world.

In addition to psychologists and designers highlighting the role of objects in problem-solving and thought construction, artists and musicians, like pianists, also stress the significance of touch in creating and playing music — a sensation that on-screen pianos frequently fail to reproduce. Similarly, computer keyboard enthusiasts wax poetic about the sound, travel, and tactile feedback of mechanical keyboards, and how their hands glide over the keys for effortless input. The same cannot be said of on-screen keyboards, often the dominant input option for people with hand motor impairments. Social scientist Howard Gardner talks about the impact of the tactile sensation of his fingers on keys, noting the soothing influence of typing, which he finds to be more significant than the satisfaction derived from creating well-written content. If presented with the choice, he would choose to use the keyboard rather than bypass it to directly transmit thoughts from his mind to the computer [218].

Ideas from psychology and design, emphasizing the significance of physical objects, provide the foundation for the MouseClicker work, which draws inspiration from their insights to focus on integrating tactile sensations into the design of ATs.

4.2 Related Work

A technology with multimodal output or feedback can utilize various sensory channels to provide information to users [211]. This can be beneficial since, in one context, feedback from one sensory channel might not be suitable or sufficient, so the user interface could present the same information through haptics instead. In the context of the MouseClicker work, I focus on haptic feedback. In this section, I provide a brief overview of prior work related to haptic feedback provided by assistive devices.

4.2.1 Haptic Feedback in AT

Haptic feedback in AT encompasses a variety of modalities, each offering unique benefits to enhance user interaction. This feedback spectrum includes force feedback, tactile feedback, and vibrotactile stimulation, each playing a unique role in augmenting user experience.

Force Feedback in AT: Force feedback or direct pressure, often seen in virtual reality and rehabilitation devices, offers users a tangible sense of resistance or pressure. These systems simulate real-world physical interactions, providing crucial sensory input that aids in motor skill recovery and spatial awareness. For instance, previous studies have shown the effectiveness of haptic feedback in improving finger independence and dexterity in post-stroke patients [219, 220], enhancing grasp control in individuals with multiple sclerosis [221], and supporting hand rehabilitation in people with tetraplegia [222].

Texture Perception in AT: Tactile feedback encompasses a broad array of sensations, from basic touch to intricate textural information. This type of feedback is particularly beneficial in assistive devices for individuals with sensory impairments, where the tactile sensation can substitute for or augment visual or auditory input. Devices like tactile gloves and Braille displays are prime examples where tactile feedback has been revolutionary.

Vibrotactile Feedback in AT: Within the tactile feedback category, vibrotactile stimulation is a widely used form. Vibration motors and piezo-actuators are commonly used to produce vibrotactile stimulation. Initially popularized for mobile device alerts, vibrations notified users of incoming calls or messages, system states and setting changes [223, 224], with rhythmic and amplitude-varied feedback. Over time, vibrotactile feedback has become a dominant haptic modality in VR experiences. In the realm of touchscreen devices, which lack inherent tactile response, vibrotactile feedback has been pivotal in emulating the sensation of physical buttons, enhancing text entry performance and user experience [225, 226]. Beyond general usage, vibrotactile feedback has shown immense value in supporting users with various disabilities. It has been effectively employed in AT for blind or visually impaired users, providing an alternative sensory channel, and conveying information that would typically be visual. This approach has been used effectively for shape recognition, reading enhancement through tactile representation of Braille, and navigation assistance, where tactile cues replace visual ones [227, 228, 229, 230]. Similarly, in the context of rehabilitation, vibrotactile signals have aided in improving fine motor skills and grasp control in individuals with motor impairments [231, 232]. For individuals recovering from stroke or those with brain and spinal cord injuries leading to sensorimotor impairments, vibrotactile feedback has been particularly valuable. It provides guided feedback for improvement and correction of movements, potentially reducing the need for constant supervision by therapists [233, 234].

Our focus on vibrotactile feedback for the MouseClicker system, particularly through coin motors, is grounded in its blend of efficacy, simplicity, widespread use, and user accessibility. The choice was driven by the need for a lightweight, compact, and cost-effective haptic actuator that had been previously widely explored, and could be easily integrated into devices. While other forms of tactile feedback, such as pneumatic or electromagnetic actuators, offer different benefits, vibration motors provide an optimal balance of feedback quality, device miniaturization, and affordability. This balance is crucial in AT, where user comfort and device accessibility are paramount. Our approach aims to ensure that MouseClicker is not only technically effective but also practically accessible to a wide range of users with severe motor impairments or quadriplegia. We plan to open-source our design with the hope that friends and family members of people

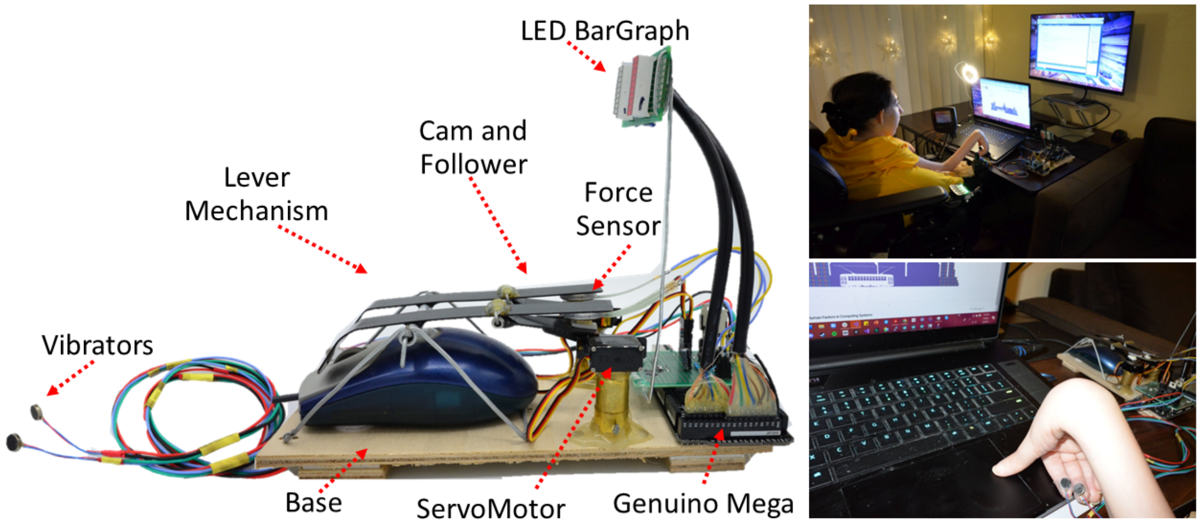


Figure 4.1: Left: Side view of the MouseClicker device showing the microprocessor, lever mechanism, vibrotactile haptic interface, and base of the MouseClicker. Right Top: shows me using the MouseClicker. Right Bottom: The vibration motors attached to my fingers for providing haptic feedback corresponding to the mouse clicks.

with severe motor impairments experiment with our design and modify it as needed without incurring high costs typical of ATs.

4.3 MouseClicker (2024)[1]

The inclusive input device presented in this work, started with a conversation about the input methods I can use as a person with motor impairment. Beyond the need for an effective input method, which is met by my on-screen keyboard, I expressed the desire for tactile sensation and a sense of "physical" connection with the input device. In particular, I cited the example of a computer mouse, saying that despite being able to use a mouse with my touchpad I had no idea what using an actual computer mouse felt like. Our ongoing conversations revealed a broader desire for the tactile experience of using physical tools like keyboards and musical instruments. While their virtual counterparts

[1]The content of this section has been previously published in **ACM Transactions on Accessible Computing (2024)**, Volume 17, Issue 1, Article No.: 5, pp 1-31 [235].

are accessible and functional - such as on-screen keyboards and digital music production software like GarageBand - the physical sensation offered by those tools was missing for me. My feeling of exclusion from the authentic experience of using a physical object highlights a critical gap in current AT designs, which typically prioritize functionality over the holistic experience of using an object [216]. This presented us with both a challenge and an opportunity to investigate the integration of other sensory modalities - such as touch and sound - into an input device, with the aim of creating a more inclusive experience for me.

In this work, we present MouseClicker, an input method co-designed with me, that enables physical agency over a computer mouse and provides the tactile sensation of clicking it. Our initial design for recreating the computer mouse experience was based on prior approaches that emphasize the importance of direct interaction in the design process [72]. These approaches suggest that direct interaction is often desirable as it allows for a more efficient and comfortable experience. Based on this, we began with an orthoprosthetic glove, emphasizing direct interaction between the user and the device to provide tactile feedback at the point of interaction. However, upon further investigation, we recognized three serious drawbacks to this approach for me. Our primary concern was the substantial expense associated with developing an exoskeleton. Our work's objective centers around making our design open-source, allowing others to recreate it inexpensively in their own homes. Furthermore, a publicly available orthoprosthetic glove might not accommodate various hand sizes and shapes, as it would be specifically tailored for me. Lastly, while the orthoprosthetic or exoskeleton solution would allow using the mouse directly by externally controlling my fingers to click the mouse buttons, it inadvertently risked diminishing my thumb control due to the mechanics involved in the glove design. Given the priority to maintain my existing level of thumb functionality, we deemed this trade-off to be unacceptable. This insight prompted a shift in our design approach from direct to decoupled interaction.

Unlike assistive input devices that often require the design of entirely new devices to replicate a desired functionality, our prototype leverages the standard computer mouse to recreate the tactile sensations and provide a physical representation of the user's actions, which is missing in digital-only options. This approach not only allows us to capitalize on the existing functionality of commonly available input devices, but it also helps ensure affordability and simplicity, presenting a novel pathway towards holistic inclusion in AT design. It is known that the sense of touch can augment any interaction method, where haptic feedback serves as a complementary communication channel to other senses such as vision and hearing [236]. Nevertheless, while vibrotactile feedback is significant for interaction design, not much attention has been given to this modality as an accessibility feature for individuals with hand motor impairments.

MouseClicker integrates tactile feedback corresponding to each mouse click. To test our decoupled interaction and tactile feedback, we performed a user study to understand the range and location of tactile feedback that most effectively simulates the sensation of clicking the left and right mouse buttons for me. By conducting a study with individuals without hand motor impairments and me who has a hand motor impairment, our objective was to ensure that the haptic feedback design is grounded in a universally recognizable standard, enhancing its potential efficacy for all users, including those with motor impairments. This methodological choice stems from prior work in AT design [222, 167, 123]. We provide details in the study design section (Section 4.3.3).

As with other AT designs, our work is tailored to suit the unique needs of one individual. However, our hope is that the tactile parameters learned through our study are generalizable, and can be integrated with other forms of hands-free computer input methods.

Our main contributions are as follows:

- A proof-of-concept prototype that is collaboratively designed with and tested by me who has severe hand motor impairments due to a progressive neuromuscular disease.
- A user study with 10 participants without motor impairments along with me, aimed at comparing my haptic perception with the rest of the participants' responses, with a focus on mechanoreceptor functionality, and testing location and intensity of vibrotactile feedback, as well as sound representing physical mouse clicks.
- Appropriation of a computer mouse to demonstrate our vision of holistic inclusion (functional + sensory) through the integration of multimodal feedback for the design of an AT input device.

4.3.1 Decoupled Haptic Feedback in AT

Using a mouse for a person without a hand motor impairment involves physically moving the mouse (proprioceptive and kinesthetic feedback), which causes a cursor to move on the screen (functional feedback), and/or clicking one of the buttons to invoke an action (visual, haptic and aural feedback). The multimodal feedback enables a user to establish the link between their *intention* of clicking a mouse button by moving the mouse cursor, the *action* of pressing the mouse button, and the *evaluation* of their action by hearing the click sound, feeling the button press down, and seeing the resulting outcome on screen. The link established between the haptic feedback and the click is coherent as the site of action and feedback received is in the same localized appendage (and sensory modality) for a person without a disability. However, for someone with hand motor impairments, when the intention is exercised through another input modality such as facial expression or gaze, and feedback is received on the hand - this relationship changes and is no longer analogous. In this scenario, the third-party (either human or machine performing input) needs to: (1) acknowledge the user's *intention*, (2) have the physical ability to perform the *action* or an equivalent, (3) recognize when the action is taken successfully, and (4) provide some form of feedback to the user in order for them to *evaluate* success or failure.

This raises an interesting question: "can the **decoupled haptic feedback** serve as a complementary communication channel for scenarios where the sites of action and feedback are not the same?" Answering this question can help us understand whether and how to integrate haptic feedback in the design of AT devices for people with hand motor impairments. Our current work is a first step towards answering this question by integrating haptic feedback that corresponds to input and establishing the feedback parameters for me, knowing that for some people with neuromuscular diseases, tactile sensations are also affected [237] and therefore a baseline of vibrotactile sensations may need to be established for each user.

4.3.2 Design Process

Our development of MouseClicker is deeply rooted in the principles of participatory design, especially given the unique requirements of individuals with severe hand motor impairments. In this regard, I played a pivotal role throughout the entire process. My participation went beyond simple consultation; I was actively involved in shaping the core design, functionality, and user experience of MouseClicker.

Our iterative design cycle is shown in Figure 4.2. There are three fundamental questions that we tried to address during this design process: (1) Does the prototype meet my needs? (2) Does the prototype create a desired user experience? and 3) Is vibration a suitable method for providing haptic feedback corresponding to mouse clicks for me? Addressing these questions in fact would cover all the three dimensions of my proposed

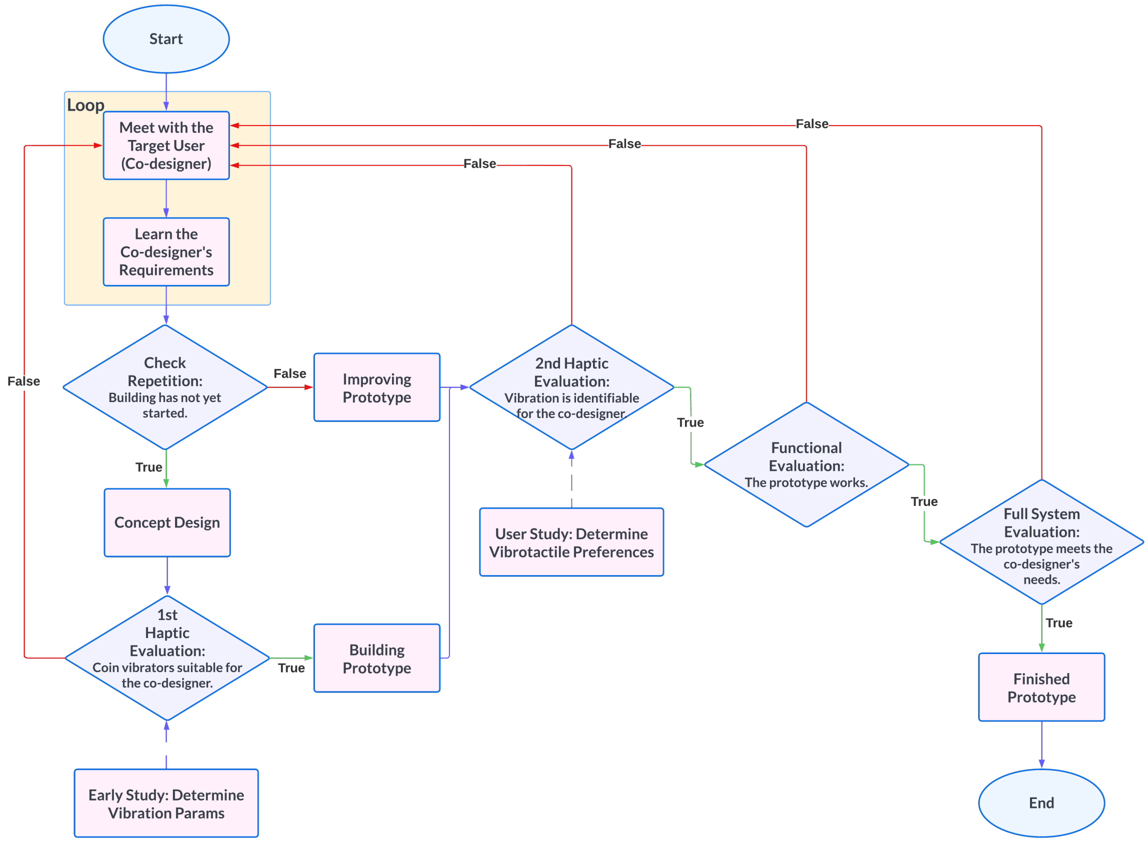


Figure 4.2: Design cycle of the MouseClicker system with the co-designer who is me that relies on one functional thumb to interact with an on-screen keyboard via a touchpad.

design space. To answer these questions, I was involved in every step – from initial brainstorming and defining requirements to participating in the design process at all stages as well as for all evaluation stages, i.e., (1) haptic feedback, (2) device functionality, and (3) full system. This is shown in Figure 4.2. To establish the target solution, we began by identifying the requirements and hopes that I had and focused on obtaining my insights through a series of brainstorming sessions followed by hardware prototype design iterations.

I can voluntarily control only one finger (right thumb) and use a trackpad to interact with the computer (Figure 4.1). I tap on the trackpad with my thumb to perform the left click, but in some situations, such as when I am tired or my hands are cold, even tapping (left click) becomes challenging and error-prone and requires the help of my caregiver. I am unable to perform complex keyboard + mouse input combinations as I can neither press any buttons nor perform multi-gestures on the trackpad. Instead, my caregiver assists me in performing complex inputs, limiting my ability to work independently. For right-clicking, I use additional software(PhaseExpress[2] in combination with Macro Recorder[3]) that has about a 1-sec lag before I see the result on the screen. I am unable to do a continuous click or scroll, common interactions that most take for granted. The bottom-right image in Figure 4.1 shows how my hand needs to be placed near the trackpad by my caregiver to allow me to use it for typing with an on-screen keyboard. After discussing with me and observing my interaction with the computer, it became clear that my needs extend beyond just having full mouse functionality. I also expressed a desire for the sensory feedback that comes with using a physical mouse.

Since enabling mouse functionality was not our primary goal in this work, we repurposed an existing mouse to focus on recreating the tactile sensations of using a physical mouse for me. To support input, our prototype uses a hands-free control mechanism to perform common functions such as a single-click, double-click, and continuous press, on the left and right buttons. Facial expressions were chosen as the input method because they provided an easy-to-use hands-free control mechanism for me. Two actuators, controlled by the user's facial expressions, physically press the left and right buttons to best approximate the experience of using a physical mouse (single click, double click, and continuous press). Vibrotactile feedback is provided on the index and middle fingers (common mouse button click fingers) through two small electric motors, rather than collocated with the facial input (i.e., directly with the site of facial input), in order to

[2]PhaseExpress: `https://www.phraseexpress.com/`
[3]Macro Recorder: `https://www.macrorecorder.com/`

provide a haptic experience analogous to the sensations most users associate with using a physical mouse. The decision to deliver feedback to the fingertips acknowledges that the core physical sensation of a mouse click centers on that tactile confirmation in the fingers. While some might expect collocated feedback, our focus was on the authenticity of the haptic sensation itself. By positioning the vibrotactile feedback at the index and middle fingers, we attempt to bridge the gap between the non-collocated input mechanism and the tactile expectations associated with using a conventional mouse. This design decision potentially delivers a more effective interpretation of the task as compared to collocated feedback.

Target System Operation and Feedback

Full control over a mouse involves moving the mouse on an XY-plane (2 axes = 2 variables,) and clicking the mouse (2 buttons = 2 variables). Considering that I am able to control the pointer's position using a trackpad independently, our design focuses on the physical button clicking, from both a functional and a feedback standpoint.

Analysis of a Computer Mouse Button. To design a system that performs *clicks*, we first analyzed the mechanical function of a common two-button mouse. The electrical switches that are implemented as buttons on the mouse produce a distinctive clicking sound. Usually, they are Single Pole Double Throw (SPDT) switches designed with a snapping mechanism in the moving contact. These types of SPDT switches produce one *click* when pressed and another *click* when released. Both clicks are easily identifiable when performing a long-press and hold action using the left mouse button, such as dragging an item on the computer screen. When performing a fast push/release action on the mouse's buttons (such as clicking on a link), the two-click sounds are often perceived as one.

Hardware

We appropriated a commonly available two-button mouse for our design to fulfill the my specific requirements the primary user. I helped ideate and design a solution that included physical actuation of a standard computer mouse. The ability to visually observe the mouse buttons being clicked and simultaneously feel the clicks on the fingers resonated with my aspiration to avoid feeling excluded, providing me with a heightened sense of "physical" interaction with my input device.

The total cost of materials for our proposed prototype is approximately $100. We believe this makes it an affordable assistive technology that not only provides the functionality of a mouse but more importantly, provides the tactile sensation of using a mouse through haptic feedback on the fingers.

Clicking Mechanism. The clicking mechanism presents a dual mechanical design for independently operating the left and right mouse buttons. Each side is actuated by an all-metal-geared micro-servo motor coupled with the lever mechanism in a cam and follower configuration. The lever position and pushing force of the end effector is acquired by its closed-loop circuitry. This enables the clicking mechanism to click on a wide range of computer mice and it compensates for loose tolerance in its manufacturing (characteristics appreciated by the maker community).

In our current prototype design (Figure 4.1), there are two main states of the device, that correspond to two servomotor-shaft positions: (a) rest, and (b) clicking (pushing the mouse button down), as shown in Figure 4.3. The input of the lever mechanism is the shaft rotation of the servomotor, and the output at the end-effector is the rounded tip of the lever that pushes down the mouse button. This allows us to provide the user with four types of feedback: (1) vibrotactile haptic feedback on two fingers to create the holistic experience of using a mouse, (2) auditory feedback in the form of a click sound from the

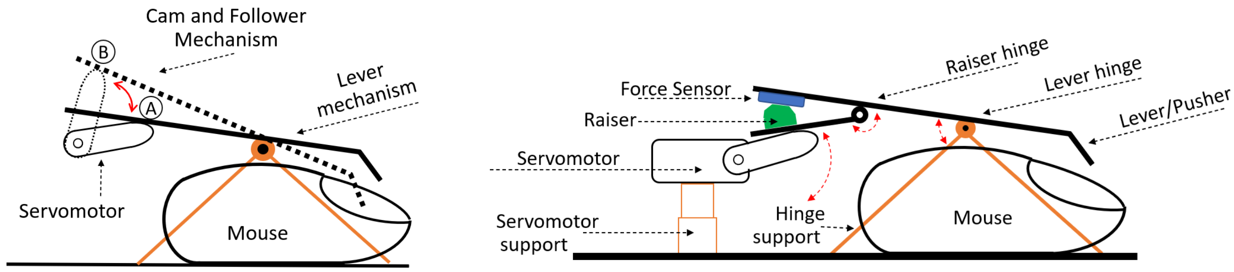


Figure 4.3: Left: The MouseClicker device showing the two main lever/pusher positions: a) rest, and b) clicking. Right: Overview showing all the parts of the clicker mechanism.

mouse itself, which was systematically tested in our experiments, (3) visual feedback from the mouse buttons being pressed down by the lever, and a LED bar-graph representing the force applied during the push, although we did not experimentally manipulate it as the benefits of visual components in enhancing user interaction has been extensively documented by prior research [238], and (4) functional feedback resulting from actions triggered by the mouse clicks on the computer.

Haptic Feedback. To provide vibrotactile feedback that could be considered a tactile representation of clicking a mouse, we focused on: (1) placement of the stimuli source on the body, (2) nature of the stimuli or the actuator, and (3) stimuli specifics, i.e., intensity, duration, and profile. We selected eccentric rotating mass (ERM) motors over reciprocating ones for vibration actuators as they are smaller and lighter.

Software

For functional mouse input, we wanted to use an off-the-shelf solution as that was not the focus of our design, but a necessary requirement to match the haptic feedback. A hands-free input method was necessary and after discussing together, it was decided to use a webcam-based facial expression recognition system for input, that was easy to implement and did not require a wearable device needed by gaze-based or BCI input

Button	Click Mode	Facial Expression
Left	Single Click	Disgust
	Double Click	Smile
	Continuous Press	Sad
Right	Single Click	Wide Eyes
	Double Click	Contempt
	Continuous Press	Jaw Drop

Table 4.1: The mouse clicking modes and corresponding facial expressions from my prior work [145] that are mapped to the mouse clicks. I selected these mappings through the customization interface we designed for this work to allow customizing MouseClicker according to personal preference.

methods. To trigger the MouseClicker, we based our input method on my prior work [146, 145], the facial expression-based system for allowing individuals with motor impairments to play video games that I presented in Section **??** in Chapter 3. In that work, we mapped different combinations of the extracted AUs to actions in video games. We utilized the first part of this pipeline, i.e., extracting AUs from the webcam stream and combining them into facial expressions to trigger MouseClicker. The facial expressions were mapped onto different clicking modes (single, double, and continuous press) for the left and right clicks as shown in Table 4.1.

Similar that prior work of mine [145], we incorporated a speech recognition system using Google Cloud Speech API[4] to activate and deactivate the prototype. This ensures that the system does not operate accidentally if the user makes a facial expression without intending to click. Lastly, similarly again, we also created a GUI to allow easy customization of the system's sensitivity to the user's facial muscle movements. Since users with motor impairments may present a wide range of abilities in the movement of their facial muscles, this interface can increase the adaptability of the proposed system beyond me. The user can choose which facial expression gets mapped to which clicking

[4]Speech-to-Text: Automatic Speech Recognition | Google Cloud: `https://cloud.google.com/speech-to-text/`

mode on MouseClicker. A list of all the available facial expressions and clicking modes for each button is provided in Table 4.1. The mappings shown in this table are the ones that I felt most comfortable using, with the easiest expressions mapped to the most frequently used mouse clicks.

4.3.3 Evaluation

Through this study, our goal is to establish a correlation between the act of clicking a mouse by controlling robotized levers through facial expressions and the corresponding vibrotactile feedback on the index and middle fingers for me. By creating this connection, the goal is to provide me with a haptic experience that confirms successful mouse clicks, allowing independent and reliable computer mouse interaction without the need for assistance. Our design does not attempt to fully replicate the proprioceptive experience of hand movements involved in using a mouse, but instead focuses on providing salient sensory feedback to indicate mouse clicks have been executed based on recognized facial expressions. My involvement in the design process from the original orthoprosthetic idea to the decoupled interaction in MouseClicker, ensured that the final experience was something I desired. Comparing my haptic preferences to those of people without hand motor impairments could help identify any differences or similarities in the way I perceive and respond to the haptic experience of clicking a mouse. If my preferences closely align with those without hand motor impairments, it suggests that the current haptic feedback provided through vibrotactile means is suitable for me. However, significant discrepancies might indicate a need for further refinement and personalization of the haptic feedback to better accommodate my unique needs and tactile sensory abilities. By exploring this comparison in our study, we can gain valuable insights into the feasibility of perceptual mapping for haptic experiences, specifically in relation to the decoupled feedback

(Section 4.3.1). The inclusion of visual feedback through the LED, in conjunction with vibrotactile feedback, was important for me to confirm that mouse clicks were successfully executed based on my facial expression inputs. This multimodal feedback provided me with assurance and confidence in controlling the mouse independently.

We conducted the evaluation in two parts: (1) a pilot test with me and two other individuals without hand motor impairments, to set an initial input frequency working range for the vibration motors, and (2) a split-plot user study with three experimental variables (position of the motor, intensity of the vibration, and click sound) in 80 randomized experimental states conducted with 10 participants without hand motor impairments. I also participated in this study. This study method is similar to other studies for AT design [167, 123, 222]. A practical challenge when evaluating our AT design was the difficulty in recruiting a sufficient number of participants with hand motor impairments. These participants were required to be not only available and willing, but also capable of coming to campus for an in-person study. To overcome this, we adopted a broader evaluation approach. Our aim was to identify and correlate perceptions shared by individuals with and without hand motor impairments. This strategy can help expedite the development of ATs that incorporate haptic feedback. The first part focused on determining an initial range of vibration parameters. We particularly wanted to learn if the vibration was consistently identifiable, and if the left and right clicks were distinguishable. Lastly, we were looking for a comfortable range of vibration intensity for all-day use.

For the second part, we employed a split-plot experimental design that further explored the outcomes from the first part. The 10-person user study was conducted to evaluate the use of ERM motors for providing haptic feedback and to collect the specifications that would allow the feedback model to be a reliable representation of the sensation experienced when clicking a mouse. To this end, we needed participants who had prior experience using a computer mouse, i.e., participants without any hand motor

Participant	Frequency	Duty Cycle
Me (Taheri)	2-3 Hz	7%-10%
U1	0.75-2 Hz	25%
U2	1.5-3 Hz	8%-25%

Table 4.2: Ranges of frequencies and duty cycles which each participant chose as representative of the sensation perceived when clicking a mouse.

impairments.

Motor Vibration Frequency Pilot Study

We conducted an early evaluation with me and two other individuals (hereafter referred to as U1 and U2) to heuristically determine the preferred values for vibration frequency and duty cycles that could mimic the sensation of a mouse click. The test equipment comprised of a wave signal generator (Siglent SDG 1032X), general purpose n-channel MOSFETs, a 5-volt power supply (Siglent SPD 303X-E), and 8mm ERM motors, i.e., coin vibrators. We applied square wave signals, sweeping a range of frequencies from 0.2 to 100 Hz and duty cycles ranging from 5% to 100%, allowing three participants (myself, U1, and U2) to freely explore the signals. We did not normalize the duration of the vibration in this test, and the participants could repeat the input signals as many times as they wanted. Table 4.2 presents the ranges of frequencies and duty cycles that each participant selected as representative of what it felt like (for U1 and U2) to click a mouse or for me what it might feel like.

The frequencies and duty cycles reflect the signal modulation settings on the function generator, corresponding to the energized time of each vibration pulse. The vibration frequencies and amplitudes perceived by the participants depended on the properties of the coin motor and were not measured directly here.

Split-plot Experimental Design

This was the main experimental phase of our research, designed to test and refine the vibrotactile feedback in MouseClicker. The study incorporated a split-plot experimental design, encompassing three key experimental variables: (1) motor position on the finger, (2) vibration intensity, and (3) click sound. We explored combinations of these three variables with 8 motor positions, 5 vibration intensities, and 2 click-sounds, amounting to 80 distinct experimental states. The layout of the 80 experimental combinations is depicted on the left side of Figure 4.4.

1. *Motor Position*: This variable determined where on the finger the vibration motor was located. We explored eight distinct motor positions, with four positions each on the index and middle fingers (values 1 to 4 for the index finger and values 5 to 8 for the middle finger). Additionally, a 0 value was used for instances when participants were unsure of the vibration motor location or when no vibration was perceived. The specific motor positions of interest are shown on the right side of Figure 4.4. The rationale for using eight positions, as opposed to the two used in MouseClicker was the need to comprehensively evaluate the spatial acuity of haptic perception, and to go beyond just identifying feedback on the two mouse-click fingers. This expanded range allowed us to explore a broader spectrum of motor placements, facilitating the identification of the most discernible and effective locations for haptic feedback. This approach not only streamlined the experimental process by minimizing biases that could arise from relocating motors but also increased our understanding of how to tailor haptic interfaces to accommodate diverse user needs. Ultimately, the results can help provide crucial insights for developing nuanced haptic interfaces tailored to users with varying motor abilities.

2. *Vibration Intensity*: This variable encompassed different levels of vibration strength,

allowing us to understand the most effective intensity for simulating a mouse click. We evaluated five levels of vibration intensity, where level 1 was a no-vibration setting (or zero intensity), level 2 was barely perceivable, level 3 was considered comfortable, level 4 was considered strong, and level 5 was uncomfortably strong and potentially overwhelming.

3. *Click Sound*: This variable explored the impact of the presence or absence of an auditory click sound by simulating the sound of a mouse click in 40 of the 80 experimental states.

Each participant in the study was randomly presented with these 80 combinations of the three variables, without any repetition. The randomization without replacement was done to ensure that each participant's experience and feedback were unique and unbiased, to help enhance the reliability of our findings. The randomized presentation also allowed us to mitigate any potential learning effects that might skew the results. A detailed illustration of an event, showcasing the varying vibration intensities, can be found in Figure 4.6. The study's depth goes beyond identifying which finger received feedback. It delves into pinpointing specific finger parts, which is crucial for tailoring effective haptic interfaces.

Test Bench for User Study. The test bench comprised of 8 coin vibrators, a relay (SPDT 5-volt), a 5-volt supply (9-volt battery through a linear voltage regulator), and a LED, all were driven by general-purpose n-channel MOSFETs and an Arduino Uno connected to a laptop through the serial port. The LED turned on for 1650 ms in all 80 events. Given that clicking a mouse happens one finger at a time, one vibration source was activated per event, as shown in Figure 4.5. The LED lit up 750ms before and after a 150ms haptic feedback period. The click sound was produced by the relay that was energized at the beginning of the haptic feedback period and turned off at the end

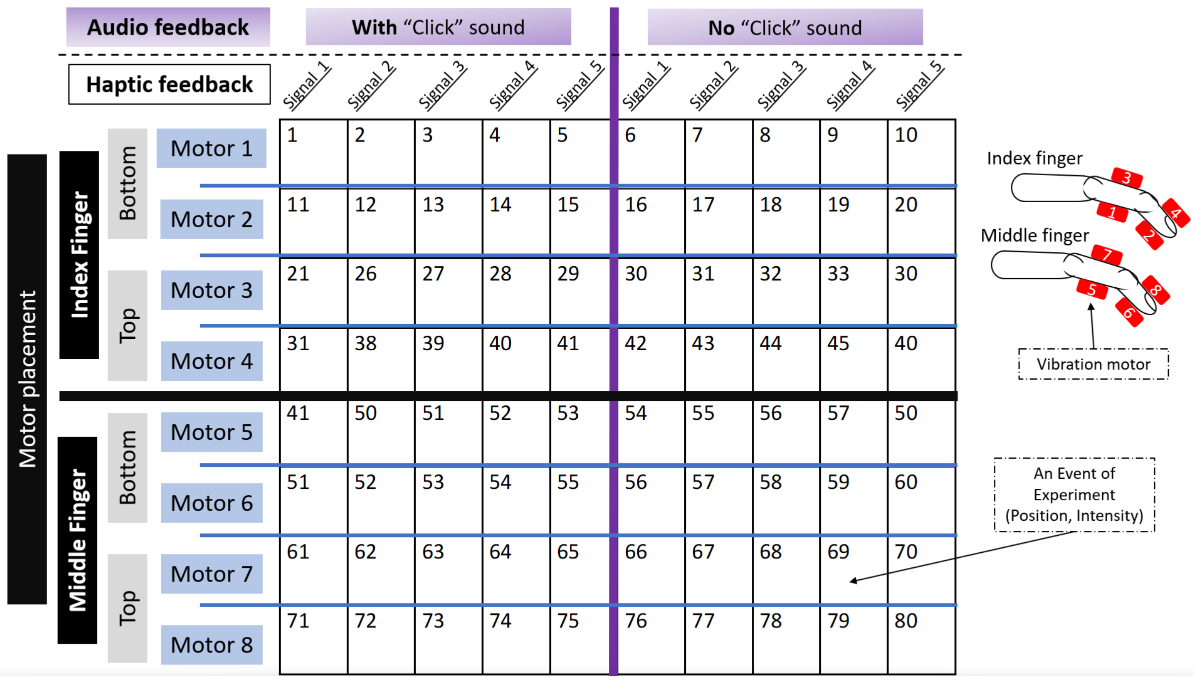


Figure 4.4: Split-plot experimental design: The 80 experimental states or "events", categorized according to three experimental variables: 1) the signal fed to the vibrator, 2) the position of the vibrator on the participant's index or middle finger, and 3) vibration with and without a clicking sound.

(Figure 4.6).

The vibration motors were positioned on the index and middle fingers at four specific locations: (1) Ventral Middle Phalanx (hereafter referred to as Ventral), (2) Ventral Distal Phalanx (or Fingertip), (3) Dorsal Middle Phalanx (hereafter referred to as Dorsal), and (4) Dorsal Distal Phalanx (or Nail). The vibration intensity was controlled as pulse trains powering the coin vibrators. The test bench sent one of the five electrical signals at a time to one of the eight motors (four on the index finger and the other four on the middle finger). The five electrical signals were: "intensity 0" (or no vibration), "intensity 1" (duty cycle (d.c.) = 10%, period = 50 ms, freq = 20 Hz, cycles = 3), "intensity 2" (d.c. = 33%, period = 15 ms, freq = 66.67 Hz, cycles = 10), "intensity 3" (d.c. = 50%, period = 20 ms, freq = 50 Hz, cycles = 7), and "intensity 4" (d.c. = 100%, period = 150 ms, freq = 6.67 Hz, cycles = 1). Notably, the duty cycles represent the on-state duration of the coin motors; in other words, the on-state was a fraction of the corresponding full period.

Participants. We recruited participants who had prior experience using a computer mouse in order to evaluate the vibration feedback. Ten participants (3 females, age range 18 - 36) were recruited by sending emails to department mailing lists. Participants were asked to complete a pre-study questionnaire that included demographic questions and information about how frequently they use a computer mouse and what they use as their primary input method for working with the computer. Eight participants selected the computer mouse (either built-in or external) as their primary input device other than the keyboard, while the other two selected the touchpad. Filling out the questionnaire took less than five minutes.

Experimental Trials. We conducted the study in-person at our lab. Participants provided informed consent prior to beginning the study. The study protocol was reviewed and approved by the UCSB Human Subjects Committee. Each participant took 20 minutes on average to complete the study. Before beginning the study, we attached eight coin vibrators to the participant's dominant hand (4 on the index finger and 4 on the middle finger), as shown in Figure 4.5. Each coin motor was fitted as a ring-like wearable interface.

Participants were asked to look at the green LED on the test bench (Figure 4.5) in order to evaluate each event. Every time the LED turned on and off, it indicated that an event had taken place. After the event, we asked the participants to identify which motor vibrated and to indicate how strong the vibration felt on a 5-point Likert scale (1 = not at all, 5 = very strong). Participants identified motor location by pointing at the motor (Figure 4.4). This process was integral to understanding how users differentiate haptic feedback, guiding the development of more nuanced haptic systems. On each event, the test bench sent a signal, corresponding to one of the five intensities and to one of the 8

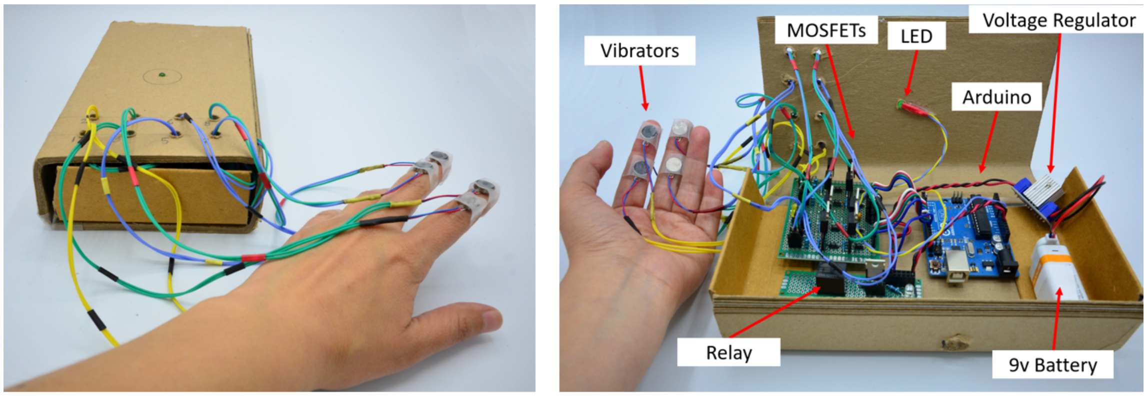


Figure 4.5: Test bench for the user study. On the left is a participant wearing the 8 vibration motors where only one is activated per event; On the right are the parts of the test bench to achieve the implementation of the complete factorial design with, 3 experimental variables for the 80 randomized and automatized experimental states.

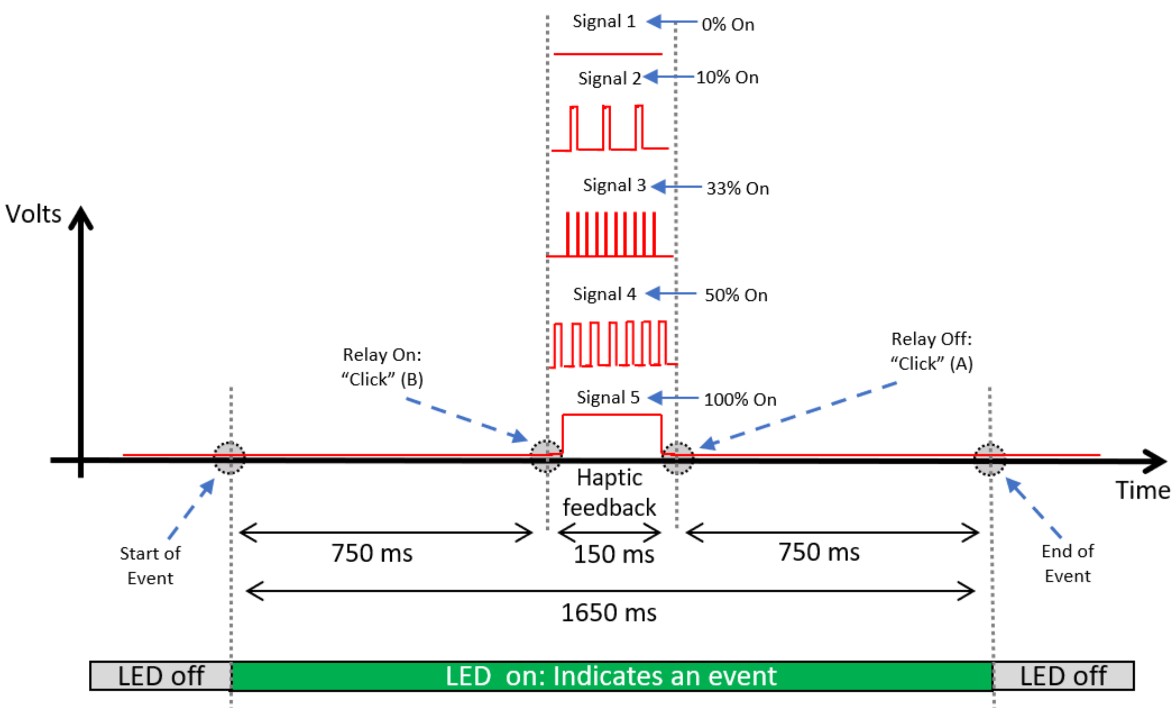


Figure 4.6: Anatomy of an event: A visual description of the event that study participants encountered at each trial. Each event is characterized by haptic feedback in the form of vibration, created by one of the five electrical signals induced in one of the eight electric motors.

vibration motors. Half of the events produced a click sound similar to those produced by a computer mouse, while the other half did not. The participant answered one question regarding the click sounds after all 80 events.

Motor Location Test with Me as the Co-designer. I conducted the same test as the 10 participants did. I reported my feedback evaluation on vibration motor locations by speaking out aloud the number of the motor, according to the finger drawing shown in Figure 4.4, instead of pointing it out with the other hand due to my inability to do so. Needing to remember motor numbers and their locations on my fingers imposed some cognitive load on me that the other participants did not experience. Evaluating the ability to identify specific motor locations on the fingers was essential to assess the precision of my haptic perception, a key factor in designing an effective MouseClicker for me.

4.3.4 Results

The results of the experimental split-plot design are presented in a 3-variable plot, illustrating the motor position, the actual and perceived intensity of vibration, and the click sound. Figure 4.8 shows the average outcomes from 10 participants. Meanwhile, Figure 4.9 presents the results of the study with me which align with the findings from other participants. The results for the group as depicted in Figure 4.8 show a smooth surface resembling an inclined plane. This suggests that the participants were able to perceive the vibration intensity values which were consistent with the actual experimental settings in all motor positions. It is noteworthy that these results were rearranged from the experimental events that were originally randomized, eliminating the possibility for participants to learn or compare successive intensity values. The surface plot for me shows greater variability, as averages tend to smooth out.

Participants Self-Consistency

Participant	Motor Position	Vibration Intensity
P1	68%	78%
P2	78%	58%
P3	80%	68%
P4	63%	75%
P5	60%	73%
P6	63%	78%
P7	65%	48%
P8	55%	68%
P9	83%	73%
P10	93%	78%
Me (Taheri)	70%	58%
Grand Averages	**70%**	**69%**

Table 4.3: Given the split-plot experimental design, we compare each participant's self-consistency. Results show that participants gave the same evaluation when encountering the same event again on average 70% of the time referring to the motor position and 69% in relation to the vibration intensity.

This visual representation also shows that the effect of the click sound was null or minimal, as there was no clear pattern related to the presence or absence of the click sound. Therefore, we focused our evaluation and analysis on the other two experimental variables - motor position and vibration intensity, disregarding the click sound variable. We found an indicator of orthogonality in the experimental results between location and intensity, given that they varied independently; that is, the accuracy of localizing the vibration varied from person to person, while the accuracy of classifying the vibration intensity was consistent across all participants.

Experimental Results of the User Study: Haptic Feedback

Overall, the experimental results for the vibration intensity showed high consistency across all participants.

Duration of the Haptic Feedback. In line with our aim to produce a haptic experience that represents pressing a mouse button, we determined that the duration of the vibration should be similar to the duration of a mouse button being pressed. Therefore, we asked participants to click on a computer mouse five times, while we measured the duration of each click using an oscilloscope (Siglent SDS-1204X-E) connected to the mouse. The group's average duration of clicking was 128 ms with a range of 74 ms to 202 ms. Given that our haptic feedback duration was 150 ms long, it falls within this observed range. Consequently, the vibrotactile stimuli that we used during our evaluation can be considered a fair and reasonable representation of clicking a computer mouse.

Click Sound. The group average accuracy for localizing motors for the events with and without click sound was 98%. Thus, we considered the effect of the click sound to be very weak, and proceeded to use this experimental variable to test the participant's self-accuracy by comparing the 40 events with the click sound with their corresponding 40 events without the click sound. The results of this test are shown in Table 4.3.

The effect of click sound was assessed after the completion of all 80 events. Participants were asked if they had heard any click sounds during the experiment. Among them, 9 of 10 confirmed hearing the sounds, with varied interpretations: a) they did not recognize the sound until it was mentioned by the researcher, b) they acknowledged hearing it but associated it with the normal operation of the test bench and said the sound was always there, presumably the sound was a consistent feature, or c) they heard it intermittently and attributed it to the functionality of the motors. Only one participant reported hearing the click sound in some of the events; nevertheless, their accuracy was not impacted by it.

Position of the Vibration Motors. A confusion matrix shows the actual motor positions (rows of the matrix) and the perceived motor positions (columns of the matrix). In the matrix, an entry on row x and column y indicates the total number of times that the vibration of a motor at position x was perceived at position y. Ideally, each entry on the matrix diagonal should be 8, and the rest should be zero, implying that each vibration motor position was correctly perceived. The average of all the confusion matrices for each participant is visualized as a heatmap in Figure 4.7:Left. According to the averaged heatmap, motors on nails were detected more frequently. This suggests that vibration on the fingers has a higher likelihood of being perceived as coming from the motors on the nails. Figure 4.7:Right shows the heatmap obtained from my feedback. The results were slightly different for me, with the motors on the ventral side of both fingers being selected more frequently than the others. Subsequently, the motors on nails were the second most perceived.

We found these results to be particularly interesting, as we had initially anticipated that the fingertips would be the most commonly perceived motor location due to its high concentration of mechanoreceptors. However, our findings indicate that despite the sensitivity of the fingertip, it was the nail that was often misinterpreted as vibrating.

In two of the trials in my study, even though the correct motor position was identified, it was attributed to the wrong finger. We believe that this discrepancy may have been due to the need to provide feedback by motor number rather than directly pointing at the motor.

The experimental results for user accuracy of each motor position are shown in Table 4.4. The results have two aspects, first, as a group where the averages per finger zone show that the most convenient place to attach the vibration motor is directly on the nail, with 61% for the index fingernail and 69% for the middle fingernail. The second best is on the fingertip, with 52% for the index and 48% for the middle finger. Nevertheless, these "best" options are eclipsed by the fact that the average for all zones in both fingers is around 51% (shown in Table 4.5). If we compare these group averages with the per-participant averages, which is the second aspect of the results, we can see that for 9 out of the 10 participants, there is a zone of greater accuracy than the group average,

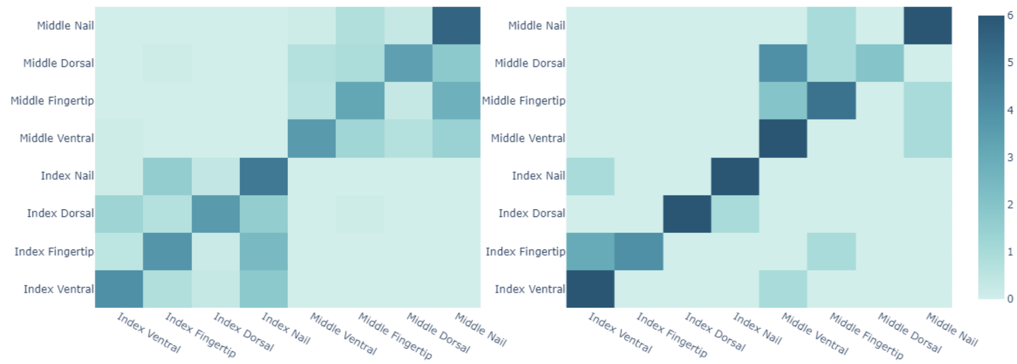


Figure 4.7: A confusion matrix with the actual motor positions as rows and perceived motor positions as columns were built for each participant. In the matrix, each entry reflects the number of times the vibration in a motor position corresponding to the row was perceived at the motor position in the corresponding column. Left: heatmap visualization derived from taking the average of the matrices for all participants. Right: heatmap visualization of my confusion matrix.

ranging from 63% up to 100% with an average of 75% for the index and 77% for the middle finger. These results highlight the need for making personal haptic assessments in order to create the most efficient haptic interface for the target user.

Intensity of the Vibration. Signal intensity was varied between 0% to 100% in each experimental trial. In most of the experimental trials, perceived intensity behaves similarly to the actual intensity and even mirrors it. This indicates that finger skin is sensitive to intensity variations regardless of where on the finger the vibration is applied. It also demonstrates that localizing the motor position on the finger has larger variability than determining the signal intensity of the vibration (Figure 4.8). That is to say, participants were consistently better at determining the vibration intensity than the vibration location.

Figure 4.10 illustrates P4's perception of both vibration motor positions and intensities on both index and middle fingers. The results of this participant are presented because they are representative, especially because all users selected the motors on the nails more frequently than on the other locations.

		Participants' Accuracy per Finger (%)											
IF Zone	MP	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Me	Avg/MP
Ventral	1	13	7	**75**	25	50	38	50	38	50	88	**75**	52
Tip	2	13	**100**	25	25	38	38	13	**63**	**63**	**100**	50	48
Dorsal	3	**63**	75	75	13	**88**	13	0	0	50	75	**75**	48
Nail	4	38	50	**63**	**88**	75	**50**	**63**	38	**63**	75	**75**	**61**
Finger Avg		31	75	59	38	63	34	31	34	56	84	69	52

MF Zone	MP	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	me	Avg/MP
Ventral	5	0	**100**	25	0	38	13	**88**	50	63	75	**75**	48
Tip	6	13	**100**	0	0	75	50	0	**63**	0	**100**	63	42
Dorsal	7	**75**	75	**50**	0	25	13	0	38	**75**	75	25	41
Nail	8	63	**75**	**50**	**75**	**88**	**63**	75	**63**	**75**	63	**75**	**69**
Finger Avg		38	88	31	19	56	34	41	53	53	78	59	50

Table 4.4: The results of the user accuracy for each motor position [MP] from the 10 participants and me. The top table is for the index finger [IF] and the bottom one is for the middle finger [MF]. The most accurate zone per participant is shown in bold numbers, as are the group averages. Individual sensitivity data on perception location can provide a starting point for designing haptic feedback devices such as gloves.

		Participants' Combined Accuracy per Zone (%)											
F Zone	MPs	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Me	Avg/MP
Ventral	1, 5	6	88	50	13	44	25	**69**	44	56	81	**75**	50
Tip	2, 6	13	**100**	13	13	56	44	6	**63**	31	**100**	56	45
Dorsal	3, 7	**69**	75	**63**	6	56	13	0	19	63	75	50	44
Nail	4, 8	50	63	56	**81**	**81**	**56**	**69**	50	**69**	69	**75**	**65**
Avg		34	81	45	28	59	34	36	44	55	81	64	51

Table 4.5: The combined average accuracy for motor positions [MPs] across the finger zone (F Zone). The participants showed different patterns of accuracy. However, there was similarity between the most accurate zones of the index and middle fingers for each participant. These accuracies are indicated with bold numbers.

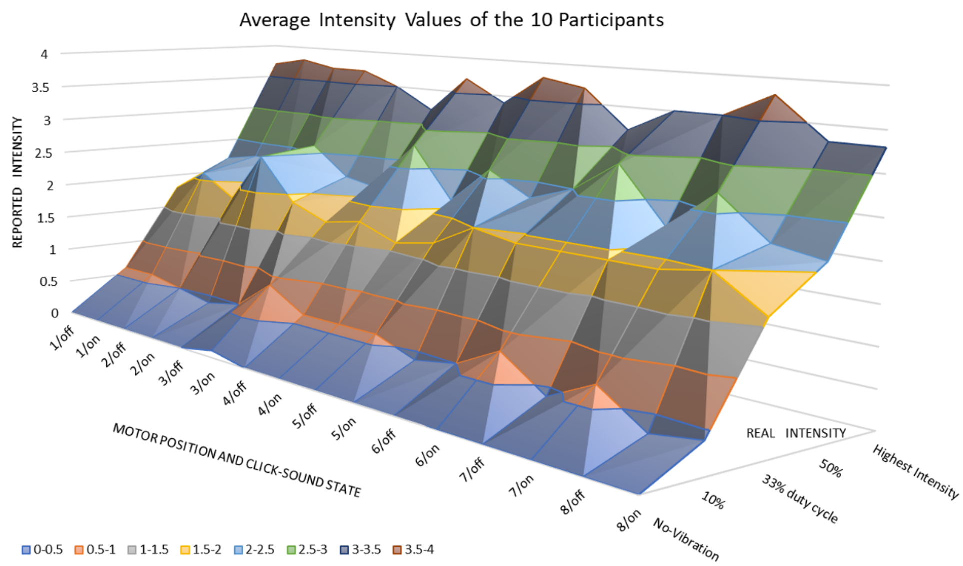


Figure 4.8: 10 participants group average of the perceived intensity plotted against actual intensities for the 8 motors, with click sound and without. 800 data points referring to vibration intensity (80 per participant)

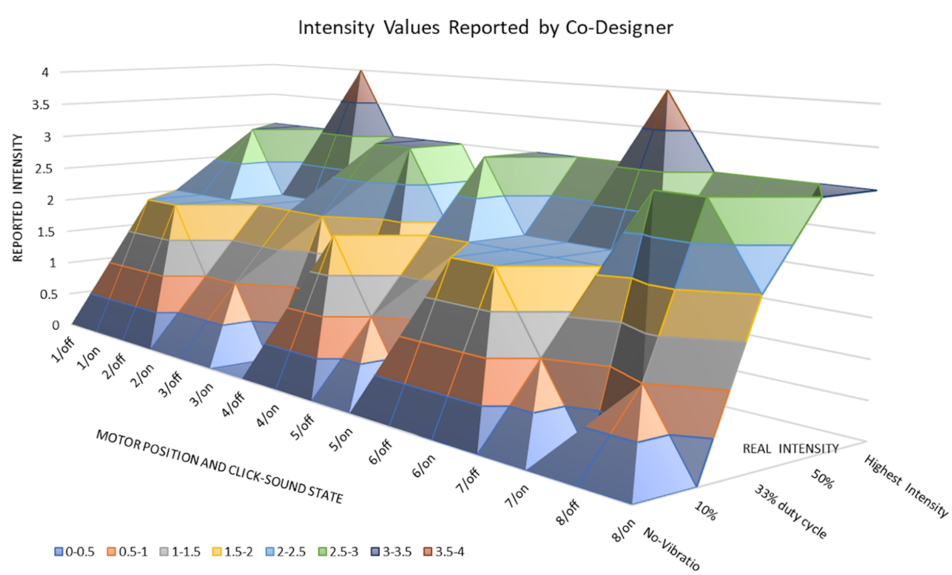


Figure 4.9: Perceived intensity values of the 80 experimental events by me as the co-designer plotted against the actual vibration intensities provided during the experimental trial.

In Figure 4.11, we also present the results obtained from my pilot study as the co-designer. As shown, the perceived intensities in both fingers are slightly more consistent with the actual intensities. However, as mentioned previously, my perception of motor positions reveals that the ventral side and nails are both frequently selected as places where vibration is felt.

4.3.5 My Reflections as the Co-designer on the Full System

We designed our prototype iteratively in collaboration with me, the co-designer through a series of tests and development iterations. Once the prototype was completed, the device was given to me so that I could test it at home for an extended period of time and provide feedback on it. The device provided to me offered all four types of feedback:

1. Vibrotactile haptic feedback on two fingers (index and middle) to create the sensation of clicking a mouse. The two coin vibration motors were attached to the index and middle fingers on the ventral side.
2. Auditory feedback in the form of a click sound from the mouse itself.
3. Visual feedback from the mouse buttons being pressed down by the levers, and a LED bar-graph representing the force applied during the push.
4. On-screen functional feedback resulting from actions triggered by mouse clicks through facial expressions.

Prior to using MouseClicker, I had to rely on assistance for tasks such as right-clicking or using keyboard and mouse simultaneously, particularly in 3D applications such as the Unity game engine, a commonly used tool for AR/VR development.

Following a month of using the device, I was able to perform my desired clicking actions whenever I needed without needing assistance. I stated:

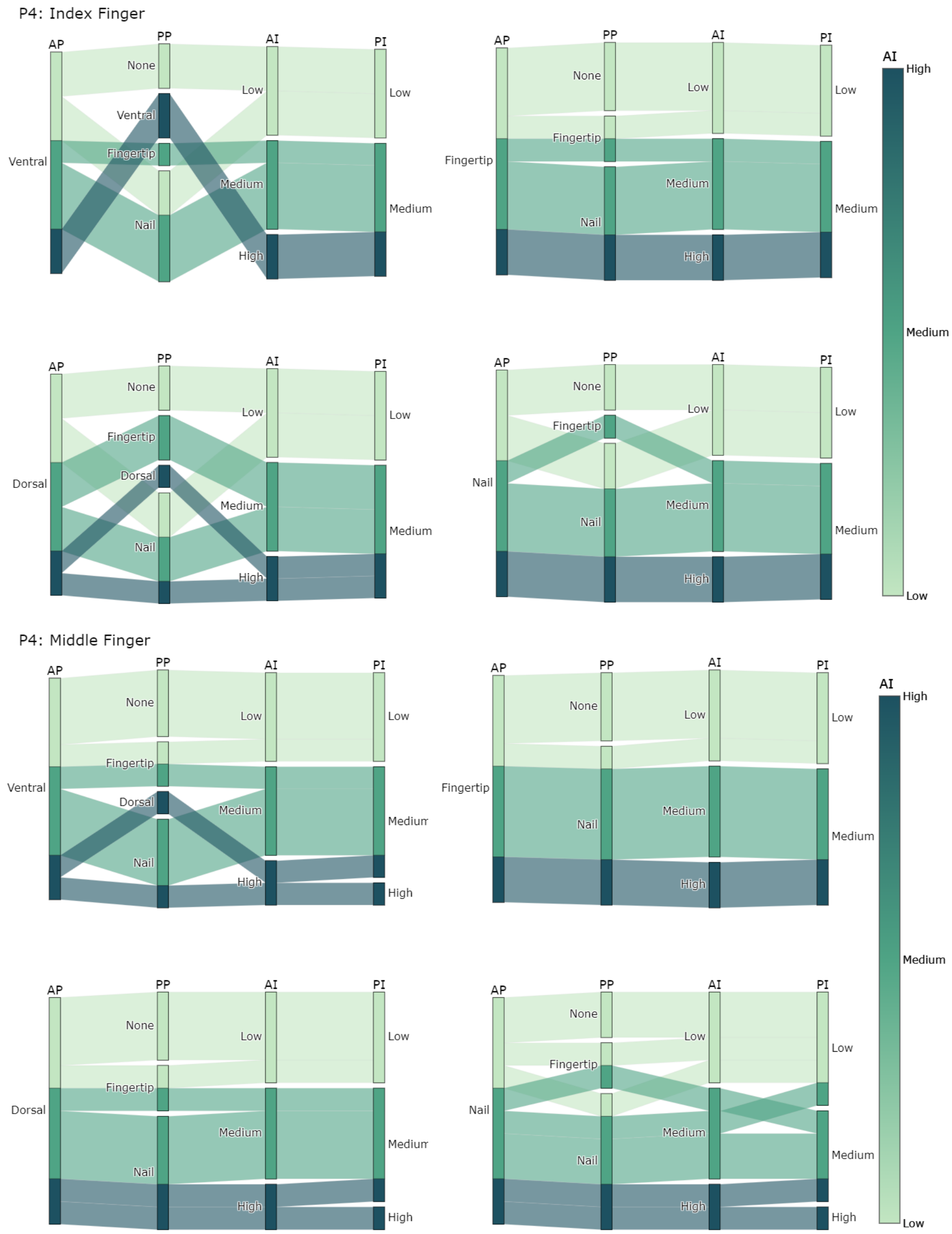


Figure 4.10: Visual illustration of actual motor positions [AA], perceived motor positions [PP], actual intensities [AI], perceived intensities [PI] showing P4's data: the top 4 plots correspond to the index finger, and the bottom 4 plots are for the middle finger.

"Before, I had to ask my mom for help with doing right clicks, or when I wanted to work in Unity as an example, I needed to use keyboard and mouse simultaneously at times and that made me in need of someone to sit next to

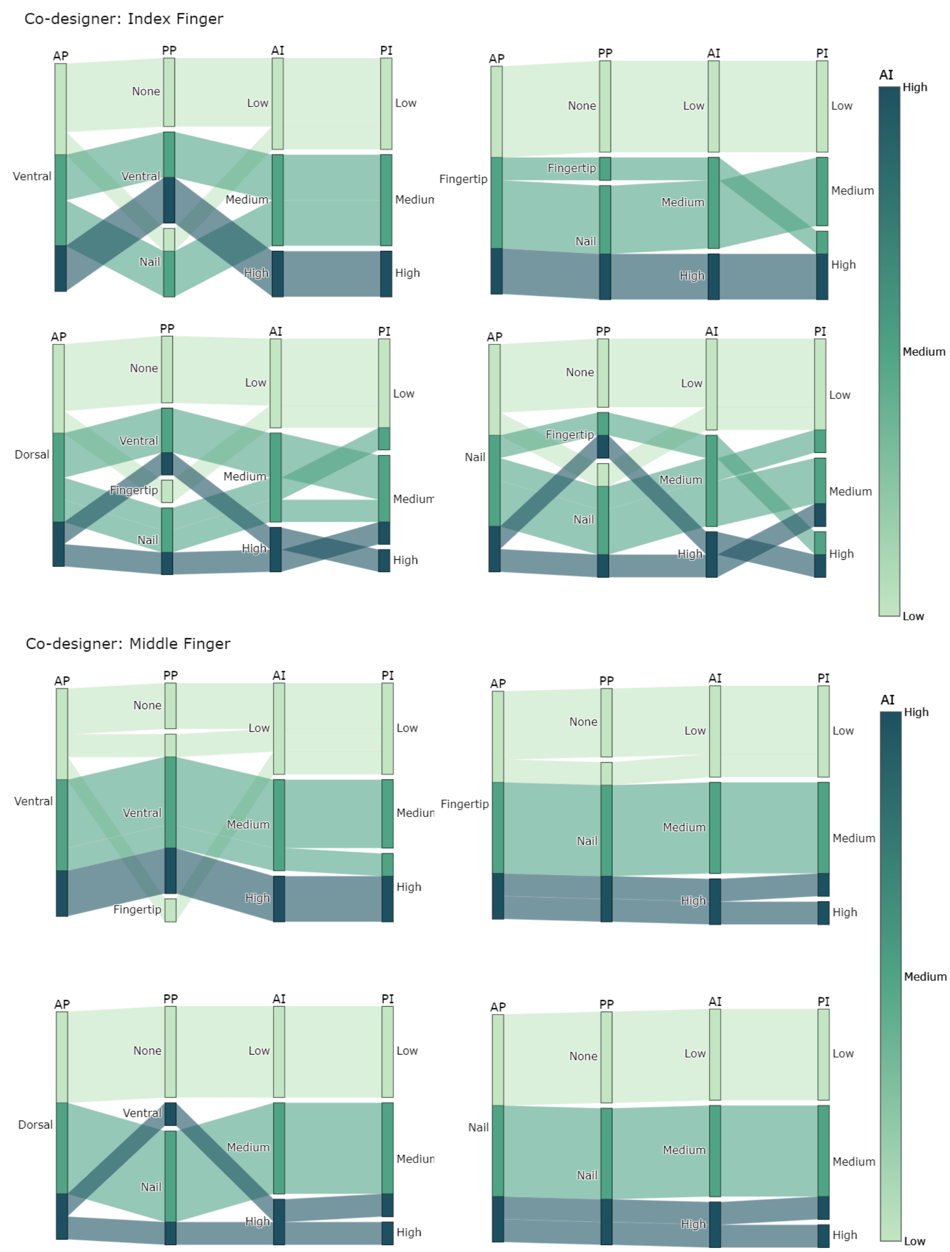


Figure 4.11: Visual illustration of actual motor positions [AA], perceived motor positions [PP], actual intensities [AI], perceived intensities [PI] obtained from a pilot study conducted with me as the co-designer: the top 4 plots correspond to the index finger, and the bottom 4 plots are for the middle finger.

me the whole time because using virtual keyboard and continuously pressing mouse buttons were not possible. The situation could become frustrating at

> some points for me and for that person. The lack of a practical solution, therefore, restricted my ability to work with various applications, such as Unity. But with the MouseClicker, I feel more independent now and that is very comforting for me."

Most importantly, I noted that receiving vibrotactile feedback from the prototype similar to what one receives when they click on a physical mouse was something I wished to have but were unable to imagine how it would feel:

> "Even though I was aware in advance that I would experience the sensation of clicking, I was nonetheless surprised by it. It was a very exciting experience. Not only could I see the result of each clicking action on the screen, which was the functional feedback from the device, but also I was getting a sensation on my fingers' skin as if I was pressing the buttons with my own fingers. It was wonderful."

The device turned out to being more helpful for me with the feedback than without:

> "[T]he fact that I would be able to experience the actual clicking on a physical mouse that everyone else can use pretty easily is something I could not experience with any available assistive devices or software. It gives me a sense of being included because not only I can use the same mouse for clicking as my other non-disabled peers use, but also I can feel on my fingers the same feeling that they experience while using the mouse."

After several hours of usage on a daily basis, the device remained comfortable and effective for continuous operation for me. Specifically, the lightweight vibration motors were easy to wear for long periods without causing discomfort, fatigue, or skin irritation.

It is important that those ATs that are intended for daily computer use to be comfortable enough and for me MouseClicker successfully met this critical requirement.

My additional feedback focused on my desire to feel the scrollwheel and use the device for moving the mouse cursor which would allow it to be a standalone device. The current prototype focuses primarily on enabling users to click hands-free and receiving simulated haptic feedback on their fingers. To the best of our knowledge, such a system has not been explored before. However, we plan to expand the device capability in the near future.

My other comment focused on the use of a common mouse available on the market. I found repurposing a commonly used physical mouse to be a particularly useful idea and appreciated that our design allowed for easy and inexpensive modification of a mouse that I could use:

> "One of the most intriguing features of this device is that by making a facial expression I could see some actual physical action taking place in front of me."

Using a facial expression to click a mouse button serves a practical purpose, but when that click was accompanied by a tangible sensation, it became a newfound ability for me. I felt empowered to manipulate a physical object and control the complete cycle of action and feedback, a capability that was previously unattainable. While it was possible to integrate haptic feedback that corresponds to my trackpad input, our current system not only gives me physical agency, it also enables a degree of future-proofing of my input capabilities, considering the progressive nature of SMA and my anticipated loss of thumb control in the future. Controlling a physical object for input, having physical agency complemented by the freedom to choose the intensity and location of the haptic feedback, has provided me with an immense sense of joy and independence.

It is firmly believed that the decoupled approach represents a small yet significant step towards supporting my independence, which can be generalized to a broader audience with similar hand motor impairments.

4.3.6 Discussion

In this study, we explored personalized vibrotactile feedback to effectively simulate mouse click sensations for individuals with severe motor impairments and quadriplegia. Our multi-part study analyzed parameters such as vibration intensity, location, and duration to quantify the tactile experience of mouse clicks. By testing with 10 participants without hand motor impairments alongside me, we aimed to draw comparisons in haptic perception between those with and without motor impairments. A key objective was to assess whether the simulated vibrotactile feedback feels authentic and intuitive even when decoupled from the site of the clicking action, which is essential for non-collocated input modalities.

The results of our study provide valuable insights into optimizing vibrotactile feedback parameters to effectively simulate mouse click sensation. A key finding was the considerable variability in localizing vibration motors on the fingers, contrasted by the consistent perception of the intensity of the vibration among the participants. This indicates that while intensity can be standardized, localization needs to be personalized in designing effective haptic feedback. Our use of vibration motors as haptic actuators is better suited for rapid-adapting mechanoreceptors in the skin, specifically Meissner corpuscles [239]. Meissner corpuscles are sensitive to low-frequency vibrations, sensitive to a range of around 10-65 Hz [240]. In our study, the vibration frequencies delivered by the coin motors fell within the range of 6 and 67 Hz, which aligns with the peak sensitivity of Meissner corpuscles. This explains why participants were able to reliably detect and differentiate the intensity of vibrotactile stimulation in our experiments. In our study, we unexpectedly found that the nail bed was the most frequently perceived location. This was surprising, given that we know that fingertips are the most sensitive, considering their high density of mechanoreceptors [241]. Interestingly, fingertips emerged as the second most perceived location. Nevertheless, the intra-participant variability highlights the need for customization, as simply targeting sensitive areas does not guarantee consistent localization. The confusion matrix heatmaps in Figure 4.7 visualize this variability, showing the locations perceived the most frequently by each participant. Accounting for this individual variability can optimize the wearing comfort and effectiveness of vibrotactile devices like our prototype.

An interesting observation from my results as the co-designer was the tendency to localize vibrations on the ventral side of the finger. This contrasts with the group trend of localization to the nails. The discrepancy highlights the value of working with end-users in AT development, to account for unique tactile perception capabilities in disability contexts. It also reinforces that localization requires personalization.

Including participants without motor impairments allowed us to address the question, "Did severe hand motor impairment alter my tactile perception?" Our user study showed that "it did not"; my finger-sensitivity aligns with the parameters observed in testing with participants without hand motor impairments, as demonstrated in Table 4.3 and Table 4.4. This emphasizes the importance of conducting comparative user studies between able-bodied users and AT users. In particular, such comparisons can contribute to advancing the collective knowledge of human factors and ergonomics for AT users, who are often underrepresented in the ergonomic literature. By acknowledging that our similarities outweigh our differences, experimentally, we can effectively pinpoint specific ergonomic characteristics of interest, thereby facilitating and expediting AT research to generate more comprehensive points of comparison.

Our findings on vibration intensity help standardize that parameter for haptic mouse simulations. Across participants, perceived intensity reliably matched actual values and showed less variability than localization. This allows the intensity to be objectively mapped to the mouse click intensity. The 150 ms pulse aligns with the average duration of human clicks, making the simulation perceptually accurate.

An unexpected finding was the minimal effect of clicking sound on vibrotactile localization. We had anticipated an interaction between auditory and tactile cues. However, the clicking sound did not enhance vibration detection. This suggests that the vibrotactile sensation alone is sufficiently salient. Minimizing multimodal feedback channels can simplify the design of devices.

This study underscores the importance of capturing vibration localization in addition to characterizing intensity for effective vibrotactile feedback in AT design. Through our quantitative analysis, we establish guidelines for parameters such as intensity, location, and duration, which are crucial for simulating realistic experiences such as mouse clicks. Our work highlights the need to account for individual tactile perception abilities and variance in perceptual abilities, underscoring the role of participatory design with end-users. This approach not only facilitates an authentic haptic experience and optimized device ergonomics, but also aids in the development of customized vibrotactile systems, thereby creating accessible and empowering AT devices.

In this work, we presented the design, implementation, and evaluation of MouseClicker, a mechatronic prototype to demonstrate the potential of repurposing existing input devices to integrate haptic feedback for people with hand motor impairments. MouseClicker enables our co-designer, who has severe hand motor impairments, to experience the sensation of using a computer mouse as a physical object, beyond the functionality it provides. In our user study on evaluating the haptic feedback, we found that localizing the vibration motor position had more variability than the input signal intensity of the vibration.

It was notable that for each participant, there was a specific zone of greater perception on the index or middle fingers, implying the need for personalized haptic feedback design. With this work, we hope to encourage researchers and designers of AT devices to consider adding sensory feedback in addition to replicating functionality for people with hand-motor disabilities.

4.3.7 Summary

Our work builds on ideas from psychology and design, emphasizing the significance of physical objects and their integration into the design of ATs. This foundation led to the creation of an inclusive input device, MouseClicker, which integrates tactile sensations into computer input methods. The design process began with conversations about input methods for individuals with motor impairments, specifically focusing on the desire for tactile feedback and a sense of physical connection with the input device.

MouseClicker was co-designed with me, as I expressed a desire for the tactile experience of using physical tools like a computer mouse. Despite the availability of virtual alternatives, the lack of physical sensation highlighted a gap in current AT designs. Initial designs using an orthoprosthetic glove were found to be expensive, non-inclusive, and potentially harmful to thumb functionality, leading to a shift towards a decoupled interaction approach.

The prototype leverages a standard computer mouse to recreate tactile sensations, making it affordable and simple while ensuring the authenticity of the tactile experience. A user study with individuals without motor impairments and myself aimed to establish a universally recognizable standard for haptic feedback. The study found that vibrotactile feedback can augment interaction methods, although not much attention has been given to this modality for individuals with hand motor impairments.

The main contributions of this work include a proof-of-concept prototype collaboratively designed and tested with me, who has severe hand motor impairments. Additionally, a user study with 10 participants without motor impairments alongside me focused on haptic perception, testing the location and intensity of vibrotactile feedback, and the sound representing mouse clicks. By appropriating a standard computer mouse, we demonstrate holistic inclusion through multimodal feedback in AT design.

Our findings suggest that decoupled haptic feedback can serve as a complementary communication channel, even when the sites of action and feedback are not the same. This insight can guide the integration of haptic feedback in the design of AT devices, providing a more inclusive experience for users. MouseClicker plays a crucial role in fostering independence and enhancing a sense of inclusion. The ability to experience the sensation of clicking a physical mouse, combined with the practical functionality, highlighted the device's impact. The feedback and user study results suggest that while the intensity of haptic feedback can be standardized, its localization needs to be personalized for effective haptic interfaces.

This work emphasizes the need for participatory design with end-users to create ATs that are not only functional but also provide a holistic user experience. By integrating tactile feedback and leveraging existing devices, we proposed a new pathway for inclusive AT design that balances functionality and sensory experiences. This approach has the potential to democratize access to technology and promote sustainability in AT development.

4.4 Conclusion

In this chapter, I explored the significance of sensation, the second component of my proposed design space, within the domain of assistive technology, focusing on how sensory feedback can enhance the user experience for individuals with motor impairments. The MouseClicker project exemplifies how integrating tactile feedback into assistive devices could bridge the gap between digital interactions and physical sensations, providing users with a more holistic and inclusive experience.

The findings from the MouseClicker project extend beyond the specific implementation of a haptic feedback system for mouse clicks. They underscore the importance of personalization and user-centered design in developing assistive technologies. The variability in haptic perception among users highlights the need for solutions tailored to individual needs and preferences. Involving end-users in the design process, as exemplified by our collaborative work with me as the co-designer, ensures that the final product is both functional and comfortable, enhancing overall user experience and satisfaction.

Multimodal feedback, integrating various sensory channels such as vibrotactile, auditory, and visual, has shown significant potential in assistive technology. This approach creates more robust and effective interfaces that cater to a wider range of abilities and preferences. By leveraging different sensory channels, we can improve usability and foster a deeper connection between the user and the device. Providing tactile feedback that mimics the sensation of using a physical mouse offers users a sense of inclusion and empowerment. For individuals with motor impairments, experiencing the same tactile sensations as their non-disabled peers can significantly enhance their sense of agency and independence. This inclusivity is crucial in promoting equal access to technology, enabling users to fully engage with digital environments.

The MouseClicker project is an example of a cost-effective approach to developing assistive technologies by repurposing existing devices, such as a standard computer mouse. This method reduces financial barriers, making advanced assistive solutions more widely available. Additionally, open-sourcing the design allows others to build and customize the device, fostering a community-driven approach to innovation in assistive technology.

The insights gained from the MouseClicker project pave the way for further research and development in the field of assistive technology. Future work can explore the integration of additional functionalities, such as scrolling and cursor movement, to create more comprehensive input devices. Moreover, the principles of decoupled haptic feedback can be applied to other assistive applications, expanding the scope and impact of this research.

My exploration of sensory modalities, particularly through the MouseClicker project, has highlighted the critical role of sensory feedback in creating inclusive and empowering assistive technologies. By addressing the unique needs of users with motor impairments and emphasizing the importance of personalized, multimodal feedback, we have laid the groundwork for more accessible and effective technological solutions. The broader implications of this work extend to the design of future assistive devices, promoting a user-centered, inclusive, and sustainable approach to innovation in assistive technology. This chapter has solidified the importance of the second component of my proposed design space, demonstrating how sensation can transform the accessibility and user experience of assistive technologies. By focusing on sensory feedback, we can ensure that assistive devices not only meet functional needs, but also provide a rich, inclusive, and empowering user experience.

Chapter 5

User Experience

In this chapter, I explore the third component of my proposed conceptual design space: user experience. The user experience component focuses on how individuals interact with and perceive technology, particularly in the scope of the user's goals and context. By understanding and enhancing user experience, we can create technologies that are not only functional but also engaging, intuitive, and satisfying for users. This chapter will go through the principles and methods used to design for user experience, and provide an in-depth analysis of the "Virtual Steps" project, which exemplifies these concepts.

5.1 Introduction

User experience (UX) is a multi-dimensional concept and a critical aspect of human-computer interaction that covers every facet of the end-user's engagement with a product, service, or system. Unlike usability, which focuses on the effectiveness, efficiency, and satisfaction [176] with which users achieve specific goals, UX is broader and includes emotional, psychological, and contextual factors that influence how users feel about their interactions [242]. In fact, some researchers view usability as an extension to UX, while others use the terms interchangeably.

User experience is rooted in the principles of User-Centered Design (UCD). UCD emphasizes designing systems with a deep understanding of the users, their needs, and their preferences, ensuring that the technology is tailored to their specific requirements [243, 244].

For individuals with disabilities, a positive user experience can significantly enhance the usability and accessibility of technology, leading to greater independence, engagement, and satisfaction [245, 246]. The principles of user experience encompass various factors, including usability, accessibility, and emotional engagement. This chapter delves into the development of the "Virtual Steps (2024)" project. By focusing on user experience, the goal is to create technologies that are not only functional but also provide a meaningful and enjoyable experience for users with motor impairments, who are interested in such experiences.

5.2 Related Work

5.2.1 Simulating Walking in VR

The use of VR to simulate novel experiences has been an active area of research that spans multiple disciplines, including neurological rehabilitation, where VR techniques resulted in both physical and cognitive enhancements for mobility and walking [247, 248]. Many studies have harnessed VR technology to simulate walking environments, which is crucial for gait rehabilitation [249]. Typically, gait rehabilitation involves walking either overground or on treadmills [250]. Moan et al. [251] developed a fully immersive virtual reality treadmill game for post-stroke rehabilitation. They found that using VR games as part of gait rehabilitation after stroke is acceptable and potentially useful, based on positive experiences from testing by both stroke survivors and clinicians. Differently, our work focuses on reproducing the visual and auditory sensations of walking in VR experience for individuals who have never walked. We aim to emulate these sensations while preserving the user's agency.

There are limitations in simulating realistic walking sensations for those who have never walked before. The study by Matsuda et al. [252] proposed a new virtual walking system that combines optic flow, foot vibrations, and a walking avatar to induce a sense of virtual walking in seated users without limb motion. In a different method, the idea of "King-Kong Effects" was presented to augment the feeling of locomotion in virtual settings [253]. Drawing motivation from cinematic special effects, the researchers suggested incorporating either visual or tactile vibrations with every emulated footstep while navigating virtually. Saint-Aubert et al. [254] investigated the impact of user posture and virtual exercise on locomotion perception in VR. Participants, wearing a VR headset, watched a first-person avatar doing virtual exercises, revealing that the sensation of walking could be adapted to various postures and exercises, indicating avenues for enriching the virtual walking experience in diverse settings.

In these studies, participants did not have mobility impairments and had their prior walking experience as a baseline to compare against the virtual experience. Our work pursues a different goal, providing walking sensations for individuals who have never walked before and do not have prior experience to anchor their mental model of how walking sensations feel. Hence, investigating the factors and principles in VR that could either enhance or hinder their experiences is crucial for the satisfactory design of VR applications for this audience.

5.2.2 Psychological Aspects of Locomotion in VR

Presence and Embodiment in VR Locomotion

Presence, often described as the feeling of *being there* in a virtual environment, is amplified when users can simulate actions intrinsic to their daily lives, such as walking [255, 256, 257, 258]. North and North [259] suggest in their study that the sensation of presence in VR is directly influenced by the user's ability to interact with the environment naturally and intuitively. In the context of walking, this means the more realistic the simulation of locomotion, the greater the user's sense of presence. The sense of presence is particularly evident when users navigate vast virtual terrains or intricate pathways, feeling genuinely immersed in the environment [260]. Habgood et al. [261] found that teleportation, a commonly used locomotion technique, reduces spatial presence compared to other locomotion techniques such as free movement and node-based navigation. In a VR power wheelchair simulator, researchers have found three factors that affect the sense of presence: display type, control over the field of view, and visualization of the user's avatar [262].

Embodiment in virtual reality goes a step further, focusing on the user's connection with their virtual avatar or representation [263]. More than simply displaying a virtual representation of the user; embodiment happens when there is a feeling of genuine connection to a virtual body. When users see that their virtual legs moving in sync with their intended actions, it bridges the gap between their real and virtual selves. For example, Banakou and Slater [264] conducted experiments that demonstrated how multisensory stimulation can induce a sense of virtual body ownership. Their findings suggest that when visual input (seeing a virtual body) is combined with synchronous tactile input (feeling touch), participants can experience the illusion of owning a virtual body. This research underscores the importance of multi-sensory integration in achieving a strong sense of embodiment in VR. Additionally, Okumura et al. [265] highlighted the role of proprioceptive drift in enhancing the sense of embodiment. They found that when there's a spatial congruence between the real and virtual bodies, users tend to perceive their actual body position closer to the virtual one, further strengthening the sense of embodiment.

In summary, the sensation of presence and embodiment in VR, especially in the context of locomotion, is influenced by various factors, including the realism of the virtual environment, the user's ability to interact naturally, the first-person visualization of an avatar, and the congruence between visual and physical cues. These prior findings have informed our experimental design that allows users to visualize themselves as a first-person avatar in an HMD VR device that plays a walking animation when the user is moving. It facilitates control of the direction and speed of a continuous movement and induces a head oscillation that emulates the visual experience of walking, and audio feedback of footsteps. The HMD position is tracked and used to move the avatar head. The user can also visualize the avatar through the reflection of a virtual mirror.

Agency and Control in VR Locomotion

Agency refers to the capacity for a user to make decisions and take meaningful actions that have effects within the virtual world. A systematic review by Radianti et al. [266] underscores two clear tiers of user engagements: 1) those taking place within the VR realm, and 2) those entailing hardware interactions, illuminating a structure of agency fostered by VR technology. The interplay of agency and control in locomotion in VR is particularly essential to enhance user experience. Cardoso et al. [267] examined real locomotion methods and highlighted the importance of interaction strategies, amalgamating devices, user engagements, and system reactions, to nurture agency and control within VR settings. Schafer et al. [268] investigate continuous locomotion control through hand gestures, providing innovative methods to improve user control in VR locomotion endeavors, thereby promoting user agency [268].

All prior research revolved around the sense of agency when walking or in motion in VR for people who had previously experienced walking in the real world. However, it is crucial to also consider those who have no prior real-world walking experience and their mobility modality was different and investigate how their sense of agency is affected.

The Bayesian integration model of Sense of Agency states human judgment of agency is influenced not only by the sensorimotor systems but also by factors at the cognitive level [269, 270, 271]. According to this model, both cognitive and sensorimotor signals go through Bayesian integration where the lower their variance the higher their weight. Based on this model we expect a user with a congenital sensorimotor impairment to still experience agency in a virtual walking environment thanks to a mental model of the phenomena that occurs at the cognitive level.

5.2.3 Cybersickness

Cybersicnkess is a common problem in VR, often attributed to the sensory mismatch between visual and vestibular systems that occurs when users receive visual cues of motion without corresponding vestibular stimulation [272]. A study showed that 68% of the users have experienced cybersickness in a virtual flight session [273]. This syndrome is also more common among female individuals [274]. Prior work has investigated techniques to reduce cybersickness including the use of galvinic vestibular stimulation [273, 275]. In an evaluation of a wheelchair simulator, users of power wheelchairs also reported moderate cybersickness [276], suggesting that this audience is also affected by cybersickness regardless of a possible similar sensory conflict during the use of assistive devices for locomotion. In our work, we carefully adjusted speed parameters to mitigate discomfort and cybersickness. The system initially implemented a snap-turn technique, but in later versions, we adopted a continuous angular movement at a comfortable speed for the user. The head oscillation parameters were also carefully tuned.

5.3 Virtual Steps (2024)[1]

Walking is more than a mere means of locomotion; it is an action that enables freedom, exploration, and independence. Certain conditions and disorders can prevent individuals from walking, including genetic disorders and congenital conditions such as CP, MD, or SMA. These conditions can affect the development of muscles, bones, or the nervous system from birth and hinder the ability to walk.

Walking produces a range of sensory stimuli: proprioceptive feedback generated by limb movement [75], vestibular feedback from head motion [76], optical flow from visual perception as they move [77], and auditory feedback produced by their footsteps [78]. Emulating these sensations is a complex task that has been the target of extensive research, especially using virtual reality. Notable methods include employing specialized equipment such as omnidirectional treadmills [79, 80], foot-support motion platforms [81], and walking spheres [82]. VR technology has been used to simulate walking, providing presence and embodiment [278, 279, 280].

However, previously proposed VR walking experiences were mainly focused on reproducing the experience of a person who is able, or at some point in the past, was able to walk. This focus is not necessarily aligned with the desires of those users who have never experienced standing and walking. Even though these users have never walked,

[1]The content of this section has been previously published in **IEEE Conference Virtual Reality and 3D User Interfaces (VR)**. © 2024 IEEE. Reprinted, with permission, from Atieh Taheri, Arthur Caetano, and Misha Sra, "Virtual Steps: The Experience of Walking for a Lifelong Wheelchair User in Virtual Reality." 2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR), pp. 168-178, Orlando, FL, USA [277].

they have developed a mental model of how it feels to walk by observing others walk and interacting with them. Due to the potential differences in these mental models, current systems may not respond in ways that users who have never walked anticipate [217]. To address this gap, it is crucial to develop VR walking simulations that specifically cater to the unique mental models of individuals who have never experienced walking, ensuring a more inclusive and effective user experience. Another limitation of prior VR walking experiences is that they rarely consider the interaction limitations that usually accompany mobility limitations. Users who never walked before may also face challenges using the input devices and interaction techniques offered in commercial VR devices because they rely on fine hand and head coordination. The lack of appropriate interaction design restricts the access of individuals with congenital motor and mobility impairments to walking experiences in VR.

In this study, I had the opportunity to co-design a VR walking experience, exploring my perceptions and emotional responses to this new sensation. Together, we experimented with different design alternatives including auditory feedback, visual representation, movement dynamics, walking speed, interaction modality, and virtual environment. Instead of concentrating on rehabilitation or therapeutic uses, our research explores the design parameters of a VR walking experience tailored to users who have no prior physical walking experience. The needs of this particular audience, including myself, can be quite distinct from those of the general population because we do not have a physical walking experience to use as a reference, except for mobility aided by devices like wheelchairs. Our contributions are as follows:

1. An initial set of features and parameter values for VR walking applications to individuals with congenital motor and mobility impairments.

2. Qualitative insights into the emotions and perceptions of a user with congenital

motor and mobility impairments while experiencing walking through VR.

Through our study, we found an initial set of factors that affect walking experiences in VR for users who have never walked and compiled how different strategies of walking sensation emulation can impact the user experience. This contribution can inform the design of next-generation VR experiments that target audiences with motor and mobility disabilities, broadening accessibility in VR and providing a novel experience to users who never walked in their lives, with potential psychological and cognitive impacts.

5.3.1 Method

To investigate the design requirements for emulating walking sensation for individuals who have never walked, we applied participatory design coupled with a *diary study* technique. As a member of the target audience, I served as the sole participant in this study, maintaining a detailed diary documenting my observations and experiences with the experimental system. My active involvement included not only in testing the system, but also in guiding, requesting features, and calibrating parameters to meet my needs. Diary studies have been successfully employed in disability research, leading to novel findings on the experience of people with disabilities in VR experiences [281]. Our decision to use a diary study over phenomenological auto-ethnography was guided by our objective to allow for the potential generalizability of our findings. While phenomenological auto-ethnography offers deep, introspective insights into a researcher's personal experience, it focuses on subjectivity and is less concerned with generalizability [282]. A relevant example of a similar approach in VR research for people with disabilities is the diary study conducted by Zhang et al. [281] to explore the impact of avatars with disability signifiers on the experiences of people with disabilities in social VR settings. We also observed the previously proposed recommendations for HCI research with autobiographical design [283].

As a member of the community of individuals who have never walked, I bring shared or similar goals and experiences, which significantly enhance the research by providing expertise in experimental decisions and offering an insider perspective in interpreting results, as suggested by Liang et al. [284].

The decision to have me, the co-author, as the participant was intentional. By focusing on someone who has never had the ability to stand or walk, the study aims to provide a deeply personal perspective on the experiences and emotions evoked by virtual walking scenarios. This unique partnership between the researcher and the participant enhances the richness and depth of the insights derived from the research. Throughout the study, I maintained a diary to record my feelings, perceptions, and reflections after each VR session. This diary became a primary data source for sentiment analysis, capturing my evolving experiences and reactions to the varying virtual walking scenarios. Given that I am also a co-author, I played an active role in shaping the research objectives, providing feedback on the virtual environment and adjustable parameters, and reviewing preliminary findings. My dual role provided a valuable iterative feedback loop throughout the research process, ensuring both accuracy and authenticity in interpreting the experiences.

Procedure

This experiment was conducted with my informed consent of the participant and was approved by the local IRB of our home institution. We adopted a participatory design approach in 9 iterations. Starting from a baseline implementation of the experimental system, I tested the system for a total duration of 3 hours and 45 minutes. In line with the principles of participatory design, we did not impose a fixed duration for each trial session [285]. Instead, I was given the freedom to engage with the VR system as long as desired during each session, allowing for a natural and in-depth exploration of the virtual space and the available features. This approach enabled me to thoroughly engage with the VR system and reflect on my experience in a manner that was not constrained by time limits. Figure 5.2:a depicts me engaged in one of my VR explorations within the experimental system.

Following each VR session, I proceeded to take notes in my diary, checking for changes compared to the previous version, and constantly evaluating certain aspects like functionality and user experience across all iterations. These diary entries were made immediately after each session, using my right thumb on my laptop's built-in touchpad and a virtual keyboard, as is my usual method. This approach was chosen to capture my immediate reactions and thoughts more authentically. After the trial and journaling, Caetano, the other co-author and developer, and I discussed the challenges I faced and idealized possible solutions based on the feedback I provided. These were then implemented in the following version by Caetano. This continuous feedback loop ensured that each iteration of the system was more refined and better aligned with the user's needs, leading to a more effective and user-centered VR experience.

Experimental System

To test our hypotheses, we developed a walking VR experience, addressing my needs and preferences, and utilized the Unity 3D XR Interaction Toolkit[2]. The application was deployed to an Oculus Quest 1[3]. Our system implemented a speech interface to accommodate my motor needs. We employed Wit.ai[4], a robust speech recognition service from Meta, to transcribe and interpret user voice commands. Over the iterations, we realized that the speech recognition system was incorrectly identifying certain words as others.

[2] https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.3/manual/index.html

[3] https://www.meta.com/quest/

[4] https://wit.ai/

Iteration	Modifications & Feedback
1	Introduced basic VR walking simulation. Feedback: Encountered issues with recognition of "left" and "back" commands. Voice recognition improvements are required. Faced an issue with backward movement.
2	Changed "walk" command to "go"; introduced head oscillation for movement realism. Fixed previous issues with backward movement. Feedback: Adjustment for head oscillation required. A bug in terrain navigation required fixing.
3	Included avatar and footsteps sound; added options to toggle avatar, head oscillation, and footsteps; fixed the bug with gravity; introduced log file for tracking. Feedback: Encountered issues with the avatar's head position, footsteps sound being out of sync with head oscillation, and slow walking speed. Head oscillation felt more unnatural and needed correction. Improvement is needed for avatar integration and movement speed.
4	Adjusted head oscillation and walking speed; better synchronization of footsteps and head movements; fixed head position bug. Feedback: Persistent issues with "left" and "back" commands. Further refined voice commands are required.
5	Implemented "lima" for left turns. Feedback: Felt monotony during long-distance virtual walks. Required having control over movement speed and direction.
6	Implemented "reverse" for moving back; added speed control commands; allowed adjustment of oscillation amplitude. Feedback: Experienced issues with "fast" command. Refining speed control and turning mechanism required.
7	Replaced continuous turning with snap turning with a velocity of 1.5 degrees/sec; replaced "fast" with "speed" for acceleration. Feedback: Not satisfied with the "speed" command. Discussed having a "go" command for both walking initiation and acceleration.
8	Implemented "go" for both walking initiation and acceleration. Feedback: Fully satisfied with voice commands.
9	Final adjustments. Feedback: Celebrated improved experience and reflected on the journey.

Table 5.1: A summary of modifications on the system over iterations and the corresponding feedback I reported.

To address this issue, we performed some research and found that, on some occasions, using keywords from the NATO (North Atlantic Treaty Organization) phonetic alphabet might better work to improve clarity and more accurate input speech recognition. For

Iteration	**Voice Commands**			**Base Walking Speed (meter/sec)**	**Head Oscillation**		
	Movement	**Turning**	**Speed**		**Amplitude (meter)**	**Stride Len (meter)**	**Adv Speed (meters/sec)**
1	"walk" + "back" "stop"	"right" + "left"	N/I	0.5	N/I	N/I	N/I
2	"go" + "back" "stop"	"right" + "left"	N/I	0.5	(0.1, 0.1, 0.1)	0.8	1
3	"go" + "back" "stop"	"right" + "left"	N/I	0.5	(0.1, 0.05, 0.1)	0.5	0.5
4	"go" + "back" "stop"	"right" + "left"	N/I	1	(0.1, 0.1, 0.1)	0.8	1
5	"go" + "back" "stop"	"right" + "lima"	N/I	1	(0.1, 0.1, 0.1)	0.8	1
6	"go" + "reverse" "stop"	"right" + "lima"	"fast" + "slow"	1	(0.05, 0.05, 0.05)	0.8	1
7	"go" + "reverse" "stop"	"right" + "lima"	"speed" + "slow"	1	(0.05, 0.05, 0.05)	0.8	1
8	"go" + "reverse" "stop"	"right" + "lima"	"go" + "slow"	1	(0.05, 0.05, 0.05)	0.8	1
9	"go" + "reverse" "stop"	"right" + "lima"	"go" + "slow"	1	(0.05, 0.05, 0.05)	0.8	1

Table 5.2: Changes in parameters over iterations. Voice commands include Movement, Turning, and Speed Commands. The head oscillation parameters encompass Amplitude, Stride Length (Stride Len), and Advance Speed (Adv Speed). Changes in base walking speed are also reported. "N/I" denotes "Not Implemented".

instance, instead of using the word "left," we adopted the word "lima".

The experimental system allowed users to move forward and backward as well as to turn left and right. Forward and backward movements were initially implemented as a sliding looking [286] locomotion technique with continuous linear movement and, later, at my request, the system was updated to support three different speed settings for forward and backward movements. One keyword activated the movement forward, another activated the movement backward, and those remained active until the user said a third keyword to stop. The user could speed up and down by repeating the keyword for the current directions. The most comfortable linear speed was 1 meter per second, allowing for 3 increment levels of 0.25 meters per second. While slower than the average human walking speed [287], this speed value was used by Lécuyer et al.[288] and found to be sufficient for me to use voice inputs effectively to avoid obstacles and reach destinations at a satisfactory speed. The angular movement was initially implemented with a snap-turn technique of 45 degrees around the user's vertical axis but was later replaced with a continuous turn of 45 degrees per second from the current orientation to a 30-degree displacement. Two keywords activated the turning, one for each direction. Furthermore, users could move their heads to turn in the direction they were looking at, allowing for fine adjustments of the turning direction. The HMD tracking only influenced the camera rotations, and translations that had to be achieved using forward and backward linear movements activated through speech. The locomotion behavior is implemented by our *SpeechCharacterController* component depicted in Figure 5.1.

The virtual environment in our system has a circular region of 100 meters in diameter with four sections in the cardinal directions. Each of the sections has different conditions that make the user adapt their walking strategy. In the North direction, there is a soccer field with a ball so the user can kick it and try to score a goal. To enhance the user's ability to hit the ball, we increased its size to a radius of up to 90 cm. This adjustment allowed me to interact effectively with the ball, even with limited locomotion inputs. In the South, there is a sinuous tunnel where the user has to turn in a constrained space of 2.5 meters wide to arrive at a secret chamber. In the East, there is a forest with sparse trees, so the user is stimulated to take turns to avoid the trees as they move. In the West, a hill with a windmill on top incentivizes the user to walk uphill and experience the view. The regions provide variability of walking conditions to the environment and encourage the user to walk around the virtual environment, but there was no goal or game associated with reaching any of the sections. The Unity assets used in the environment are freely available online[5][6].

Extremity joint tracking and inverse kinematics can enable full-body movement reconstruction in VR avatars and offer benefits in terms of embodiment and presence [289]. However, this method was not practical in our scenario. I face motor restrictions that impede real-life walking; therefore, tracking my body would be ineffective for simulating a walking experience. As an alternative to provide visual stimulus in the walking simulation, our system includes a full-body avatar with a walking animation, both freely available on Adobe Mixamo[7]. The user can see the avatar in their peripheral vision and also through a virtual mirror (shown in Figure 5.2:b). The avatar's head was visible only through the mirror, being kept out of sight by adjusting the camera near-clip beyond the head. In future attempts to replicate this work, researchers may opt to cull the back faces of the avatar's head instead. We also adopted a head oscillation movement as additional visual stimuli. This was achieved by moving the camera around the initial local position to simulate gait-induced head oscillation, as proposed by Lecuyer et al. [288]. Lecuyer et al.'s head oscillation model comprises a three-dimensional amplitude (meters) vector parameter and a period determined by the ratio of stride length (meters)

[5] `https://www.syntysearch.com/`
[6] `https://assetstore.unity.com/publishers/25353`
[7] `https://www.mixamo.com/`

to advance speed (meters per second). The values for this parameter adopted during our iterations are documented in Table 5.2. The head oscillation mode I preferred had an amplitude of 5 centimeters in all directions, stride length of 80 centimeters, constant advance speed of 1 meter per second, and a period of 1.6 seconds. The head oscillation behavior is implemented by our *HeadOscillator* component attached to the camera as shown in Figure 5.1. As a complementary auditory stimulus, each footstep produces a sound that mimics stepping on grass, synchronized with the user's gait. Footstep sound effects were preferred when triggered in sync with all lateral oscillation extremes of the head, i.e., at every 0.8 seconds. All of these stimuli can be toggled or tweaked to create different experimental conditions. The footstep sound effect is played by a *FootstepSFX* GameObject, and the *Avatar* GameObject holds the 3D model of the body. Both of them can be turned on and off by the user thanks to the *FeatureToggle* component. The relationship of these components is illustrated in Figure 5.1.

5.3.2 Data Analysis

Caetano and I both contributed to the analysis of the data. As the single participant in this study, I reported my perception and experience with the experimental system over the course of 9 days in a diary. Across this period, a total of 2661 words were collected. The authors, including myself and Caetano, independently coded the diary entries and derived our own set of themes. Subsequently, we collaboratively refined and merged these themes into a unified set [290].

In addition to the identified themes, we also performed a text sentiment analysis across each iteration. We initially used an online tool [8] based on DistilBERT [291]. The sentiment scores range from 0 to 1. A score near 0 indicates a low likelihood, and near 1 indicates a high likelihood that the text conveys this sentiment. In order to

[8] `https://huggingface.co/bhadresh-savani`

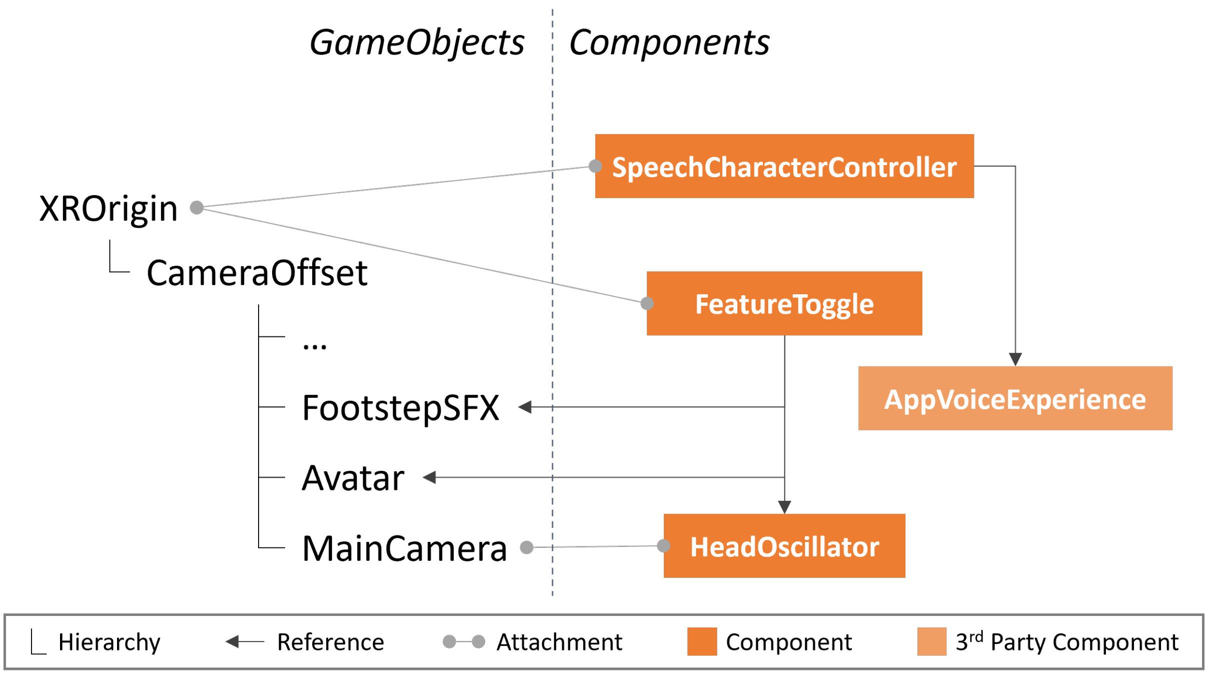
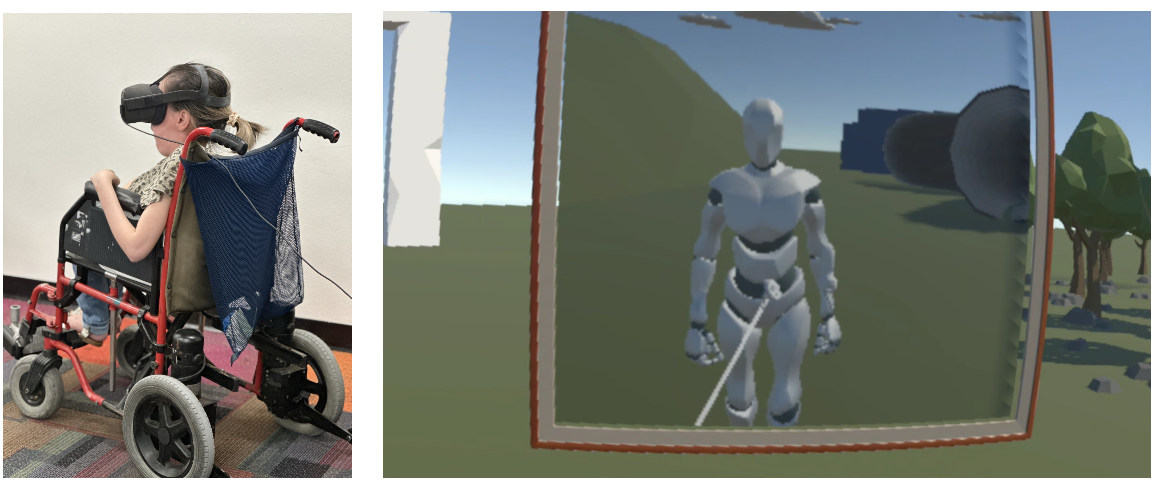


Figure 5.1: Unity-based Experimental System with Oculus Integration SDK and Wit.ai service. The left side displays the GameObject hierarchy, while the right side illustrates component attachment to GameObjects and their references.



(a) (b)

Figure 5.2: (a) Me testing the experimental system. (b) Virtual mirror in the experimental system.

further understand the sentiment conveyed through my diary entries, we employed the

Natural Language Toolkit (NLTK) package [9] in Python, which facilitated the deployment of two different sentiment analysis methodologies: VADER (Valence Aware Dictionary and sEntiment Reasoner) [292] and TextBlob [293]. VADER, a lexicon, and rule-based sentiment analysis tool, was utilized to quantify sentiment in my entries, providing scores for positivity, negativity, and neutrality, along with a compound score. It requires no training data and is adept at analyzing text on social networks, among others. Positive, negative, and neutral scores are in the range of $[0, 1]$ for each aspect. Each score represents the proportion of the text that falls into these categories. Therefore, a higher positivity score indicates that a higher proportion of the text is assessed as positive, and similarly for the negativity and neutrality scores. The compound score, on the other hand, is computed by summing the valence scores of each word in the lexicon, adjusted according to the rules, and then normalized to be between -1 (most extreme negative) and $+1$ (most extreme positive). Conversely, TextBlob, grounded on the Naive Bayes algorithm, delivered not only sentiment polarity scores but also subjectivity scores for each entry. The polarity score ranging from -1 (extremely negative) to $+1$ (extremely positive) served as an indicator of the sentiment orientation of the text. The subjectivity score, ranging from 0 to $+1$, denotes the extent to which personal feelings or opinions are expressed in the text.

We also logged the combination of active features and head pose every second in a log file, enabling us to extract statistics and plot the trajectory of each trial.

To provide a clear overview of the iterative development process of our VR system, two tables have been included. Table 5.1 presents a summary of the modifications made in each iteration, along with my feedback. It offers insights into the evolving user experience and system refinement. Table 5.2, on the other hand, focuses on the specific parameter values adjusted across iterations, including voice commands, base walking speed, and

[9] `https://www.nltk.org/`

Themes	Frequency	Ratio	Variance
Emotional Engagement	78	48.44%	31
Mental Model of Walking	19	11.8%	5.11
User Interface & Control	10	6.21%	0.86
Embodiment & Presence	20	12.42%	6.94
Agency & Control	28	17.39%	4.61
Cybersickness	4	2.48%	1.02

Table 5.3: Frequency and ratio of themes and their variance across iterations.

head oscillation. This table gives a technical perspective on the changes, showcasing the incremental adjustments in system settings that were guided by my feedback.

5.3.3 Results

Thematic Analysis

My diary chronicling my experience using VR to walk for the first time provides a rich account full of insights. Several key themes emerged from a close reading of my diary. Table 5.3 illustrates the identified themes' frequency, ratio, and variance. This table provides a statistical overview of how frequently each theme was mentioned, its proportion relative to the total thematic mentions, and the variance indicating the fluctuation of each theme across different iterations.

Emotional Engagement. Throughout the experiment, I reported diverse emotional responses, ranging from excitement to frustration. During the first session, a sense of "excitement and nervousness" dominated the experience, likely due to the novelty of the VR walking experience and the inherent expectations. As articulated at the beginning of my diary after Iteration 1, on Day 1:

> "I felt a mix of excitement and nervousness since I didn't know what to expect, having never walked before in my life."

While initial excitement was high, technical challenges such as speech recognition errors led to some frustration. I wrote on the same day:

> "My excitement waned a bit, but I was determined."

I was "determined" to move forward despite these setbacks which illustrates a sense of resilience.

The walking speed also had a significant impact on my emotional state. Initially, the "painfully slow" speed was a point of frustration. However, upon gaining control over the speed, I felt "freedom and agency," as I described it as "amazing to move however fast or slow I wanted on a whim."

Emotional engagement is crucial for the user experience, especially for participants who have never walked before. The findings suggest that while the VR experience can elicit strong positive emotions, technical limitations can also lead to negative emotions like frustration, affecting the overall engagement level.

Mental Model of Walking. Even though I had never physically experienced walking, I had my own mental model of what that experience would feel like. In the early iterations, I found the experience somewhat disorienting due to the lack of synchronization between visual and auditory elements. Specifically, on Day 3 and Iteration 3, I observed that the "footsteps didn't quite sync up with the head bobbing," leading to a disrupted sense of realism. I noted in my diary:

> "The footsteps didn't quite sync up with the head bobbing. It was like hearing someone else's steps rather than my own."

The sound of the steps also played a crucial role in matching the virtual experience with my mental model. Initially, the footsteps were out of synchronization, creating a "sense of disconnect." Over time, this was rectified, and I noted that the "perfected motions and footstep sounds" enhanced my experience. The feeling of "disconnect" could be explained by a mismatch between the mental model and the sensory stimulus which is known to attenuate the sense of agency [269, 270, 271].

Head oscillation or bobbing was another feature that contributed to the sense of realism. Initially, I found the head bobbing "unusual" but still "amazing" in Iteration 2, on Day 2. Over time, I experimented with different settings and found that a moderate level of head bobbing felt "comfortable" and positively contributed to the experience. By Iteration 9, Day 9, I expressed:

> "[..] at 1, I feel as if I'm truly walking, just like a person without a disability. It feels amazing and I love it."

The sense of realism in a VR walking experience is integral for immersion. My experience highlights the need for better integration between auditory and visual elements to foster a more naturalistic experience.

User Interface and Control. Voice command recognition was a significant concern for me, particularly in the early iterations. The system frequently confused commands, such as mistaking both "walk" and "left" for "right," making the experience cumbersome and less intuitive. In Iteration 1 on Day 1, I expressed frustration:

> "The system struggled to recognize my command to 'walk' forward, mistaking it for 'right' almost 99% of the time."

This statement reflects the initial challenges encountered with voice command recognition, highlighting the need for refinement. Over subsequent iterations, all these issues were gradually addressed, leading to a more intuitive experience by Iteration 8, Day 8.

For physically disabled users who rely on voice commands, the accuracy and reliability of the interface are paramount. Failures in command recognition can significantly impair the user experience and lead to disengagement.

Embodiment and Presence The sense of embodiment evolved significantly across iterations, influenced by various factors. Notably, the introduction of a virtual avatar in Iteration 3 on Day 3 seemed to enhance my sense of embodiment. However, it introduced new distractions, such as the head appearing in the view due to the camera position. This issue was adjusted in Iteration 4, on Day 4, by increasing the camera near-clip beyond the head. Reflecting on the sense of embodiment produced by the Avatar in Iteration 3, on Day 3, I reported:

> "Looking down and seeing my legs moving as I ascended [the hill] was magical! This produced the strongest feeling yet of truly walking myself up the slope."

This reflection highlights the profound impact of the avatar on my sense of embodiment, enhancing the feeling of walking up a hill. Additionally, the virtual mirror allowed me to see the reflected virtual movements of my virtual body, as expected of a physical mirror. I recognized the reflected body as my representation but not an accurate depiction of my physical body. In my diary, following Iteration 9, Day 9, the final iteration, I articulated my feelings about this representation:

> "I'm looking at my reflection - albeit an avatar robot - but it's still me in the mirror, [...]. It's a strange yet wonderful feeling to see myself standing and walking when the real me sits immobile."

The mirror might have induced cognitive dissonance by presenting an image that was at odds with my real-world bodily experience. While it offered a novel and thrilling opportunity to "stand," it also conflicted with my long-standing embodied experience of being in a wheelchair. This duality could have limited the sense of full embodiment within the VR environment.

The settings for the head oscillation influenced my sense of embodiment. Allowing me to adjust these settings enabled me to find the most comfortable configuration. When set to zero, the experience resembled "rolling my wheelchair," but adjusting it to a moderate setting made me feel as if I was "truly walking". I also noted in my diary that the synchronization between the head oscillation and the footstep sound was impacting the sense of embodiment:

> "The footsteps didn't quite sync up with the head bobbing. It was like hearing someone else's steps rather than my own. This mismatch disrupted what I imagined to be a natural rhythm of walking, creating a sense of disconnect."

This statement, from Iteration 3, Day 3, highlights the ongoing adjustments in the VR system and their impact on the sense of embodiment. The sense of embodiment and presence is crucial for VR applications, especially those aiming to replicate real-world experiences like walking. While the avatar increases the sense of presence, attention to detail is needed to avoid distractions that could break immersion.

Agency and Control. My sense of agency evolved significantly throughout the diary entries. During the initial iterations, as evidenced in Iteration 1, Day 1, the inability to accurately execute voice commands led to a limited sense of agency. I felt confined by the system's inaccuracies, as evidenced by the struggles with the "walk", "left", and "back" commands.

As the study progressed, improvements in voice recognition and the introduction of speed controls significantly enhanced my sense of agency. The successful implementation of the "go" command for acceleration was a pivotal moment. I expressed extreme happiness and a "wonderful sense of freedom and agency," indicating a high level of control over my virtual experience. I specifically remarked upon in Iteration 8, Day 8:

> "Using 'go' for acceleration was the best choice. I was extremely happy to be able to control my walking pace. [...] It felt amazing to move however fast or slow I wanted on a whim."

I also had noted in Iteration 4, Day 4:

> "For the first time in my life, I felt what it was like to climb a hill under my own power. I can't wait to explore more tomorrow!"

A strong sense of agency is essential for a rewarding VR experience, especially for individuals who have physical disabilities. The ability to control one's speed or direction in the virtual environment can profoundly impact the user's emotional state and overall satisfaction with the VR experience. Therefore, optimizing the user interface for intuitive interactions is crucial for enhancing the user's sense of agency.

Cybersickness. Interestingly, despite the complexities involved in simulating walking for someone who has never physically experienced it, I felt no instances of motion sickness. During Iteration 2, Day 2, I explicitly stated in my diary when I felt head oscillation to be "exaggerated":

> "[head oscillation] oddly reminded me of a past experience of sitting on a horse with my cousin. Fortunately, there was no motion sickness at all."

And another time at Iteration 7 on Day 7 when I was trying continuous turning as I explicitly noted:

> "I had been forewarned that this method of turning might induce motion sickness, but I did not experience any discomfort."

Sentiment Analysis

This subsection delves into the sentiment analysis results obtained from three different methodologies: DistilBERT, VADER, and TextBlob. The emotional landscape across different iterations of the study will be explored, highlighting specific emotions and events. Each method offers a unique perspective on my experience, contributing to a comprehensive understanding of emotional responses to virtually walking.

Specific Emotions and Corresponding Events. As illustrated in Figure 5.3, the sentiment of *"surprise"* was notably high during the first and last iterations. During the initial exposure to walking in VR, my diary revealed a mixture of excitement and nervousness, corroborating a high *"surprise"* sentiment score of 0.43. The concluding iteration led to another spike in *"surprise"* with a score of 0.45, likely due to the integration of all previous settings, which culminated in a fulfilling and somewhat unexpected final experience.

The emotion of *"fear"* spiked significantly in the fifth iteration. This is aligned with my diary entry, in which I discussed a newfound concern about the monotony of rather long-distance virtual walks. I directly related this feeling to the helplessness I often experiences while using a wheelchair and someone else is pushing it in the real world. This connection between virtual and real-world experience provides valuable context for the elevated *"fear"* score of 0.78.

The levels of *"joy"* were remarkably elevated during the third and seventh iterations, with scores of 0.93 and 0.99, respectively. The third iteration introduced bug fixes and options to toggle various features, while the seventh incorporated continuous linear turning and speed controls. Both of these enhancements likely contributed to the high scores of *"joy"* expressed in the graph.

Interestingly, the sixth iteration showed a complex emotional landscape with elevated levels of *"sadness"* and *"anger"*, with scores of 0.79 and 0.18, respectively. This iteration introduced speed controls, and diary entries hinted at possible difficulties or dissatisfaction with this new feature.

Throughout the study, the sentiment of *"love"* remained low, most likely because this emotion was not a relevant factor in this context.

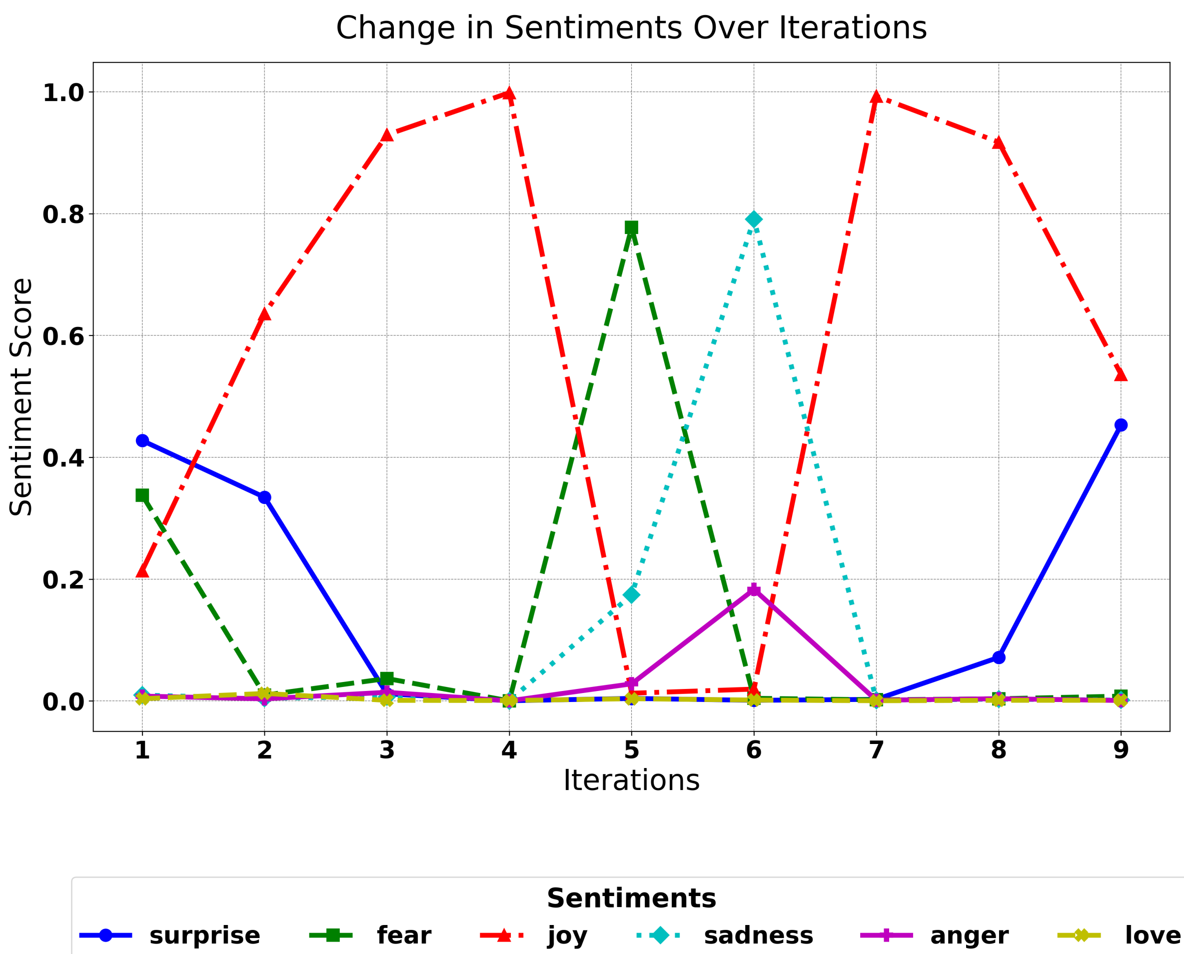


Figure 5.3: DistilBERT sentiment scores over 9 iterations: variations in emotions—surprise, fear, joy, sadness, anger, and love—across iterations in the graph align closely with significant events and system enhancements, providing an understanding of my emotional journey.

VADER and TextBlob: A Detailed Emotional Journey.

Initial Encounters: Cautious Optimism (Iterations 1-3). Both VADER (Figure 5.4:a) and TextBlob (Figure 5.4:b) sentiment analyses aligned with the DistilBERT findings of a mix of excitement and apprehension during the initial iterations. VADER's compound scores ranged from 0.82 to 0.95, indicating a generally positive yet cautious sentiment. TextBlob's polarity echoed this trend, ranging from 0.13 to 0.2.

Emotional Highpoint: Awe and Freedom (Iteration 4). In the fourth iteration, VADER's positive score soared to 0.24, and the compound score reached 0.99, corroborating the heightened sentiment of "joy" reported by DistilBERT. TextBlob's polarity peaked at 0.34, confirming a highly positive emotional state. These peaks are visible in Figure 5.4:(a and b).

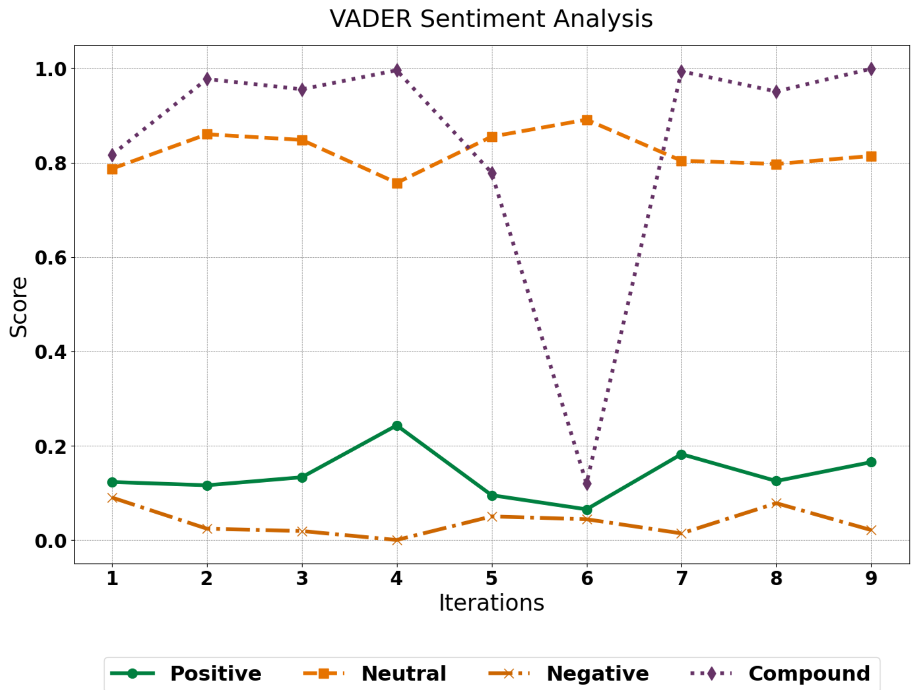
Emotional Complexities: Mixed Feelings (Iterations 5-6). The fifth and sixth iterations saw a decline in overall positive sentiment, which is consistent with the spike in "fear" observed in DistilBERT. VADER's positive scores dropped to 0.09 and 0.06, respectively, while the compound scores also decreased. TextBlob's polarity scores mirrored this trend, as shown in Figure5.4:(a and b).

Final Iterations: Satisfaction and Reflection (Iterations 7-9). The final iterations witnessed a resurgence in positive sentiment, consistent with the elevated levels of "joy" in DistilBERT. VADER's positive scores rebounded to 0.18 in the seventh iteration and remained relatively high through the ninth. The compound scores also increased, culminating in a near-maximum score of 0.999 in the final iteration. TextBlob's polarity scores were consistent with this trend.

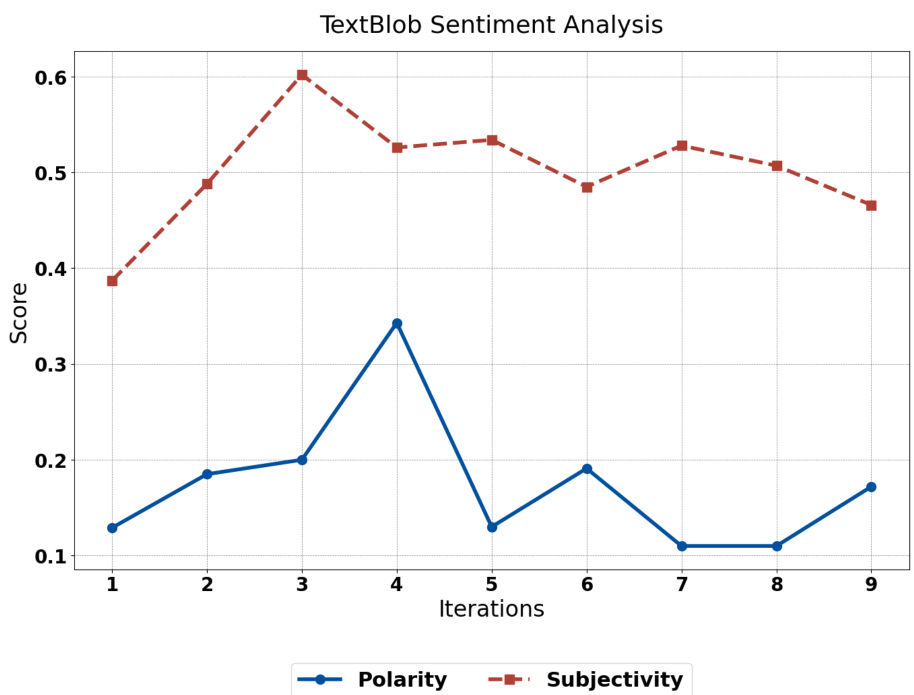
Subjectivity Across Iterations. TextBlob's subjectivity scores provided additional depth to understanding of my experience. The scores ranged from 0.39 to 0.6, indicating varying levels of personal engagement and emotional investment across iterations. These are well-captured in Figure 5.4:(a and b) for VADER and TextBlob, respectively.

Trajectory Analysis

I tested the experimental system for a total of 3 hours and 45 minutes, covering a distance of 5.725 kilometers during the span of 9 days. On average, iterations lasted 12 minutes, with the longest iteration lasting 26 minutes. The average iteration length was 370 meters, while the longest iteration extended to 1.18 kilometers. The average speed during the iterations was approximately 0.5 meters per second. These are statistics



(a) VADER Sentiment Scores



(b) TextBlob Sentiment Scores

Figure 5.4: Sentiment scores over 9 iterations: (a) VADER sentiment scores showing the proportions of positive, neutral, and negative sentiments, as well as the compound score, across all iterations. (b) TextBlob sentiment scores showing polarity and subjectivity scores across all iterations.

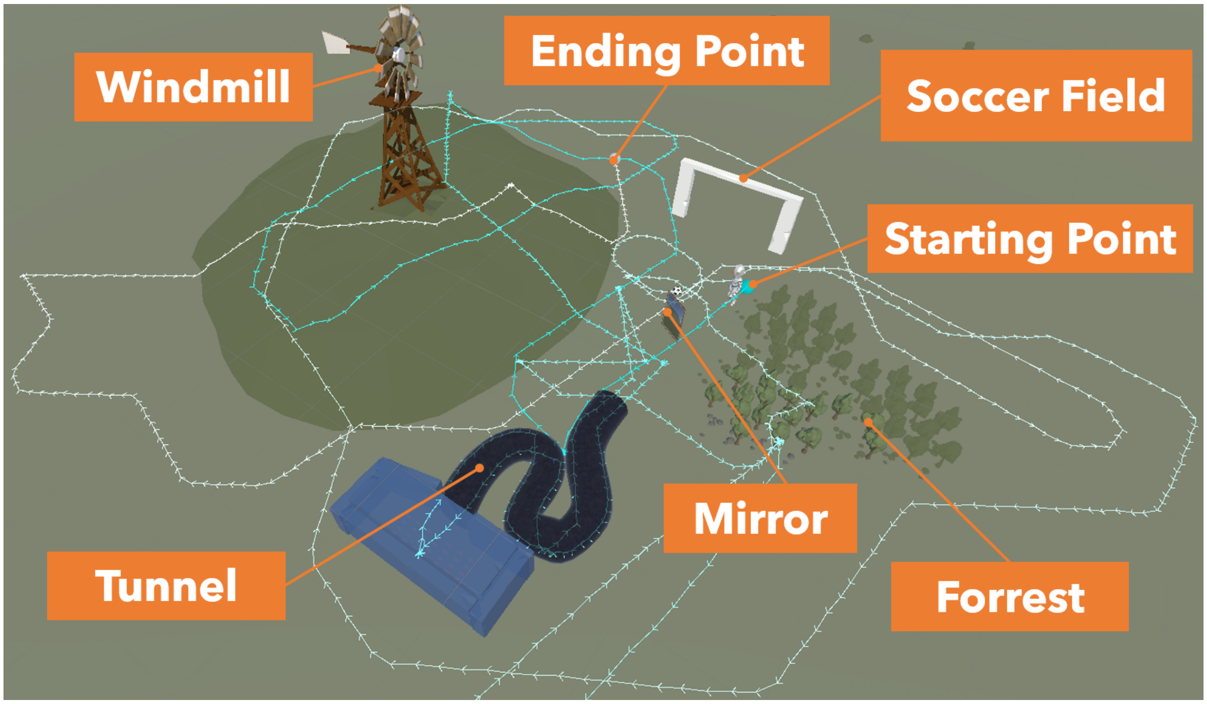


Figure 5.5: The virtual environment provided the setting for the virtual walking experience, featuring landmarks and props that motivated me to explore. My trajectory began at the cyan sphere and ended at the white sphere, with directional arrows indicating the path's orientation.

from the third iteration onward; the logging feature was introduced in that iteration. Figure 5.5 shows the trajectory I walked in the virtual environment.

5.3.4 Discussion

This exploratory study provides insights into the subjective experience of virtually walking for individuals who have never walked before. Our participatory design approach enabled an iterative process where the feedback from me, both a researcher in our team and the study participant as a member of the target user group, directly shaped system enhancements to better meet my needs and desires. The themes that emerged from the diary study analysis highlight key considerations for creating compelling and emotionally engaging VR walking experiences for people with disabilities.

The choice of the diary method for data analysis played a crucial role in this research. This approach allowed me to document thoughts and feelings in realtime, providing a rich and nuanced understanding of my experience with the VR system. Unlike observation or video analysis, the diary method empowered me to express my perspective in my own words, offering insights that might not be evident through external observation. Additionally, compared to post-trial interviews, diaries can capture immediate reactions and changes in perception across different stages of the experiment, which is crucial for understanding the evolving experience of a lifelong wheelchair user in a VR walking simulation. This method's introspective and longitudinal nature made it particularly suitable for this exploratory study, where the participant's subjective experience was paramount [294, 295].

The sentiment analysis reinforces the importance of managing user expectations and technical limitations to avoid frustration. As observed in the initial iterations, inaccuracies in speech recognition and lack of control over speed disrupted immersion and caused negative reactions. However, once these issues were addressed, emotional engagement improved dramatically. The final iterations produced high levels of "joy", indicating satisfaction with the experience. Our findings reveal an interplay between the senses of agency, embodiment, and presence in simulating the experience of walking. My mental model of walking had to be carefully considered in syncing visual and auditory elements like footsteps and head bobbing. A user able to walk in the physical space may also express discomfort when experiencing a misalignment between their intentions and sensorimotor stimuli, as indicated by models of the sense of agency [269, 270, 271]. We speculate that in my case, my sense of agency predominantly stems from my mental model of walking, at the cognitive level, given my sensorimotor system's limitations. This underscores the importance of developing VR experiences that are congruent with the mental models of users facing mobility impairments.

Customization was key; options to tweak head oscillation and walking speed enhanced the sense of control and embodiment. The virtual body avatar increased embodiment but could also be distracting if not properly calibrated. Overall, a high degree of realism and synchronicity is needed to avoid breaking immersion. The life-long experience of disability colors the subjective experience of virtual walking. Connections were drawn between feelings of helplessness in the real world and virtually walking long distances. Managing expectations and emotional support may be as important as technical accuracy.

The introduction of the virtual mirror produced a unique reaction, allowing me to see myself standing and walking despite my physical condition. I reported this in my diary as a "strange yet wonderful feeling" when looking at the virtual mirror. We attribute this perception to the previously demonstrated impact of tool embodiment on extrapersonal space estimations [296]. We speculate that the virtual mirror allowed me to estimate my extrapersonal space, but the avatar not depicting the wheelchair confused my sense of embodiment, producing a strange feeling. The sensation of "strangeness" could be attributed to the dissonance between my lifelong physical experience and the virtual representation of my body. For someone who has never walked, seeing oneself standing and walking in a mirror can be an unfamiliar experience, challenging long-held perceptions of self and mobility. The "wonderful" aspect likely stems from the empowering experience of virtually performing a physically unattainable action. This duality of emotions reflects the complex interplay between physical reality and virtual embodiment.

A critical consideration of this study is the concept of cybersickness which occurs due to decoupling virtual input control from motion. In the physical world, this decoupling for me may manifest itself as the use of a joystick to move the wheelchair or having someone else push the wheelchair. In the virtual environment, a different form of decoupling occurs. By adopting speech as an input modality, there was a chance that the user's mental model of walking would be challenged by the decoupling of locomotion through a virtual input. Interestingly, despite our anticipation of potential cybersickness, I felt no such symptoms. Although the reasons for cybersickness are debated [297], we believe that this was related to a comfortable speed parameterization, perhaps because the levels of sensory mismatch in the VR experience were similar to those I experience in the wheelchair.

5.3.5 Summary

In the work, we explored the experience of walking in a VR for individuals who have never walked due to congenital conditions. This study considered the unique mental models and interaction limitations of these users to create a an experience that is both inclusive and engaging.

We employed participatory design and diary studies, with myself as the sole participant, to develop and refine the VR system over nine iterations. The system included features such as head oscillation, footstep sound, voice command recognition, and a virtual body avatar to enhance the sense of walking to make the experience as close as possible to what I had in mind walking should feel like. Emotional engagement, embodiment, agency, and the avoidance of cybersickness were key considerations.

Our thematic analysis revealed significant insights into the emotional and cognitive experiences of VR walking. Emotional engagement was high, though technical limitations initially caused frustration. The synchronization of auditory and visual stimuli, customization options, and a realistic virtual body avatar were crucial for a positive experience. The virtual mirror provided a unique perspective, allowing me to see myself standing and walking, which produced both a sense of wonder and cognitive dissonance.

Sentiment analysis showed varied emotional responses across iterations, with high levels of joy and surprise in the final iterations. The study found that managing user expectations, providing customization options, and ensuring realistic synchronization of stimuli are essential for an effective walking experience in virtual settings.

This research contributes to the design of VR systems for individuals with congenital motor and mobility impairments, broadening accessibility and providing novel experiences with potential psychological and cognitive benefits.

5.4 Conclusion

This chapter has explored the third component of my proposed conceptual design space: user experience. By delving into how individuals interact with and perceive technology, especially in the context of accessibility, we aimed to enhance the overall user experience for individuals with disabilities. The principles of user-centered design, emotional design, accessibility, and inclusivity have been central to our approach, ensuring that the technologies we create are not only functional but also engaging, intuitive, and satisfying.

The "Virtual Steps" project served as a case study to illustrate these principles in action. Through a participatory design process and a diary study methodology, we gathered rich, qualitative data that provided insights into the emotional and cognitive aspects of user experience. This iterative approach allowed us to incorporate the unique perspectives and needs of our target users at every stage of the design process.

In conclusion, this chapter has demonstrated the profound significance of focusing on user experience in the design of accessible technologies. The intricate relationship between user engagement, emotional response, and the practical functionality of technology underscores the necessity for a holistic approach to design. The "Virtual Steps" project serves as a testament to the potential of VR to provide meaningful experiences for individuals with disabilities, offering them new forms of mobility, independence, and empowerment. As we continue to advance in the field of human-computer interaction and accessible technology design, it is imperative to prioritize user experience. By adopting user-centered and participatory design methodologies, we can ensure that the technologies we create are inclusive and meet the diverse needs of all users. This ongoing commitment to improving user experience will ensure that technology remains a powerful tool for inclusion and empowerment, ultimately enhancing the quality of life for individuals with disabilities.

It is important to acknowledge that not all members of the disability community may view this type of work through the same lens. The aim of this exploration with the Virtual Steps project was not to "fix" a physical reality but to expand the spectrum of experiences that can be lived and felt. This approach recognizes that the value of VR lies in its ability to act as a bridge to the unimaginable, transforming the concept of limitations into one of limitless possibilities. For some, the idea of virtually walking may resonate deeply, offering a new form of engagement with an experience previously inaccessible. For others, it may not hold the same appeal or may be perceived as unnecessary. The critical takeaway is that VR should be seen not as a prescriptive tool but as a versatile platform that can cater to diverse desires and aspirations within the community. Ultimately, the goal is to empower users by providing options that respect their individual choices and expand the landscape of what is possible, embracing VR not just as a technology, but as a means to reimagine and enrich the human experience in ways that honor personal agency and diverse lived realities.

These diverse perspectives highlight the broader implications of expanding VR's role in human experience, which extend beyond the scope of this project. There are several key areas where future research and development can build on the findings of this chapter:

- Enhanced Customization: Future VR systems should incorporate more advanced customization options, allowing users to tailor their experiences to their individual needs and preferences. This could include adjustable environmental settings, personalized avatars, and adaptive feedback mechanisms that respond to the user's real-time inputs and emotional states.

- Multisensory Integration: Integrating multisensory feedback, such as haptic feedback, temperature changes, and olfactory cues, can further enhance the realism and immersion of VR experiences. This holistic approach can provide users with a richer and more engaging virtual environment, closely mimicking real-life experiences.
- Longitudinal Studies: Conducting long-term studies with a diverse group of participants can provide deeper insights into the sustained impact of VR experiences on individuals with disabilities. Understanding how these experiences influence users over time can inform the development of more effective and sustainable VR applications.

Chapter 6

Conclusion

This dissertation has traversed a comprehensive exploration of accessible human-computer interaction, structured within a novel conceptual design space, with a particular focus on individuals with motor impairments. Through a series of innovative projects and user studies, I have demonstrated the potential of a holistic approach to create more effective, engaging, and empowering assistive technologies. My proposed design space encompasses three critical components: interaction, sensation, and user experience, each of which has been meticulously examined in Chapter 3 through 5 through one or more exemplary projects to uncover how technology can bridge the gap for individuals with motor impairments, providing them with innovative solutions that enhance their interaction with digital environments. By considering these components in tandem, I have shown that it is possible to develop assistive technologies that go beyond mere functionality to address the full spectrum of user needs, preferences, and experiences.

Interaction: My research commenced by addressing the significant challenges faced by individuals with motor impairments when interacting with digital systems. Initially, my focus was on developing and evaluating a novel hands-free input technique for playing video games, driven by my deep desire to play video games again after losing the ability to do so at the age of 14 or 15. Individuals with severe motor impairments, like myself, who could benefit from this form of entertainment and social interaction are often overlooked in the design of video games and the tools to play them. Through evaluating a facial expression-based video game controller, we demonstrated that leveraging non-traditional input modalities can provide an inclusive and engaging experience for individuals with severe motor impairments and enhance accessibility. This facial expression-based input technology has the potential to unlock new possibilities for social connection and enjoyment for those who need it most. With the emergence of LLMs, new avenues for interaction have opened up, empowering users to engage with technology in ways that were previously inaccessible. Through the design and development of Virtual Buddy, a conversational AI system, we showcased how LLMs can be utilized to create more accessible and personalized interactions for users with motor impairments. PromptAssist, an accessible text-to-image interface, further illustrated the significant potential of LLMs and that how advanced AI technologies can be harnessed to enable creative expression for individuals with limited physical capabilities. All these projects collectively highlight the importance of flexibility and customization in the input methods. By offering a range of interaction techniques and the ability to tailor them to individual needs, we can significantly enhance the accessibility and usability of digital technologies for people with diverse abilities.

Sensation: The second component of the design space explored the ways in which systems convey information to users through different sensory feedback channels. The MouseClicker prototype was a pivotal project in this dimension, integrating tactile feedback to simulate the sensation of clicking a conventional computer mouse, for users with hands motor impairments. This work demonstrated that multimodal output, including visual, auditory, and tactile feedback, is crucial to improving usability and creating a more inclusive user experience. By focusing on sensory feedback provided by assistive devices, we could create solutions that are intuitive and easy to use, in addition to being functional. The emphasis on output modalities highlighted the importance of delivering feedback in ways that are accessible and meaningful to users, catering to their diverse sensory and cognitive processing needs. It showed that while some aspects of vibrotactile feedback, such as intensity, can be standardized, others, like localization, require individual customization. This finding has implications for the development of future assistive technologies that incorporate tactile feedback.

User Experiences: The third component of my design space emphasized creating immersive and inclusive user experiences. This component was exemplified through the Virtual Steps project. This virtual reality application allows individuals who have never walked in their lives, due to a congenital conditions or other reasons, to experience the sensation of bipedal locomotion in a virtual environment. By focusing on the emotional and cognitive aspects of the user experience, we were able to create a deeply engaging and meaningful experience that went beyond the mere simulation. This project highlighted the importance of considering the unique mental models and expectations of users, including those who are experiencing it for the first time. It demonstrated that by carefully designing visual and auditory feedback and enabling the users to adjust the associated parameters in virtual environments, we can create experiences that are not only accessible but also emotionally resonant and potentially transformative for users. By prioritizing user experiences, the goal was to foster a sense of agency and empowerment, enabling users to navigate digital environments with comfort and ease.

6.1 Synergies and Trade-offs

There are significant synergies between the components of my proposed design space.

- Interaction and Sensation: The integration of innovative interaction methods with appropriate sensory modalities creates a more holistic and inclusive experience. The PromptAssist project, which made text-to-image generation tools accessible for individuals with motor impairments, effectively combined LLM-based input and visual feedback to create a seamless and engaging user experience, or in the MouseClicker project, facial expression as input and haptic feedback as output created a holistic experience.

- Interaction and user experience: The integration of hands-free input methods, such as facial expression-based controls, enhances user independence and experience. For instance, my facial expression-based input method enabled users to engage in gaming experiences that were previously inaccessible, thereby enriching their user experience.

- Sensation and user experience: The combination of sensation and user experience has shown that the addition of multimodal feedback, particularly haptic feedback, greatly improves the user's sense of agency and control. The MouseClicker project demonstrated how tactile feedback can provide users with a sense of physical agency, improving the user's overall experience by making digital interactions feel more concrete and fulfilling.

However, these synergies are accompanied by trade-offs that must be carefully managed. Enhancing one aspect should not come at the expense of another. When designing accessible technology, we may encounter the following trade-offs:

- Complexity *vs.* accessibility: This is a major trade-off. While the integration of advanced interaction methods and sensory modalities can enhance user experience, it can also introduce complexity. Ensuring that these technologies remain accessible and straightforward for people with different technical proficiency is a critical consideration. For example, while the MouseClicker provided rich haptic feedback, its initial design iterations using an orthoprosthetic glove highlighted the trade-off between functionality and user comfort.

- Customization *vs.* standardization. Developing deeply personalized solutions specifically tailored to meet individual requirements offers the best user experience but is not easily scalable. Conversely, standardized products may not fully meet the unique needs of every user but can be more easily distributed and adopted. For instance, the very personalized interfaces developed for me as a participant in my facial expression-based input as well as in PromptAssist were highly effective but posed a few challenges in terms of scalability that we needed to resolve before other users tested the interfaces.

- Cost *vs.* functionality: Advanced technologies often come with higher costs, which may hinder broad adoption. Finding the right balance between integrating sophisticated features and maintaining assistive technologies affordable is essential. Projects like MouseClicker aimed to repurpose existing devices to keep costs low while still providing enhanced functionality.

6.2 Broader Implications

The implications of my research extend beyond the specific technologies and systems developed. They provide valuable insights into the broader field of assistive technology and accessible HCI, highlighting the importance of a holistic approach that considers interaction, sensation, and experience. My work underscores the necessity of considering these three components all together to create more holistic and effective assistive technologies that meet the diverse needs of users. This holistic perspective is essential for designing solutions that are not only accessible, but also empower the users. By integrating the three components, we can develop technologies that offer a seamless and inclusive interaction experience, enhancing the overall quality of life for individuals with disabilities.

The conceptual design space proposed in this dissertation offers a framework that can guide future research and development in accessible technology. It provides a structured approach for considering the various aspects of user-system interaction, encouraging designers and researchers to think holistically about accessibility from the earliest stages of the design process. My research highlights the critical importance of moving beyond what Rogers and Marsden [298] term as the "rhetoric of compassion" in developing assistive technologies. By embracing a "rhetoric of engagement" through participatory design and co-creation, we avoid the pitfall of "Does he take sugar?" mentality - where researchers make assumptions about user needs without directly involving them. Instead of asking metaphorically "Does he need this feature?" our approach empowers users with motor impairments to be active participants throughout the research process. This shift from designing 'for' users to designing 'with' users yields deep insights into their specific needs, challenges, and preferences, ensuring that the resulting technologies are both practical and impactful. Moreover, this participatory approach fosters a sense of empowerment and ownership among participants, as their voices are not just heard but are central to the creation process. By transforming users from subjects of study to co-creators, we not only develop more effective and tailored solutions but also challenge the traditional power dynamics in assistive technology research. This approach aligns with Rogers and Marsden's vision of HCI research that does not just help others, but empowers them to innovate for themselves, ultimately leading to assistive technologies that genuinely enhance users' daily lives and experiences.

However, it is also essential to acknowledge that even with a co-design approach and alignment with a comprehensive design space, the resulting technologies may not resonate with everyone within the community. While co-design ensures that the solutions developed are deeply informed by the lived experiences of users, it does not guarantee universal acceptance or relevance even within that specific community. The diversity within the community of people with disabilities implies that each individual has unique preferences, needs, and levels of comfort with new technologies, and not everyone may find value in the experiences these technologies offer. This reality illustrates that even when the design process is inclusive, and the outcomes are carefully tailored, there will be instances where some members may feel the technology does not address their specific context or aligns with their perspective on disability and accessibility. Therefore, it remains crucial for researchers and designers to continuously engage with the broader community, remain open to feedback, and be prepared to adapt or even rethink their approaches in response to diverse viewpoints. The goal should always be to provide a spectrum of choices that allow individuals to determine how, or if, they wish to engage with these innovations.

In prior work, the integration of multiple sensory channels into output modalities has demonstrated the significant benefits of multimodal feedback [299, 300]. By combining visual, auditory, and tactile feedback, we ensured that the information provided by our systems was accessible and engaging. This approach enhances the usability of assistive technologies and provides a richer, more immersive experience for users. The ability to tailor feedback to the sensory and cognitive preferences of users is crucial for creating inclusive technologies that cater to the diverse needs of individuals with disabilities.

The focus on cost-effective solutions in all my projects is noteworthy. By repurposing existing devices and open-sourcing our designs, the aim was to reduce financial barriers and make advanced assistive technologies more widely available. This approach aligns with findings from Hurst and Tobias's study [301], which highlighted how custom-built assistive technology can often be less expensive yet more effective than off-the-shelf solutions. According to their study, individuals were motivated to create their own assistive technology due to increased control over design elements, passion, and cost savings.

Since I was very young, I have often wondered why individuals with disabilities are not the main target audience for the technologies developed. It always struck me as puzzling and a bit frustrating that the burden of customization often falls on us, the users, who must adapt these tools to meet our specific needs. Meanwhile, those without disabilities, for whom customization might be easier, are presented with products already tailored to their needs. This mindset has driven much of my work, pushing me to challenge the status quo and advocate for a design approach that places individuals with disabilities at the center, rather than on the periphery. This philosophy is reflected in my approach to repurposing existing technologies. By taking devices that are widely available and reimagining them to meet the needs of individuals with disabilities, we shift the narrative. We make these technologies not just accessible, but intentionally designed with us in mind. This method not only reduces costs but also empowers users by making customization an inherent part of the design process, rather than an afterthought. It will also promote sustainability and democratize access to technology, enabling a larger population to benefit from our innovations, much like the open-source communities and DIY cultures.

Moreover, this approach emphasizes the critical importance of both software and hardware customization in the development of truly inclusive technologies. In my work, the facial expression-based video game controller illustrated the potential of software customization. By leveraging advanced computer vision algorithms, our software could accurately interpret a variety of expressions and map them to specific in-game actions. Through extensive testing and user feedback, it became evident that software customization could significantly enhance user experience, making technology more inclusive by offering a personalized, adaptive interface tailored to the unique needs of each user and providing them with new avenues for engagement and creative expression. However, the MouseClicker project brought to light another essential dimension: the need for hardware customization. By integrating tactile feedback into an existing physical device — a standard computer mouse — we were able to create a more immersive and authentic experience for users with motor impairments. This endeavor highlighted that while software customization is crucial for adaptability and user interface personalization, the physicality of the interaction should not be underestimated. By embedding tactile elements such as vibration motors, we could offer users a more nuanced and responsive interaction with their devices. This integration allows users with limited motor control to receive immediate and intuitive feedback from their actions, thus enabling a more seamless and engaging experience. The dual focus on both software and hardware customization ensures that assistive technologies not only function effectively but also resonate with the users' sensory and physical experiences. While software customization allows for adaptability and personalization of the user interface and interaction methods, hardware customization provides the tangible, physical connection that enhances the overall user experience. Together, these elements create a more comprehensive solution that addresses the diverse and specific needs of individuals with disabilities.

6.3 Future Directions

While my research has made substantial strides in accessible HCI, there are numerous avenues for future work that can build upon my work. Expanding the functionality of systems like MouseClicker to include additional features such as scrolling and cursor movement can create more comprehensive input devices. This would enhance the usability and independence of users with motor impairments, making these systems even more valuable. By continuously iterating and improving upon our designs, we can ensure that designed technologies adapt to meet the evolving needs and desires of users. Another important future direction is improving the user interface, allowing for personalization and flexibility. Additionally, automated adaptation to disease progression would enable the system to continue being meaningful to the user for a long time.

The principles of decoupled haptic feedback and multimodal output, that we explored in MouseClicker, can be applied to a wide range of assistive applications. Virtual reality environments, educational tools, and rehabilitation devices are just a few examples of areas where these principles can provide significant benefits. By expanding the scope of these technologies, we can develop more inclusive and impactful solutions. The application of our findings to diverse contexts can drive innovation and enhance the accessibility of a wider range of digital and physical environments.

Personalization and adaptability are also critical areas for future research. Developing adaptive systems, such as improving the interface for my hands-free video game controller that can personalize feedback and input methods based on individual user preferences and abilities, is a promising direction. Machine learning and artificial intelligence can play a crucial role in creating user-centered and intelligent assistive technologies that adapt to the needs of each user. By leveraging these advanced technologies, we can create more responsive and intuitive systems that provide a seamless and customized interaction experience for users with disabilities.

Another important area for future work is the value of longitudinal studies to assess the prolonged impact and usability of our systems. These studies can provide a deeper understanding of the effectiveness of our technologies and highlight aspects that need improvements. By understanding how these systems perform over time, we can refine and optimize them to better meet the evolving needs of users. Long-term evaluations can also help us understand the broader social and psychological impacts of our technologies, providing valuable feedback for future iterations and developments.

6.4 Final Thoughts

The journey of this dissertation has been driven by a deep commitment to advancing accessibility and creating meaningful technological solutions for individuals with disabilities. By exploring the interplay between interaction, sensation, and user experience, within the scope of user's goals and context, I have laid the groundwork for more inclusive and effective assistive technologies. My research has demonstrated the transformative potential of technology when designed with empathy, inclusivity, and an understanding of user needs and conditions.

In this endeavor, I have had the unique experience of serving a dual role as both a researcher and a participant in all my research projects. This dual perspective has provided invaluable insights into the real-world challenges and needs of individuals with disabilities, allowing for a more authentic and user-centered design process. Being both the creator and end-user of these technologies has highlighted the importance of designing solutions that are not only innovative but also practical and impactful in daily life.

As we move forward, it is essential to continue embracing a user-centered approach, fostering collaboration between researchers, designers, and end-users. Together, we can push the boundaries of accessible technology, ensuring that everyone, regardless of their abilities, can fully participate in and benefit from the digital revolution. This collaborative and inclusive approach will drive innovation and ensure that our technologies remain relevant, effective, and empowering.

It is also crucial to recognize that the community of people with disabilities is not a static, separate group but rather a dynamic and integral part of the broader population. Each person can become disabled at some point in their life due to a range of factors such as age, illness, or injury. Therefore, drawing a strict line between individuals with disabilities and the rest of the population is not only unproductive but also detrimental in the long term. Such a separation can lead to exclusionary practices and hinder the development of well designed technologies that benefit all users.

This dissertation represents a step towards a more inclusive future, where technology serves as a bridge, not a barrier, empowering individuals with disabilities to lead independent, fulfilling lives. It is also important to recognize that technologies like VR do not aim to alter one's reality or suggest that it needs correction or fixing. Instead, they serve to enrich and expand the lived experiences of individuals who choose to explore them, turning certain limitations into new possibilities. However, it is equally essential to respect that not all members of the disability community may wish to engage with these tools, and their perspectives are also important in guiding responsible and inclusive technology development. The insights and innovations presented in this work have the potential to inspire further research, drive innovation, and contribute to the progress of accessible HCI. By continuing to prioritize accessibility and inclusivity in our technological advancements, we can create a world where everyone has the opportunity to thrive. This vision of inclusivity and empowerment through technology will continue to guide our work as I move forward, striving to make the digital world accessible to all.

In conclusion, this dissertation has emphasized the importance of a holistic, user-centered approach to designing assistive technologies. By addressing the components of interaction, sensation, and user experience, we have developed solutions that are not only functional, but also deeply enriching and empowering for users. This is not the end of the journey; it represents an ongoing cycle of learning, innovation, and collaboration. The future of accessible technology is bright, and with sustained effort and dedication, we can continue to make significant strides towards a more inclusive and equitable world. By embracing the notion that disability can affect anyone, we pave the way for a society that designs for diversity and fosters resilience and adaptability in all aspects of life.

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