Designing Superpowers: Investigating the Empowering but also Negative Effects of Human Augmentation

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Abstract

Human-Computer Interaction (HCI) research has increasingly investigated human augmentation technologies as they can expand human capabilities beyond biological constraints, producing “superpower experiences” where users perceive extraordinary abilities. While promising, their experiential aspects remain underexplored, as prior work has focused more on the functional enhancement than on how users experience such superpowers, including both empowering and negative effects. This thesis introduces the concept of “unfortunate superpower experiences”, referring to augmentations that offer notable capabilities while also generating undesirable negative effects. Such effects are intrinsic to augmentation, as extending human abilities can disrupt existing bodily balances, making it crucial to consider both benefits and costs. Through three case studies around augmented perception, cognition, and action, this research examines how users experience unfortunate superpowers and how such experiences evolve. The resulting insights are distilled into the Superpower Experience Framework, which articulates the interrelations of embodied awareness, agency, and temporal stability, offering guidance for the design of future superpower experiences.

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Thesis including published works declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes 6 original papers published in peer-reviewed venues. The core theme of the thesis is superpower experiences. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of me, the student, working within the Faculty of Information Technology under the supervision of Asst. Prof. Don Samitha Elvitigala, Prof. Florian 'Floyd' Mueller, Assoc. Prof. Barrett Ens, Dr. Gun Lee and Dr. Nathan Semertzidis.

The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research. In the case of chapters 2,4,5 and 6 my contribution to the work involved the following:

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I have not renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

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Chapter 1

Introduction

The concept of augmenting human capability has long been central to the evolution of computing and design since the mid-twentieth century. Engelbart's early conception of augmentation framed computing as a means to improve human problem-solving capacity rather than as a tool for automation (1962). This perspective established a foundation in which technology operates as a partner in amplifying human intelligence. With the emergence of Human–Computer Interaction (HCI), this early notion of augmentation evolved from a focus on computational interfaces to a more embodied and situated understanding of the human-computer relationship.

This progression has led to a broader conception of augmentation. While early research primarily focused on enhancing cognitive performance, contemporary work extends to the sensory and motor domains (Figure 1.1). Fernandes (2016) highlighted that wearable technology often replicates the function of existing tools, while augmentation technology aspires to generate new ways of perceiving, acting, or thinking. Recent HCI research frames augmentation as the active integration of computation, perception, and actuation into the human body and mind, exploring how such integration reconfigures human abilities and identity (De Boeck & Vaes, 2024; Guerrero et al., 2022; Pedersen & Duin, 2021; Raisamo et al., 2019). Through this integration, augmentation technologies promise to extend human capacities beyond natural limits, enabling users to sense, think, or act in ways that appear to exceed their innate capabilities (Kim et al., 2024; Kunze et al., 2017; Prattichizzo et al., 2014). The resulting experiences can feel extraordinary, akin to what this thesis describes as “superpower experiences”. Such experiences occur when technological actuations seem to originate from within the body and become integrated into one’s sensorimotor or cognitive repertoire. They are compelling because they blur the boundary between biological capacity and technological extension, and they alter what users believe themselves capable of doing.

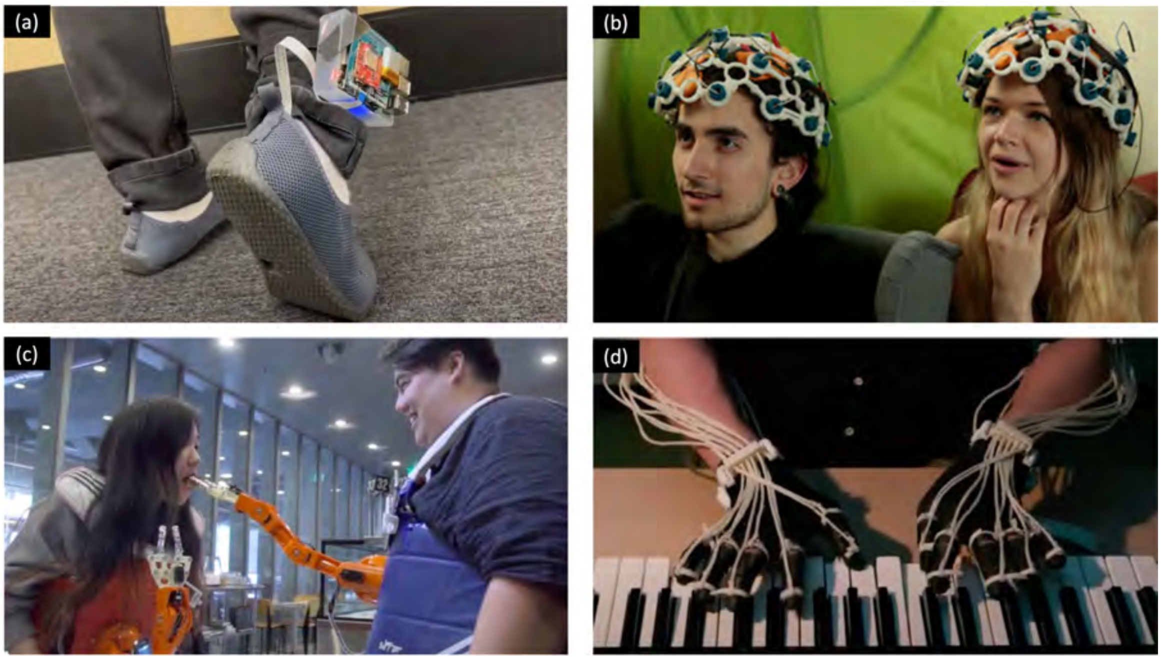


Figure 1.1: Examples of human augmentation technologies. (a) RadarFoot (Elvitigala et al., 2023), (b) PsiNet (Semertzidis et al., 2024),(c) Arm-A-Dine (Mueller et al., 2020b), (d) Soft exoskeleton glove (Takahashi et al., 2019).

While human augmentations are often framed as empowering, the lived experience of using them is more complex (Buruk et al., 2020; Svanæs, 2013). When technologies modulate directly in the body’s sensorimotor or cognitive processes, they can also disrupt embodied expectations and introduce uncertainty, discomfort, or loss of control. For example, stimulation-based systems may cause sudden, unfamiliar involuntary muscle movements, sensory augmentation may overload perception, and cognitive augmentation may blur boundaries of intention and decision-making (Limerick et al., 2014; Mueller et al., 2020a). These negative effects are not incidental; instead, they are integral to how augmentation is experienced because the body interprets technological modulation as part of its own sensorimotor system, thus disruptions also become part of the embodied experience.

To investigate this complexity, this thesis introduces the concept of “unfortunate superpower experiences”, referring to augmentations that provide notable capabilities while also generating undesirable negative effects. Understanding such unfortunate superpower experiences deserves attention in HCI for two reasons. First, they expose critical aspects of user experiences that are often hidden when augmentation is evaluated only by its functional success. Feelings of loss of control, fear, or insecurity are integral to how people interpret and integrate augmented abilities into their sense of self. Such disruptions could also serve as contrasts that make the remarkable aspect of augmentation more apparent. When users feel their bodies act in unfamiliar ways or struggle with fatigue and disorientation, these difficulties can emphasise how strongly augmentation departs from ordinary human experience, highlighting its “super” qualities (Benford et al., 2012; Dunne & Raby, 2013). Second, examining negative effects can provide valuable design insights. In the same way that research on dark patterns in user interfaces (Gray et al., 2018; Greenberg et al., 2014; Maier, 2019) has informed more transparent and ethical design, exploring the “unfortunate” side of superpower experiences can guide how designers might create augmentation technologies that are safer, more trustworthy, and more sustainable. Therefore, unfortunate superpower experiences are not simply obstacles to be eliminated but also design resources for critical reflection that can inform how we should and should not design human augmentations.

1.1 Research Motivation

Although augmentation technologies have advanced rapidly, research in human augmentation has largely prioritised technical performance and ergonomic efficiency (De Boeck & Vaes, 2024; Pedersen & Duin, 2021). These perspectives tend to frame the body as a substrate that can be extended or manipulated, potentially ignoring it as a lived and situated site of experience. As a result, the experiential dimensions of augmentation receive less attention, including how individuals interpret bodily sensations, respond to involuntary movements, and understand changing agency when bodily action becomes entangled with computational control.

This limitation has been evident in studies of muscle stimulation and neural-feedback interfaces (Guerrero et al., 2022; Raisamo et al., 2019). Electrical muscle stimulation (EMS) technologies enable novel forms of interaction and embodied expression, but they introduce unfamiliar sensations and involuntary movements that can disrupt users' sense of control and intentionality (Faltaous et al., 2024; Knibbe et al., 2018b; Takahashi et al., 2019; Tamaki et al., 2011; Villa et al., 2025). Similarly, changes in perception or decision-making in augmented cognition introduce moments of uncertainty that provoke renegotiation of expectations for agency and identity. These limitations demonstrate that augmentation is not only about enhancing human capabilities but also about reshaping the relationship between users and their own bodies and cognition.

The motivation for this thesis arises from the need to understand these changes more comprehensively. Existing research offers limited insight into how augmentation mediates the relationship between bodily agency, experiential awareness, and perceived capability. In particular, the interaction between the positive and the negative effects has not been examined through a conceptual framework that accounts for both. Without such an understanding, designers may neglect how instability and discomfort influence how users evaluate, trust, and integrate superpowers into their sense of self.

To address this gap, the thesis frames these experiences as "fortunate" and "unfortunate" superpower experiences to reveal the mechanisms through which augmentation influences perception, cognition, and action. Fortunate superpower experiences illustrate how augmentation can enhance users' capabilities in ways that feel integrated and supportive, while unfortunate experiences reveal how the same systems can generate ambiguity, instability, or vulnerability that complicate users' relationships with their augmented abilities. This perspective builds on research on uncomfortable interaction (Benford et al., 2012), speculative design (Dunne & Raby, 2013), and dark patterns (Gray et al., 2018), using discomfort as a lens for reflection and design, thereby fostering critical and generative thinking, and extending these discussions to embodied technologies that act through the human body rather than through interface logic.

Ultimately, this research is motivated by a broader question: "How can the design of augmentation technologies move beyond the rhetoric of enhancement to embrace the full spectrum of lived experience?" Addressing this question is necessary not only for creating safer, more ethical augmentation systems but also for rethinking what it means to integrate technology into one's own body. This exploration extends beyond usability and efficiency, delving into an understanding of human-technology intimacy and offering a critical lens on the embodied, ambivalent relationship between the self and augmented technologies.

1.2 Research Question and Objectives

Building on the motivation outlined above, this research seeks to advance understanding of how superpower experiences can be designed, examining both the benefits associated with enhanced capability and the challenges that arise when technology directly modulates bodily processes. The central research question guiding this work is: ***How do we design superpower experiences while considering their fortunate and unfortunate effects?***

To address this question, the following research objectives are established:

Objective 1: Explore the design of superpower experiences through human augmentation technologies. This objective investigates how technologies, such as EMS-based systems, may extend human capabilities in ways users perceive as superpowers. It focuses on understanding how specific design decisions influence user perceptions and engagement, and how these systems achieve a balance between experiences of empowerment and disruption.

Objective 2: Develop and implement prototype systems that embody superpower experiences. A series of prototypes was designed and deployed to explore augmentation across perception, cognition, and action. These prototypes provide entry points for examining how augmentation can both enhance abilities and generate challenges or unintended outcomes.

Objective 3: Investigate user experiences emerging from superpower interactions. Through empirical user studies, this objective examines how participants experience, interpret, and adapt to superpower experiences. These studies helped identify patterns and insights that can inspire the design of future superpower experiences.

Objective 4: Synthesise findings into a descriptive and prescriptive framework for superpower experience design. Insights from design, implementation, and user studies were integrated into a framework. The framework serves to both describe the trajectories of superpower experiences and to guide designers in creating future superpower experiences that account for both fortunate and unfortunate effects.

1.3 Research Scope

This research is situated within the domain of Human–Computer Interaction, with a focus on human augmentation and its experiential consequences. The scope is defined by three main boundaries to ensure a meaningful contribution.

First, this research focuses on electrical muscle stimulation (EMS) as the primary mode of actuation for the human body. EMS provides a distinctive means of integrating computation and physiology, enabling systems to induce bodily movement directly. Unlike external robotic augmentation, EMS produces actions through the user's own muscles, generating an inherent and intimate sense of capability as though the augmented motion originates from the self. This embodied quality makes EMS a unique medium for exploring the phenomenological boundary between voluntary action and technological control, and thus an ideal lens for examining the emergence of superpower experiences.

Second, the investigation is primarily situated in experimental and speculative design contexts rather than large-scale deployment or commercial applications. By employing three case studies, the research explores augmentation as a form of reflective provocation, enabling the study of both positive and negative experiential outcomes. These studies serve as boundary objects for theorising about agency, awareness, and trust in future augmentation systems.

Third, this research does not aim to optimise technical performance or physiological efficiency. Instead, it prioritises the qualitative understanding of how augmentation is experienced in everyday interaction. The goal is to reveal how users interpret, negotiate, and adapt to augmentation, especially when their expectations are disrupted. The resulting insights are therefore interpretive rather than prescriptive, offering theoretical contributions to HCI discourse on augmentation and experience.

Within these boundaries, the thesis does not claim to represent all possible forms of augmentation but seeks instead to understand the experiential spectrum, from fortunate to unfortunate, which defines how people live with augmentations.

1.4 Case Studies

To answer my research question, I investigate the design of superpower experiences through three case studies, each focusing on different aspects of augmentation experiences: augmented perception, cognition and action.

1.4.1 Case Study 1: Wi-Fi Twinge

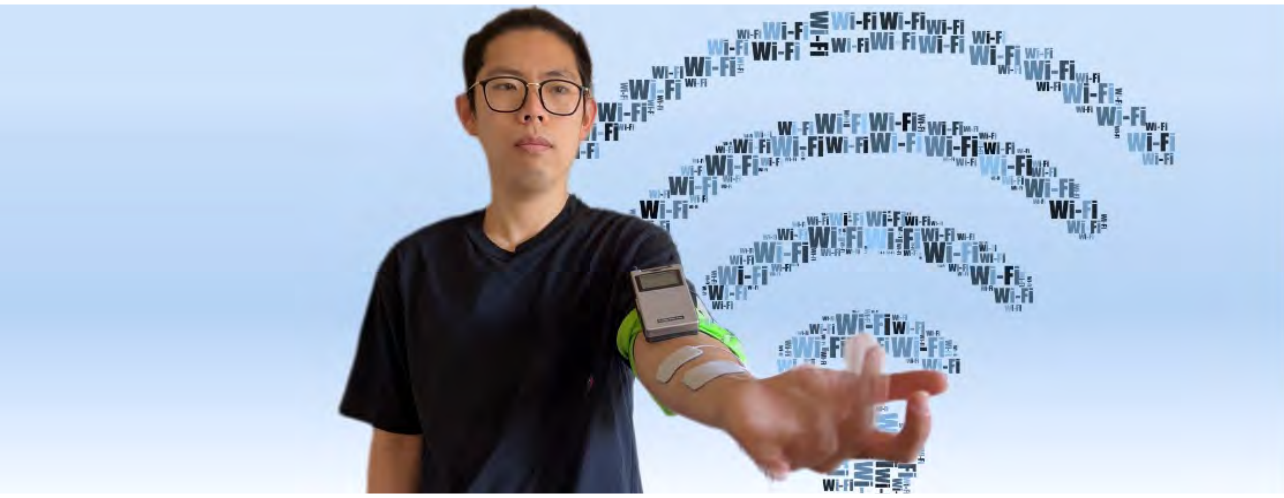


Figure 1.2: Wi-Fi Twinge, a system that aims to help understand superpower design by twinging the user's hand via electrical muscle stimulation in the presence of ambient Wi-Fi.

To explore augmented perception, I designed Wi-Fi Twinge (Figure 1.2), a system that extends human perception to unseen Wi-Fi signals via electrical muscle stimulation (EMS) that makes the user's hand twinge in the presence of a strong Wi-Fi signal. Wi-Fi Twinge allows people to have an embodied sense of Wi-Fi signals by receiving different electrical stimulation wave patterns based on the surrounding Wi-Fi signal. Sensing Wi-Fi expands the human senses and provides a superpower experience of amplifying human perception via the body's inherent embodied sensation, which is the proprioception of flexion in reaction to Wi-Fi. This interaction contrasts with simply observing a reading of an external device, allowing the user to feel the digital phenomena and react to them as if they were tangible elements of their surroundings (Schmidt, 2017). At the same time, the superpower is also unfortunate in that it creates short-term bodily twinge reactions in the form of involuntary hand movements. A 5-day in-the-wild study with 12 participants suggested that Wi-Fi Twinge can elicit negative physical sensations and interfere with activities because of low control of the body but also increases users' awareness of their bodies and the environment, indirectly changing their activities. This study highlights how embodied awareness affects user perception in superpower experiences, which is considered one of the dimensions in the framework.

1.4.2 Case Study 2: EmoPals

Figure 1.3: EmoPals explores how we would design telepathic superpowers: if one user is happy (left), the brain-computer interface senses this and sends electrical muscle stimulation commands to the other user's face to make them smile (right), even over a distance.

To explore augmented cognition, I designed EmoPals (Figure 1.3), a system that extends human emotional communication beyond conventional boundaries through embodied affective interaction in the form of facial expressions.

It amplifies mental processes related to understanding, sharing, and transmitting emotional states. EmoPals establishes an emotional connection between a pair of users that goes beyond spatial limitations, where each participant can sense and experience the other's emotional states from their own body, whether in the same space or not. EmoPals consists of a pair of networked emotional brain-to-muscle interfaces. The emotional state of the wearer is classified (happy, sad, neutral) through electroencephalography (EEG) from a brain-computer interface and replicated on the face of the other user through EMS, which actuates the muscles of the face to elicit a smile, sadness or neutral expression. A 5-day in-the-wild study with 12 participants revealed that while the system can strengthen emotional connection and facilitate empathy, it can also amplify negative emotions and lead to social discomfort, highlighting the importance of considering the sense of agency and the awareness of conflicts between body and cognition. These findings led to articulating a new body relationship diagram and five design recommendations for creating future telepathic superpowers. Overall, this study informs how embodied awareness and control affect superpower experiences.

1.4.3 Case Study 3: Flytrap Hand

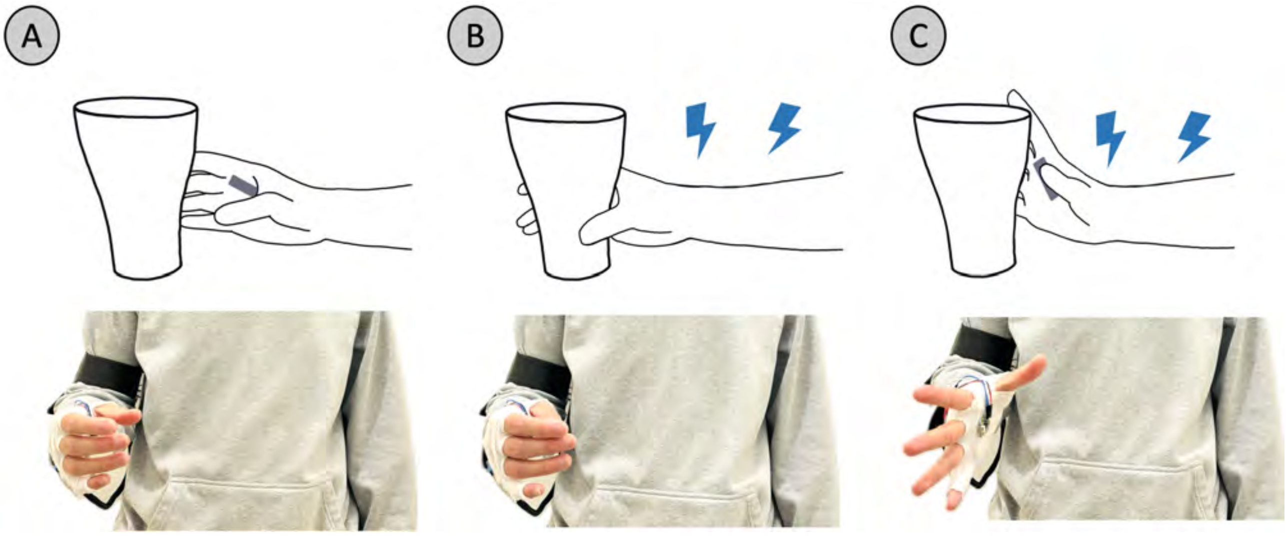


Figure 1.4: Flytrap Hand: when the user's hand approaches an object (a), the system triggers the user's fingers to contract and grasp the object with increased speed (b), the object is released when the user raises their little finger or after a random amount of time has passed (c).

To explore augmented action, I designed Flytrap Hand (Figure 1.4), a system that automates grasping and releasing actions through EMS. While the system enhances grasp speed, it may also lead to negative effects, such as involuntary hand movements, thus impeding hand function and affecting daily activities. To explore how intentional and unintentional negative design affects user experience and the user's perception of agency, two distinct release mechanisms were implemented: one is randomised time control, where the grasp is released randomly after a given duration depending on the task; the other is body control, where the user releases objects intentionally by lifting their little finger. A study with 12 participants showed that Flytrap Hand improved the accuracy of picking up an object and reduced physical exertion, but also increased cognitive load, decreased user trust in one's superpower, and reduced the sense of agency. This study demonstrated how different types of control and temporal stability influence the perceived fortunate or unfortunate experiences.

1.5 Contributions to Knowledge

This thesis makes the following contributions to knowledge:

- This research contributes to design knowledge by documenting the design of three experiential prototypes: Wi-Fi Twinge, EmoPals, and Flytrap Hand. Each system explores a distinct mode of human augmentation: perception, cognition, and action. Through the development and evaluation of these systems, the thesis provides empirical and methodological insights into how augmentation can be designed and experienced as superpowers.

- This research contributes to design theory by introducing and elaborating the concept of the superpower experience as a lens for understanding human augmentation. It extends existing frameworks of human augmentation to encompass experiences that are simultaneously fortunate and unfortunate. This theoretical perspective shifts focus from performance and efficiency toward experiential aspects, enriching the theoretical understanding of how agency, trust, and embodiment evolve in HCI.

- This research presents the Superpower Experiences Framework, the theoretical conceptualisation of how to design and analyse augmentation through the dynamic interaction of agency, awareness, and temporal stability. The framework was derived from the synthesis of findings across the three case studies, each of which surfaced recurring experiential patterns and tensions. These insights revealed how users move between empowering, reflective, background, directive, intrusive, and deceptive superpower states over time. The framework provides a high-level understanding of the design space of human augmentation, offering descriptive value for researchers analysing how users interpret and position their superpower experiences, and prescriptive value for designers by guiding them toward an intended user experience.

1.6 Research Ethics

All data collection in this thesis obtained ethics approval from the Monash University Human Research Ethics Committee (MUHREC). This research includes four studies, which are discussed in more detail in Chapters 4, 5, 6 and 7. All participants volunteered for the study with written informed consent.

1.7 Thesis Structure

This thesis consists of eight chapters as follows:

Chapter 1 provides an overview of the research topic, along with the articulation of the motivation, research scope, contributions, and thesis structure.

Chapter 2 presents a review of related research that has informed, guided, and motivated the present thesis.

Chapter 3 articulates the research methodology, explaining the Research through Design (RtD) process and the mixed-methods approach employed.

Chapters 4, 5, and 6 present three case studies: Wi-Fi Twinge, Emopals, and Flytrap Hand. These chapters detail the development and evaluation of each prototype and the subsequent interpretation of the results they yielded.

Chapter 7 presents a framework derived from the findings from the three case studies, articulating the design space of superpower experiences, and providing design strategies for designers of superpower experiences systems. This chapter also details the study conducted to validate the framework, including the methods and results.

Chapter 8 concludes the thesis with articulations of limitations, future research directions and final remarks.

Chapter 2

Related Work

This chapter reviews what has been learned from existing research in the field of Human Augmentation (HA) that establishes the theoretical foundation for this thesis. It begins with an overview of the state of the art in Human Augmentation within HCI and summarises existing frameworks (Section 2.2). This is followed by a discussion of key concepts central to superpower experiences as a result of HA, including ownership, agency, and the ethical dimensions within HCI (Section 2.3). Finally, it concludes by identifying the gaps and opportunities for advancing design knowledge through the perspective of superpower experiences (Section 2.4).

2.1 Human Augmentation in HCI

Throughout history, humans have sought ways to enhance human abilities. From the use of simple tools in prehistoric societies to complex machinery in industrial eras, the pursuit of augmentation has been a feature of human development (De Boeck & Vaes, 2024). Early examples include prosthetic devices, mechanical levers, or eyeglasses, which aimed to compensate for physical limitations and enable activities that would otherwise have been impossible or at least very hard to do (Clark & Erickson, 2004; Mann, 1997). Advances in electronics, computing, robotics, and biotechnology have expanded the possibilities of augmentation, enabling augmentations that not only restore lost capacities but also provide abilities beyond typical human performance, such as enhanced strength, extended sensory perception, or improved cognitive processing (De Boeck & Vaes, 2024; Raisamo et al., 2019).

Human Augmentation (HA) has been formally defined in multiple ways. Verbeek (2008) frames HA as the extension of human capacities through technological modulations, emphasising the integration of humans and technology as a relational process. Guerrero et al. (2022) define HA as “the systematic use of technological systems to enhance or supplement human performance across physical, sensory, and cognitive domains.” These definitions highlight two core elements of augmentation: functional enhancement, which refers to measurable improvements in task performance or capabilities, and experiential enhancement, which refers to the user’s perceived capabilities during interaction with the augmentation technology.

2.1.1 Classification of Human Augmentation

Human augmentation has been previously classified into three main categories (Figure 2.1) based on the human capacities they target and the mechanisms through which they operate: augmented perception, augmented cognition and augmented action (Pirmagomedov & Koucheryavy, 2021; Raisamo et al., 2019). This classification facilitates both the systematic study of HA and the design of systems.

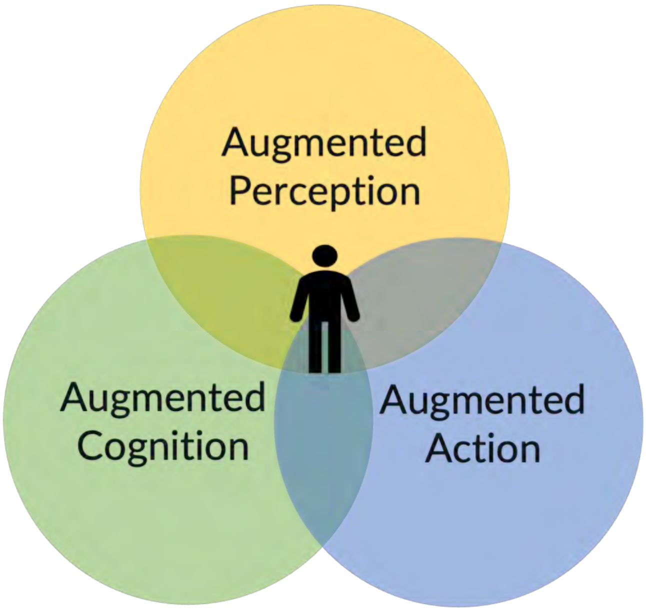


Figure 2.1: Classification of Human Augmentation.

Augmented perception aims to extend, substitute, or enhance perceptual capabilities through which humans perceive their environment, including visual, auditory, olfactory, gustatory, and tactile dimensions. Perception enhancement extends the natural limits of human senses, such as through night vision, thermal imaging, or augmented reality (AR) overlays that provide information beyond the normal visual spectrum (Avveduto et al., 2017; Bertram et al., 2013; Fan et al., 2014). For example, Kenna and Ryan (2016) designed a head-mounted wearable device that enhances the perception of quiet and distant sounds through a set of embedded microphones and speakers, empowering users with a super-hearing superpower, similar to prior work on "augmented hearing" (Mueller & Karau, 2002). Perception substitution reroutes information from one modality into another, allowing humans to access environmental cues through alternative perceptual channels. These technologies are particularly valuable for people with sensory impairments or perceptual deterioration, offering alternative ways to experience the world. For example, haptic actuators describing surroundings to a blind person (Shull & Damian, 2015) or translating auditory information for a hearing-impaired person (Petry et al., 2018). Other research explores the creation of a new sense, in which augmentation introduces perceptual modalities beyond the standard human sensorium, for example, granting humans a novel navigational sense to perceive magnetic north through tactile or auditory feedback (Nagel et al., 2005; Schumann & O'Regan, 2017).

Augmented cognition aims to restore diminished mental functions or improve existing cognitive capabilities, enabling humans to process information, solve problems, and regulate emotions more effectively (Doswell & Skinner, 2014; Semertzidis et al., 2020). Restorative cognitive technologies are designed to compensate for deficits caused by injury, illness, or aging, helping users regain attention, memory, reasoning, and learning capacities. For example, computerised cognitive training environments can guide patients through structured exercises to restore working memory or executive function, providing adaptive feedback that supports incremental recovery (Dingler et al., 2016; Sellen et al., 2007). Improvement-oriented augmentation seeks to enhance cognitive performance, such as intelligent tutoring systems, adaptive learning platforms, and real-time decision-support devices that provide users with enriched information and feedback that accelerate learning, optimise problem-solving, and facilitate complex reasoning tasks (De Greef et al., 2007; Yang et al., 2019). Similarly, brain–computer interfaces (BCIs) enable bidirectional communication between neural activity and external devices, supporting cognitive enhancement by allowing users to interact directly with digital environments, control devices, or receive tailored feedback (Cinel et al., 2019; Matarić, 2017).

Augmented action aims to restore lost functions or improve the ability of humans to perform physical actions (Raisamo et al., 2019; Schmidt, 2017). On the restorative side, systems such as prosthetic limbs and powered exoskeletons have been developed to compensate for motor impairments, enabling users to regain mobility, independence, and participation in daily activities (Chen et al., 2019; Esquenazi et al., 2017). These devices are designed to replicate or substitute natural movement patterns, typically guided by principles of ergonomics and biomechanical alignment to maximise user comfort and safety. For example, exoskeletons support patients in re-learning motor functions by providing repetitive, controlled motion assistance, and advanced prosthetics interpret muscle signals to restore manipulation abilities. Beyond restoration, augmented action technologies also aim to improve, including amplifying strength, endurance, dexterity, and agility, and even enabling capacities that exceed biological limits. For example, wearable devices provide extra limbs for multitasking (De Vries & De Looze, 2019; Prattichizzo et al., 2014) or jet-packs allow a person to fly (Huber et al., 2018). Electrical muscle stimulation (EMS) systems also have been used to enhance physical ability by directly inducing or guiding muscle activity, allowing users to execute movements with enhanced precision, coordination, or speed (Kasahara et al., 2019; Nishida et al., 2017).

2.1.2 Existing Frameworks of Human Augmentation

Although human augmentation has been widely discussed across computer science (Dégallier-Rochat et al., 2022; Kim et al., 2009), engineering (Brown et al., 2017; McFarland & Wolpaw, 2011), and design (De Boeck & Vaes, 2021, 2024), relatively few attempts have been made to establish frameworks that guide its design. One of the most influential contributions in this regard is offered by Raisamo et al. (2019), who propose a framework for HA technologies (Figure 2.2). This framework conceptualises HA systems as comprising three primary functional stages: sensing, information fusion and analysis, and actuation. Each stage represents a functional layer through which augmentation technologies acquire, process, and deliver enhancements to the user.

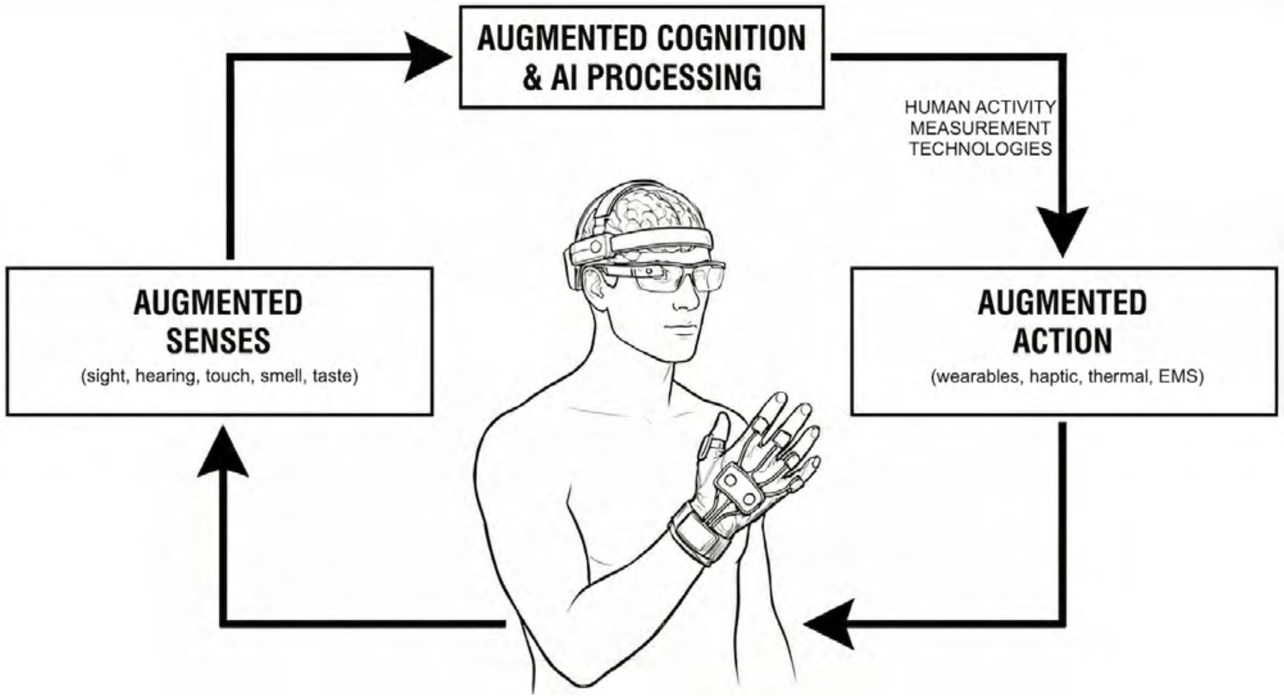


Figure 2.2: Illustration of the framework for human augmentation proposed by Raisamo et al., adapted from Raisamo et al. (2019).

The sensing stage collects data from the user and the environment through various modalities, including wearable sensors, motion trackers, and physiological monitors. This stage establishes the foundation for augmentation by providing accurate, real-time representations of the user's state and context. The information fusion and analysis stage integrates and processes multimodal data streams to extract meaningful patterns, generate predictions or determine suitable augmentations. Finally, the actuation stage delivers augmentation to the user by directly altering the user's capabilities. Raisamo et al. justify this partitioning by emphasising the modularity, which facilitates both a clear conceptual understanding and a systematic study of HA systems. The framework establishes a common language for describing the flow of information between users and technology, enabling researchers and designers to compare systems and optimisation objectively.

The framework proposed by Raisamo et al. primarily addresses functional and technical dimensions, with comparatively limited attention to experiential aspects of augmentation. While the framework explains how augmentation operates and how outputs are delivered to users, it does not account for how users perceive, interpret, or emotionally respond to these augmentations. For example, a study by Jabban et al. (2022) shows that although advanced prosthetic feedback systems improve task performance, many users express discomfort and are concerned about how it affects their body image and identity. This framework, while describing the flow of technical components, does not capture these subjective responses, such as how much feedback feels like part of the body (embodiment), how much control the user feels they have (agency), or whether the user feels empowered or burdened. These subjective dimensions are critical because the same technical function can be experienced very differently depending on factors such as context, familiarity, or expectations.

Furthermore, the framework treats augmentation as a unidirectional process from system to user, and thus does not fully consider interactive or recursive effects, in which users adapt their behaviour based on feedback, creating a dynamic interplay between user and technology. The historical context in which Raisamo et al. developed their framework may partially explain these gaps. Much early HA research focused on assistive or rehabilitative applications, where restoration of lost function was the primary goal. Consequently, enhancement or experimental augmentation beyond normative human capabilities received less attention, and the frameworks did not consider the broader implications of augmenting abilities beyond the user's baseline. As HA research expands into an interdisciplinary field, the experiential effects of augmentation become increasingly salient.

As such, I consider the contribution of Raisamo et al. as an important foundation for understanding the technical and functional dimensions of HA, yet I now seek to extend the research beyond these functional dimensions by introducing the concept of “superpower experience” as a novel experiential lens. This lens focuses on user experience, such as agency and ownership, emphasising how human augmentation technologies are integrated into human experience.

2.2 Superpower Experience: Experiential Dimensions of Human Augmentation

Building on the framework proposed by Raisamo et al., this section shifts the focus to the experiential dimension of augmentation. The notion of superpower experience can be defined as a user experience in which interactions with augmentation technology lead to the perception of extended human capacities, accounting for both positive effects, such as empowerment and skill amplification, and negative effects, such as loss of control or cognitive dissonance. By shifting emphasis from what augmentation does to how augmentation is experienced, the superpower experience offers a novel lens that deepens our understanding of augmentation technologies and informs their design for both functional effectiveness and experiential resonance.

2.2.1 Ownership and Agency

I believe ownership and agency are central constructs in understanding the superpower experience. Ownership refers to the degree to which users perceive augmented capabilities as part of their body and self, integrating both cognitive affective acceptance and bodily experience (Blanke & Metzinger, 2009a; Braun et al., 2018; Grechuta et al., 2019; Tsakiris et al., 2007). Ownership emerges when users integrate the augmented system into their mental representation of the body or cognitive repertoire, resulting in the sensation that the augmentation “belongs” to them. In the context of superpower experiences, ownership is not limited to physical augmentation; it extends to perceptual and cognitive augmentation as well. For example, perceptual augmentation that highlights invisible environmental cues can be experienced as part of the self when users adapt their sense-making to incorporate information as though it were innately available, facilitating the sense of having a superpower (Cinel et al., 2019; Mueller & Karau, 2002). However, sudden system failures, unpredictable behaviours, or mismatches between user intention and system action can disrupt this sense of ownership, reminding users of the artificiality of the augmentation, leading to negative experiences such as frustration, disorientation, or cognitive fatigue.

Sense of agency further mediates superpower experiences. It refers to the “experience of initiating and controlling an action” (Braun et al., 2018).

Agency involves the feeling of voluntary control of bodily movement and the judgment of the cognitive experience of ownership (Synofzik et al., 2008b). It distinguishes self-generated and self-controlled actions from actions generated and controlled by others (Moore, 2016). For example, we have mostly accurate and voluntary control over our body movements, which assures us that it is obedient to our own will rather than being compelled by a machine or someone else. Although most human actions are accompanied by subjective experiences of agency, involuntary movements have no agency due to a lack of subjective control, such as reflex movements (Haggard, 2017b). In HA, agency may be compromised when systems autonomously initiate actions, provide preemptive assistance, or modulate feedback in ways that are not fully predictable, such as through EMS, because users have less control over their bodies (Nishida et al., 2017; Patibanda et al., 2017). Although there are positive effects, such as improved accuracy or performance, people may simultaneously have a negative experience of being forcibly controlled by the system, thereby diminishing their sense of agency.

2.2.2 Unfortunate Superpower Experiences

While prior research often emphasises the benefits of augmentation, such as improved performance, the superpower experience perspective highlights the simultaneous presence of both positive and negative effects. Human augmentation rarely results in a purely positive experience, as the introduction or enhancement of capabilities interacts with users' existing perceptual, cognitive, and physical capabilities, creating uncertainty, unpredictable outcomes, and even misalignment between user intention and system behaviour. Within the field of HA, these tensions have been increasingly recognised (Duin & Pedersen, 2023; Kasahara et al., 2019; Nishida et al., 2017; Patibanda et al., 2017), highlighting the potential benefit of carefully examining what I call "unfortunate superpower experiences".

Building on the definition of superpower experiences, an "unfortunate superpower experience" can be understood as a superpower experience in which the perceived benefits of augmentation are accompanied by non-trivial negative effects. Those negative effects can be particularly salient, disruptive, or ethically consequential. In other words, the same process that grants the user enhanced capability, such as muscle stimulation, sensory amplification, or predictive automation, also introduces unintended experiential consequences. These may include loss of agency, cognitive dissonance, physical or cognitive discomfort and social friction (Duin & Pedersen, 2023; Martin & Whitley, 2013; Pedersen, 2020), which are not merely design flaws but constitutive features of the augmentation process. A main reason is that augmentation needs to operate through bodies with finite sensory, cognitive, and physiological capacity. The human body is not a neutral substrate but a tightly coupled perceptual and motor system in which changes in one dimension often require trade-offs in another. For example, increasing muscular capability through external stimulation may strengthen physical performance while reducing the user's sense of bodily control over movement due to mismatches between expected and actual motor outcomes (Hassan et al., 2017; Kasahara et al., 2019; Nishida et al., 2017). Similarly, perceptual augmentations may extend sensory awareness, but can also overwhelm users with unexpected stimuli, increasing attentional load and fatigue (Bertram et al., 2013; Chernyshov et al., 2018; Kenna & Ryan, 2016).

Moreover, augmentation technologies can also exacerbate ethical issues related to fairness, privacy, autonomy, and professional responsibility (Duin & Pedersen, 2023; Haring et al., 2019; Verbeek, 2008). Prior studies have noted that users may struggle with the dilemma of balancing the benefits of augmentation with responding to broader social or ethical implications (Kak, 2020; Martin & Whitley, 2013; Pedersen, 2020). Framing these challenges through the lens of unfortunate superpower experiences allows researchers to examine how these risks are subjectively experienced and negotiated by users.

I therefore believe that the design of augmentation systems must account for the unfortunate superpowers. Research on "dark patterns" provides an instructive analogy (Di Geronimo et al., 2020; Greenberg et al., 2014). Dark patterns highlight designed scenarios in which users are manipulated or subjected to friction that conflicts with their interests (Greenberg et al., 2014). Within augmentation design, I believe that intentionally incorporating unfortunate superpowers can serve as a method for examining how users confront loss of control, negotiate trust, and adapt to unfamiliar bodily or cognitive conditions (Dickinson et al., 2022; Wang et al., 2024). Such approaches do not aim to harm but expose the thresholds where augmentation shifts from empowerment to intrusion. They can also help designers become aware of common mistakes in advance to help determine what should and should not be designed. In this sense, the concept of unfortunate superpower functions as a critical lens to explore the paradoxes of augmentation, which are not failures to be eliminated, but core elements for understanding what it means to extend, alter, and even destabilise the human condition.

2.3 Research Gaps

In summary, despite the growing amount of research on human augmentation, significant gaps remain in our understanding of how these technologies are experienced by users. Existing frameworks, such as Raisamo et al. (2019), offer valuable functional and structural perspectives on augmentation systems but tend to overlook the experiential dimensions, including how users perceive, embody, and interpret augmented capabilities.

This gap highlights the need for a more experience-centred approach that considers augmentation as a process of psychological and bodily negotiation. In particular, few studies have systematically explored how feelings of agency and ownership evolve when technology interferes with bodily control. Addressing them requires not only technological development but also critical reflection on the unintended negative effects of augmentation. To explore this, the thesis presents three case studies that investigate unfortunate superpower experiences from perception, cognition, and action perspectives.

Collectively, these studies investigate not only functional performance but also user experiences. They inform the development of the Superpower Experiences Framework, which captures how users experience, negotiate, and respond to augmented capabilities, including both positive and negative effects. Thus, the present thesis seeks to answer the research question: ***How do we design superpower experiences while considering their fortunate and unfortunate effects?***

The following chapters present the methodology, case studies, and findings that advance theoretical understandings and provide design guidance for human augmentation systems.

Chapter 3

Methodology

This chapter details the research methodology employed in the exploration of superpower experiences. Situated within the HCI tradition of Research through Design (RtD), the study employs the creation of three novel artefacts as both investigative tools and vehicles for theoretical contribution (Section 3.1). Each artefact was designed with speculative and critical intent, provoking reflection on the interplay between automation, agency, trust, and bodily control. Field studies (Section 3.2) were conducted to capture participants' situated experiences. The chapter then outlines the qualitative and quantitative methods (Sections 3.3) used to analyse these findings and to develop the conceptual framework discussed in later chapters.

3.1 Research through Design

This research adopts Research through Design (RtD) as its central methodological orientation. RtD is an established methodology within HCI that advances knowledge by generating, iterating, and reflecting on the design of artifacts as a means of inquiry (Gaver, 2012; Zimmerman et al., 2007). Building on Schön's concept of the reflective practitioner (1992) and Frayling's taxonomy of design research (1994), RtD emphasises the creation of artifacts not only as outcomes but as vehicles for provoking reflection, and generating situated understanding (Gaver, 2012; Zimmerman et al., 2007). In this approach, the artefact is positioned as a central research instrument, and the process of designing, making, and experiencing it becomes the basis for producing transferable insights.

Within HCI, RtD is often employed to investigate emerging and speculative technologies where established theories offer limited predictive guidance (Gaver, 2012; Koskinen et al., 2013). The superpower experiences examined in this thesis represent “unknown unknowns” that cannot be fully understood through analytical or empirical studies alone. By iteratively designing and evaluating prototypes, the research engages directly with the experiential, contextual, and sociotechnical dimensions of interaction, producing knowledge that is grounded in practice yet extends beyond a single artefact or use case (Bardzell et al., 2015). The prototypes, therefore, function as research instruments (Zimmerman et al., 2007) and critical probes (Bardzell & Bardzell, 2013; Dunne & Raby, 2013; Galloway & Caudwell, 2018; Pierce et al., 2015). They are designed to elicit responses, provoke reflection, and experience potential futures, allowing knowledge to emerge through making and critical engagement (Bardzell et al., 2015). This approach links conceptual exploration with empirical engagement, enabling the investigation of phenomena that exist at the frontier of technological possibility.

RtD in this thesis was realised through a sequence of design cycles. Each cycle contained four interrelated activities: concept development to theoretically frame issues of superpower experiences (Figure 3.1); prototyping and development across augmented perception, action, and cognition; situated deployment in naturalistic settings to capture lived experience; and finally, reflexive interpretation through the quantitative data and rich qualitative transcripts, ensuring that insights were grounded in both technical function and human experience. These activities were documented in design journals and analytic memos to ensure traceability of design decisions and to support reflexive interpretation. Rather than seeking engineering solutions, I aim to create provocative systems that elicit rich, situated responses from participants, thereby generating transferable conceptual insights.

3.2 Field Research

While the design of each prototype formed the generative core of the RtD process, understanding how superpower experiences are enacted in real-

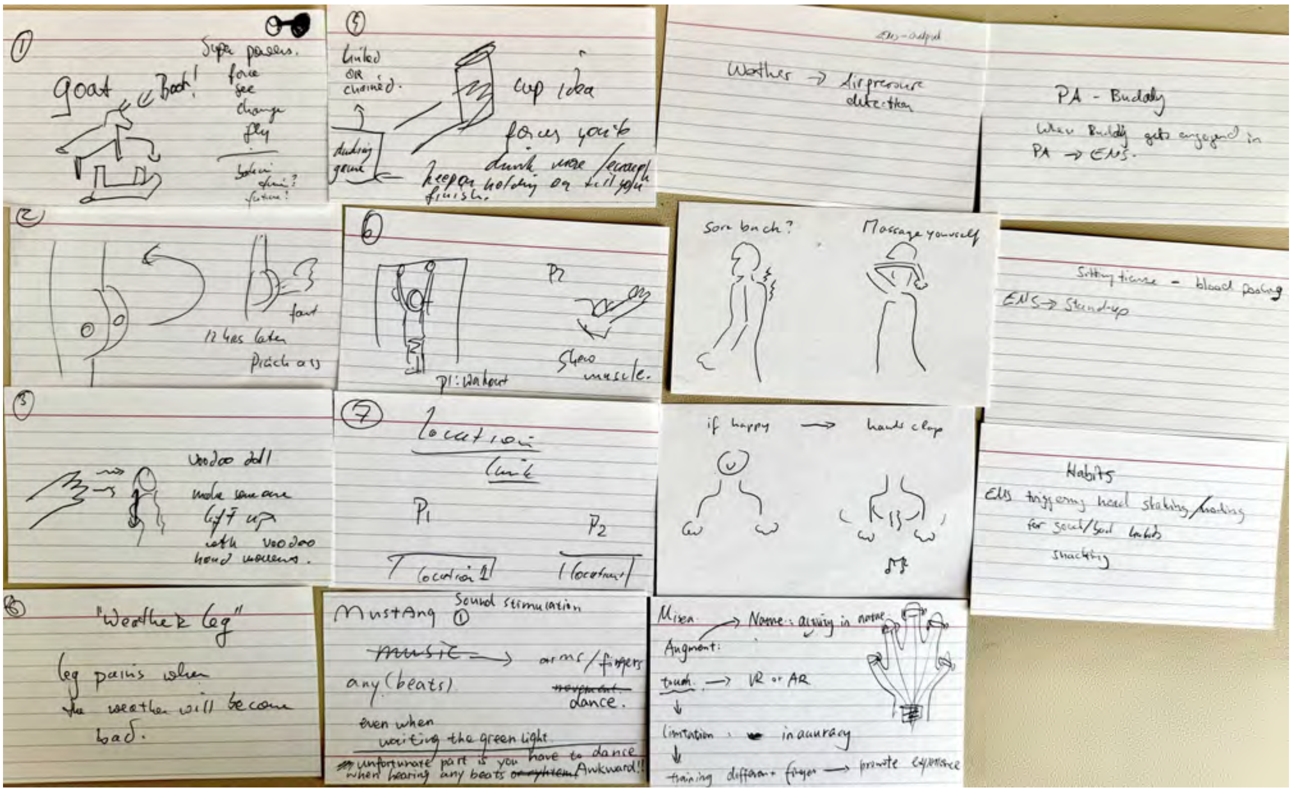


Figure 3.1: Index cards showcasing initial brainstorming and concept development sketches within the RtD process.

world contexts required empirical investigation with participants. Field research was therefore employed as an essential component of the RtD cycles. Field research is an empirical research method conducted in natural settings, where participants interact with systems in their everyday environment (Blomberg et al., 1993; Burgess, 2002, 2003). This approach contrasts with controlled laboratory experiments by offering opportunities to observe how participants engage with, adapt to, and understand the augmentations over time and across contexts.

The strength of such an approach lies in its high ecological validity, which refers to the degree to which the research findings reflect the real-world conditions of participants' everyday lives (Bronfenbrenner, 1979). This is particularly important for augmentation systems, as it ensures that the observed superpower experiences and interaction patterns are not artifacts of the laboratory environment but rather authentic use behaviours (Andrade, 2018). Furthermore, it encourages participant autonomy and natural appropriation, allowing individuals to use the system at their own pace and in their own man-ner (Koskinen et al., 2013). This autonomy often produces unanticipated usage patterns and personal meaning-making, thereby contributing to the generation of theory.

For the first and second case studies, a field research method was employed to capture both immediate reactions and evolving interpretations as participants engaged with each system. Participants were invited to use the systems in naturalistic settings such as their homes, offices, or public spaces over five consecutive days, for approximately thirty minutes per day, at times of their own choosing. This approach allows interactions to integrate naturally into the flow of participants' everyday routines, providing insights into how engagement, reflection, and adaptation developed over time.

The third case study, Flytrap Hand, was first conducted as a within-subjects, counterbalanced mixed-method study to compare two control mechanisms of the system under a set of predefined tasks. This controlled-comparative design enabled a detailed examination of how participants negotiated agency and trust across different modes of bodily automation, while ensuring that individual differences were controlled through counterbalancing. In addition to the task-based comparison, a field research method was also employed following the development of the Superpower Experiences Framework. This subsequent field study aimed to validate the framework by situating the Flytrap Hand system in participants' everyday environments. Through a five-day field study, this research examined how superpower experiences evolve across contexts and over time. The findings from this field research provide an empirical foundation for the theoretical insights proposed in the thesis.

3.3 Qualitative and Quantitative Methods

To investigate how superpower experiences are perceived, embodied, and enacted, this research adopts a mixed-methods approach (McKim, 2017; Tashakkori & Creswell, 2007), employing both qualitative and quantitative methods. The integration of both types of data was essential to capture the richness and complexity of user experiences while also ensuring analytical rigour and comparability across design iterations.

3.3.1 Qualitative Data Collection and Analysis

Qualitative methods were employed to understand participants' lived experiences with the augmentation systems. These approaches have become fundamental to understanding technology as an experience within HCI (Adams et al., 2008; Blandford et al., 2016; Prpa et al., 2020), which aligns with the aim of this thesis.

Data collection comprised semi-structured interviews and reflective diaries. Semi-structured interviews (Blandford, 2013; Longhurst, 2003) were conducted after participants engaged with each system to elicit reflections on their sensory experiences, emotional reactions, and perceptions of agency and control. The flexible conversational structure of these interviews allowed for emergent discussion and unanticipated insights, ensuring that participants' individual interpretations guided the inquiry and enabling them to elaborate on meaningful experiences, thereby generating rich, detailed narratives (Adams, 2015; Knott et al., 2022). Participants also recorded short reflective diaries throughout the field study, documenting evolving perceptions, emotional responses, and patterns of appropriation. This field data enabled the capture of changes in experience over time, reducing the limitations of single-session observation and mitigating retrospective bias (Bentvelzen et al., 2022; Wall et al., 2004).

All qualitative data were transcribed and analysed using reflexive thematic analysis (Braun & Clarke, 2006, 2019a). Reflexive thematic analysis is a method for identifying, interpreting, and reporting patterns of meaning within qualitative data, emphasising researcher reflexivity and the active role of interpretation in theme development (Braun & Clarke, 2019a). Its flexibility and ability to capture both semantic and latent content make it well-suited for exploring complex, context-dependent experiences (Braun & Clarke, 2021; Fereday & Muir-Cochrane, 2006). The analytic process began with open coding to identify meaningful units related to control, agency, adaptation, bodily awareness, trust, and affective response. Codes were iteratively refined and clustered into higher-order themes through selective coding, incorporating comparisons within and across participants (Charmaz, 2014).

3.3.2 Quantitative Data Collection and Analysis

Quantitative methods were employed in this research to provide structured, comparable measures of user experience and behaviour, complementing the rich qualitative data collected across the case studies (Cohen, 2013; Lazar et al., 2017).

For all case studies, participants completed standardised instruments measuring Sense of Agency (Tapal et al., 2017) and Sense of Bodily Ownership (Grechuta et al., 2019) after interacting with each system. These questionnaires employed Likert-type items to quantify participants' perceived control over the systems and the extent to which the systems felt integrated with their bodies. The resulting numerical data were analysed statistically through non-parametric Wilcoxon signed rank tests to identify patterns, differences across conditions, and relationships between agency and ownership. This approach enabled an objective, comparable assessment of the experiential dimensions of superpower interaction, complementing qualitative methods to facilitate a deeper understanding.

In the third case study, Flytrap Hand, quantitative measures also included task performance metrics such as completion time, success rate, and perceived workload, as well as questionnaires capturing user preferences and perceived comfort. These metrics enabled a detailed comparison of two control modes under predefined task conditions in a within-subjects, counterbalanced design. Statistical analyses, including descriptive and inferential methods, were used to evaluate differences between conditions and to examine how system configurations influenced both objective performance and subjective experience (Cairns, 2019; Cairns & Cox, 2008; Robertson & Kaptein, 2016). Descriptive statistics (Kaur et al., 2018; Nick, 2007) such as means, standard deviations, and frequency distributions were first computed to summarise patterns in task performance, workload, and questionnaire responses. Inferential analyses (Amrhein et al., 2019), including paired-sample t-tests and repeated-measures ANOVAs, were applied to identify significant differences between control modes and to assess the impact of system design on measures of agency, bodily ownership, and task efficiency. Effect sizes and confidence intervals were also reported to provide additional information about the magnitude and reliability of observed effects.

Chapter 4

Case Study 1: Wi-Fi Twinge

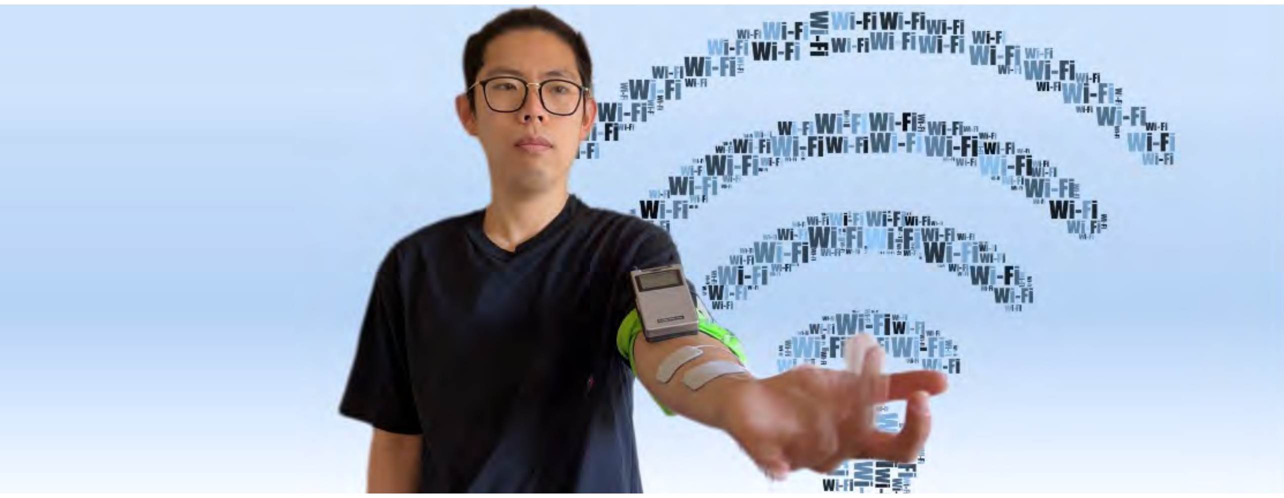


Figure 4.1: Wi-Fi Twinge, a system that aims to help understand superpower design by twinging the user's hand via electrical muscle stimulation in the presence of Wi-Fi.

This chapter details the first case study, which investigates superpower experiences aimed at exploring augmented perception through the design and deployment of "Wi-Fi Twinge" (Figure 4.1). This system uses electrical muscle stimulation (EMS) to extend human senses, enabling users to "sense" invisible Wi-Fi signals as an allergy-like twinge reaction to Wi-Fi signals.

4.1 Associated Publication

This chapter builds upon the following publication, which is a full paper resulting from this case study:

- Siyi Liu, Nathan Semertzidis, Gun A. Lee, Florian Mueller, and Barrett Ens. 2024. Exploring Superpower Design Through Wi-Fi Twinge. In Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24). Association for Computing Machinery, New York, NY, USA, Article 4, 1–16. https://doi.org/10.1145/3623509.3633352. Video

4.2 System Design

Wi-Fi Twinge is a prototype system that allows users to sense imperceptible Wi-Fi signals through the use of EMS by inducing involuntary flexion of the hand, in particular, the fingers and wrist. Despite providing people with the potentially "fantastic" ability to sense the strength of Wi-Fi signals, I anticipate that the low sense of agency people experience over their fingers and wrists when actuated could result in an unfortunate superpower experience.

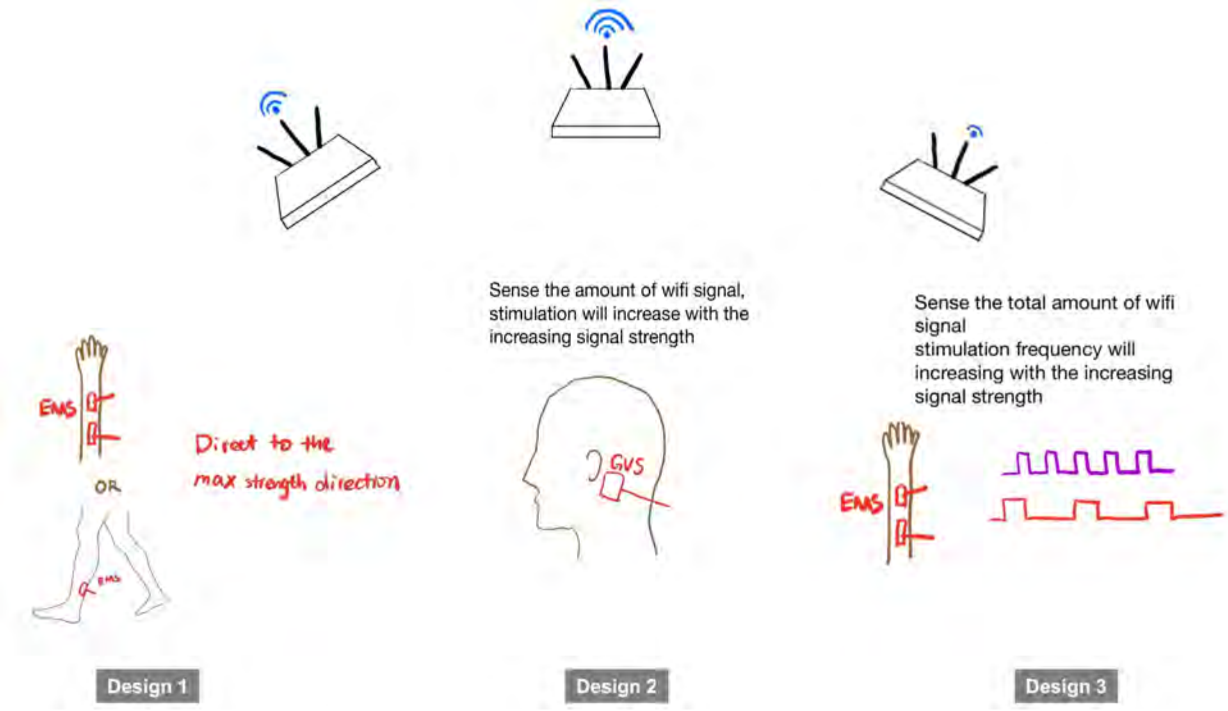


Figure 4.2: The design iteration of Wi-Fi Twinge.

Wi-Fi Twinge comprises two main components: a "Raspberry Pi" and an EMS device ("Comfy EMS") with 2 self-adhesive electrode pads (Figure 4.3). The Raspberry Pi is a small microcomputer ($88 \times 58 \times 19.5$mm) that continuously monitors the surrounding Wi-Fi signals' strength. It controls the circuit via a

$5\,$V relay connected to the EMS device. The battery-powered EMS device then stimulates the participant's forearm with two electrode pads (4×4cm) based on the current Wi-Fi signal strength.

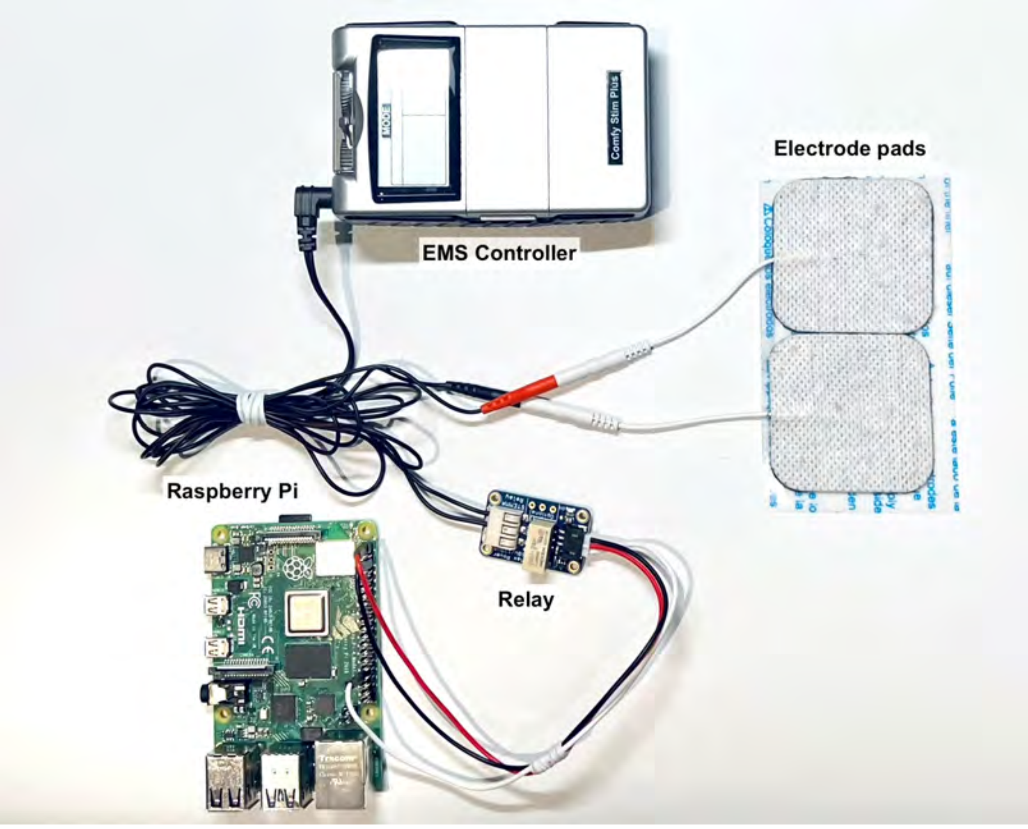


Figure 4.3: Wi-Fi Twinge's components.

4.2.1 Wi-Fi sensing

I chose to sense Wi-Fi signals because Wi-Fi is easily sensed with mobile devices and does not need much power, allowing this device to feature a small form factor that enables participants to wear the device for long periods. There was no need to recharge the device throughout the day. In addition, Wi-Fi is almost ubiquitous and has become a common part of people's daily lives, used both during work and leisure time. As I anticipated that participants might want to engage with this device at any time, using Wi-Fi would ensure that they could do so, whether it was work or leisure time. Furthermore, Wi-Fi has been considered within the larger discussion around electromagnetic pollution that highlights the negative consequences of too many wireless signals (Jaffar et al., 2019; Markov & Grigoriev, 2013; Wongkasem, 2021), hence speaking nicely to the unfortunate effects of superpowers. Therefore, I believed that focusing on Wi-Fi could be a worthwhile topic to investigate as part of an unfortunate superpower. I also considered other technologies, such as Bluetooth; however, I selected Wi-Fi as it seems to be more prevalent (at least for now) and also has a further reach in terms of physical distance and hence would allow me to collect more data. However, I encourage future work to investigate other phenomena that can be sensed but are usually invisible to users, to further enhance my understanding of designing superpowers.

Wi-Fi Twinge system detects both 2.4 GHz and 5 GHz signals and takes the average value of signals' strengths in a 2-second time window to smooth noisy data and then passes the value in 5-second epochs to the classification system. Since Wi-Fi technology has become ubiquitous, people are usually exposed to multiple Wi-Fi signals, especially in the workplace and on campus. Therefore, I measured the total decibels relative to a milliwatt (dBm) of received signal strength and then applied a logarithmic scale to cap out the maximum value. The system classifies five levels of signal strength based on the total sum of strengths, from none, weak, normal, medium, to strong, and then triggers the corresponding stimuli.

4.2.2 Mapping Wi-Fi signals to hand movements

To offer people the superpower of "feeling" Wi-Fi signals, I decided to consider sensory information in the form of muscle actuation that I hoped would facilitate an embodied experience (in contrast to, for example, reading a signal strength number on a screen), potentially resulting in the user believing that sensing Wi-Fi signals have become part of their own abilities (i.e., a superpower). By mapping Wi-Fi signals to EMS-triggered hand movements, I also support the experience of perceiving Wi-Fi signals while the user might be busy otherwise, all while supporting ambient awareness (Leonardi, 2015). For example, users do not explicitly need to click on a Wi-Fi signal strength button during conversations to achieve this function. Furthermore, I believe that this embodiment approach suits a wider range of users, as participants did not need to know how to reveal Wi-Fi strength on their laptop or mobile phone, they did not need to know what a "high" or "low" dB value is, nor were they required to know that Wi-Fi signal strength is measured in dB. As such, the embodiment approach could be seen as more culture and expertiseagnostic than the common screen-based apps for Wi-Fi strength.

I chose EMS-triggered hand movements rather than other parts of the body because the hand is profoundly important to most humans, serving a variety of basic functions such as interacting with objects, making gestures, and communicating (Jones & Lederman, 2006). Therefore, I believe that involuntary hand movements caused by muscle actuation, as a result of an unfortunate superpower, might lead to various negative effects impacting daily life. However, at the same time, I believe that they might be seen as reasonable in terms of the scope and degree of influence on the user, as they do not lead to serious loss of control compared to other parts of the body (such as the legs that might cause a user to fall, risking serious permanent injury).

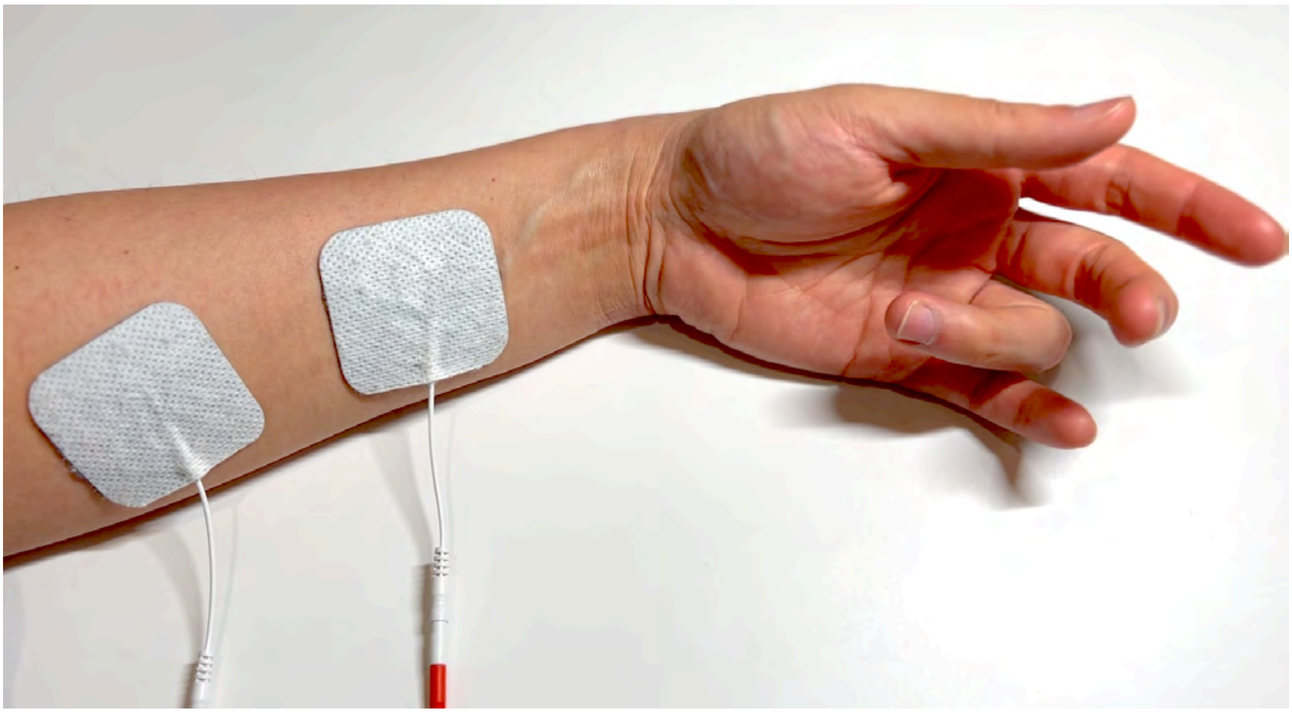


Figure 4.4: EMS's electrode placement and finger flexion.

To induce hand movements, I employed EMS as its use has been described previously in the literature as a successful way to promote body movement (Faltaous et al., 2022; Lopes et al., 2016; Patibanda et al., 2023b). In addition, I was inspired by prior work that found that EMS use can facilitate novel bodily experiences, providing both positive and negative sensations (Knibbe et al., 2018a; Patibanda et al., 2023a). This aligned well with my intention to investigate superpower design, including its positive and negative effects. The EMS device contains two electrodes (Figure 4.4). The negative electrode is placed between the finger flexors and the wrist flexors. The positive electrode is placed over the tendinous portion of the forearm. Stimulation results in finger flexion with some wrist flexion and even some thumb adduction.

4.2.3 Wave patterns for muscle stimulation

The EMS device I used delivers an electrical signal at a fixed pulse width and pulse rate, where the intensity can be adjusted only manually (through a dial on the device). I could have designed my own EMS device to have more control; however, prior HCI research has suggested using commercial EMS devices for actual and perceived safety reasons (Knibbe et al., 2018a; Lopes et al., 2015). Therefore, I chose other attributes of EMS as variables: duty cycle and frequency to form 4 different monophonic wave patterns for muscle stimulation (Figure 4.5). Duty cycle is the ratio between the duration of the active signal and the total work cycle, describing the on/off phase of the electrical pulses. A higher duty cycle indicates a higher percentage of ON time. In descending order of signal strength, I set the duty cycle to 0.8, 0.5, 0.29, 0.13 and 0 to reduce actuation time by 0.2s in turns. Frequency is the count of the total work cycles (on and off phase in total) per second. Higher frequency means I turn the EMS on and off more frequently. I set the frequency to 1 Hz, 0.83 Hz, 0.71 Hz, 0.63 Hz and 0 Hz so that the total work cycle increases sequentially by 0.2s to match Wi-Fi signal strength levels.

I chose to adjust the duty cycle and frequency because I believed that the chance of muscle fatigue could be reduced by providing different lengths of breaks between each actuation, as prior work highlighted that EMS designers need to consider muscle fatigue (Faltaous et al., 2022). Furthermore, I believed that this approach might enable participants to easily discern distinct stimulus wave patterns by both extending the resting time and reducing the actuating time concurrently. I also considered other wave patterns, such as polyphonic waves, which might be associated with less intense EMS sensations on the skin; however, monophonic waves are believed to be able to generate a larger contraction torque and less fatigue than polyphonic waves (Kono & Rekimoto, 2019; Laufer et al., 2001).

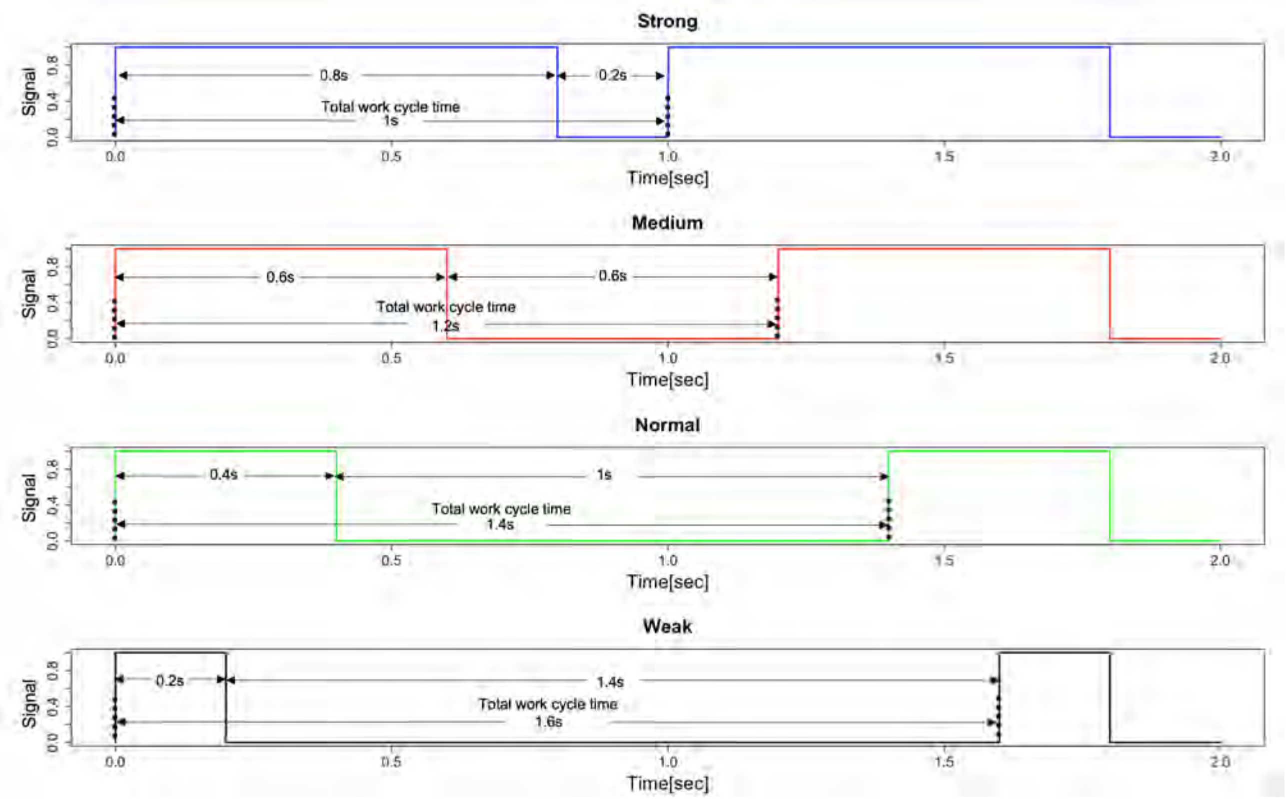


Figure 4.5: The EMS's signal for four levels of Wi-Fi strength from "strong" to "weak". Note that when the Wi-Fi strength is below "weak", no EMS simulation is presented (i.e., 0Hz). In the diagram, 0 and 1 represent the ON and OFF states; frequency is the count of total work cycles per second, i.e., frequency equals the inverse of the total work cycle time.

4.3 Study

The following section discusses the methods employed to conduct the field study with Wi-Fi Twinge.

4.3.1 Participants

I recruited 12 participants (6 men, 6 women, none non-binary and none self-described), aged between 27 and 33 years (M = 29.08, SD = 2.02). Participants were recruited through advertisements using my lab's mailing list and social media accounts. Eleven participants reported being right-handed and one left-handed. Two participants had prior experience with EMS.

4.3.2 Study procedure

Before starting the study, participants received an introduction to the system and study procedure. After informed consent was obtained, participants were given the system and instructions on how to use it, including how to power it on and how to operate it, how to place the two electrodes on their non-dominant forearm and when the system needed to be removed, for example, when showering, bathing or swimming. I also provided them with a video containing these instructions for reference at home.

To calibrate the system, the participant was asked to stretch and flex their wrists and fingers on their non-dominant forearms to identify the best location for the electrodes. The electrodes were attached either by the participants themselves or by me. Next, I checked the placement and calibrated the amplitude of the EMS current. Based on repeated tests, I applied a constant EMS pulse-width of 200 µs and a pulse-rate of 100 Hz. Starting from 0 mA, the participant was guided to slowly increase the intensity by turning a dial on the EMS device until the desired intensity of movement was reached, where the participant's fingers and wrists flexed. The participant was given approximately one minute to familiarise themselves with the stimulation. The intensity setting, as shown on the EMS device's dial, and the placement of electrodes were photographed; the photo was given to the participant for later reference. During the study, I informed the participant that they could readjust the intensity level to achieve a comfortable actuation, as long as they could ensure that their fingers and wrists were engaging in flexion movements.

After the calibration, the study began. Each participant was asked to wear the system for 30-40 minutes daily over 5 continuous days. To ensure that the participant had enough wear time and protect them from muscle fatigue, the system was set to turn off automatically after 40 minutes. There were no prescribed tasks, as I aimed to understand the user experience in real-life situations. The participant was instructed that they could use the Wi-Fi Twinge system at any time of the day and anywhere, whether working, studying, entertaining, etc. I also instructed the participant to "simply go about their daily activities as usual" (Figure 4.6).

After each use, the participant was asked to complete a digital diary to record the activities they did, the time at which they wore the system, and how they

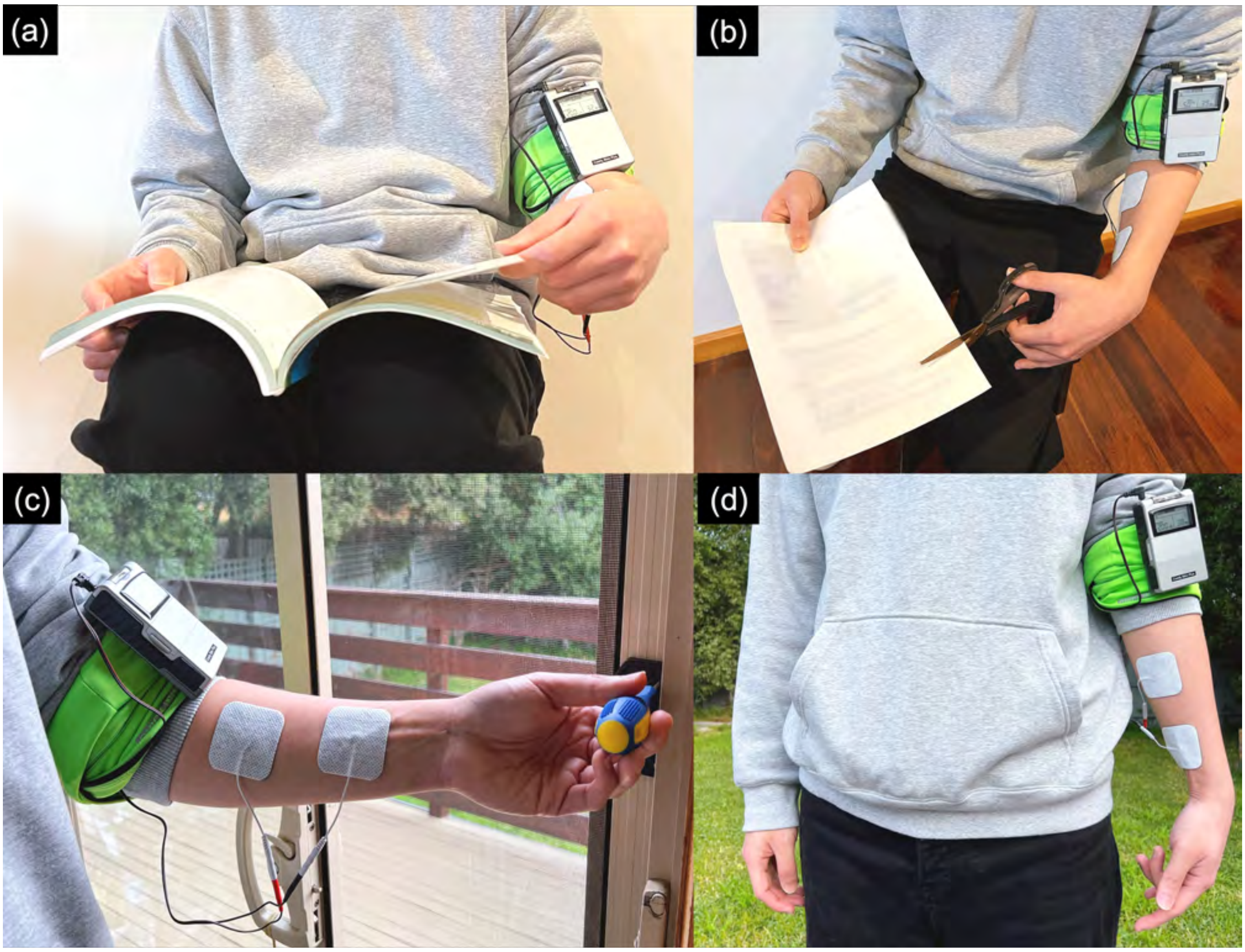


Figure 4.6: Some of the daily activities of the participants wearing the Wi-Fi Twinge system. (A) Turning the pages of a book. (B) Using a pair of scissors. (C) Using a screwdriver. (D) Walking in the park.

felt while wearing the system. At the end of the 5 days, the participant was asked to complete the Sense of Agency Scale (SoAS) (Tapal et al., 2017). I chose to ask participants to fill out the SoAS survey because I wanted to investigate how the experience of initiating and controlling actions of participants was affected by involuntary hand movements to understand the design of superpowers that can control the human body. I used this scale because it has been validated with good psychometric properties (Hurault et al., 2020). Of course, other surveys would have also been possible, such as surveys around the cognitive and physical load to understand the mental and physical effort required by participants in the study (Hoogendoorn et al., 1999; Sweller, 2011). However, I did not investigate any specific tasks and participants engaged in different activities during the study. Therefore, I believed that it would be difficult to gain meaningful insights from this data. Taken together, I believe that the use of the survey represents a valid and practical approach to answering my research question. However, I acknowledge that other surveys, including yet-to-be-developed ones around superpowers, used in future studies might complement this work.

Along with completing the SoAS, the participant was required to take part in a semi-structured interview that lasted approximately 30 minutes. The interviews included 16 questions about the participant's interactions with the system and any potential physical and emotional effects. Questions that I asked were, for example: "How did you use the system? How did it feel on your arm? Did the system affect your daily life? Did it affect your emotions? When using the system in your daily life, who do you think is in control, you or the system?" In addition, to minimise the impact of calibration differences, I considered calibration differences in the interviews by always asking what the EMS experience was like, including how it felt and how the resulting movements looked. Furthermore, I asked the participant to demonstrate how they used the system, including what intensity setting they used.

4.3.3 Data analysis

As the Sense of Agency Scale is ordinal in a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree), I performed a non-parametric one-sample Wilcoxon signed rank test for each factor to compare with the baseline, including Sense of Positive Agency (SoPA), Sense of Negative Agency (SoNA) and total Sense of Agency (SoA) score. I asked the participant to complete the same survey again after 6 months as the baseline, in which participants directly responded to their sense of agency in daily lives without any experimental conditions. I initially used the results of the study by Hurault et al. (2020) as a baseline. However, in considering feedback from colleagues, I acknowledged that employing two samples (i.e., using a sample from another study as a baseline) may introduce a confounding effect to the comparison due to uncontrollable contextual differences inherent in the sample and design. As the SOAS is a subjective survey, the unique context of each sample may lead to differences in the interpretation of the questions, which may lead to response bias. Therefore, I decided to conduct a second round as a new baseline to allow for a multiple comparisons analysis, which

I could use to understand participants' sense of agency without the use of the system. However, this was a retrospective decision made six months after the completion of the study, hence the time distance. Nevertheless, this came with the serendipitous advantage that the decay of the participant's memory using the system may have reduced their ability to compare their normal sense of agency with the sense of agency they felt while using the system, thus giving a purer report of their everyday sense of agency, leaving comparison purely to statistical analysis. I acknowledge that the 6-month follow-up survey might have included other unknown confounding effects.

To analyse the interview data, I employed a reflexive thematic analysis to identify themes by distilling and articulating meaning from the data(Braun & Clarke, 2006, 2019b). Interviews were audio-recorded and transcribed for qualitative analysis in NVivo. In total, the analysis identified three high-level themes.

4.4 Results

In this section, I detail the results yielded from the analysis of participants' responses to the Sense of Agency Scale and describe three high-level themes that I derived from the analysis of the interview data.

4.4.1 Quantitative analysis of sense of agency

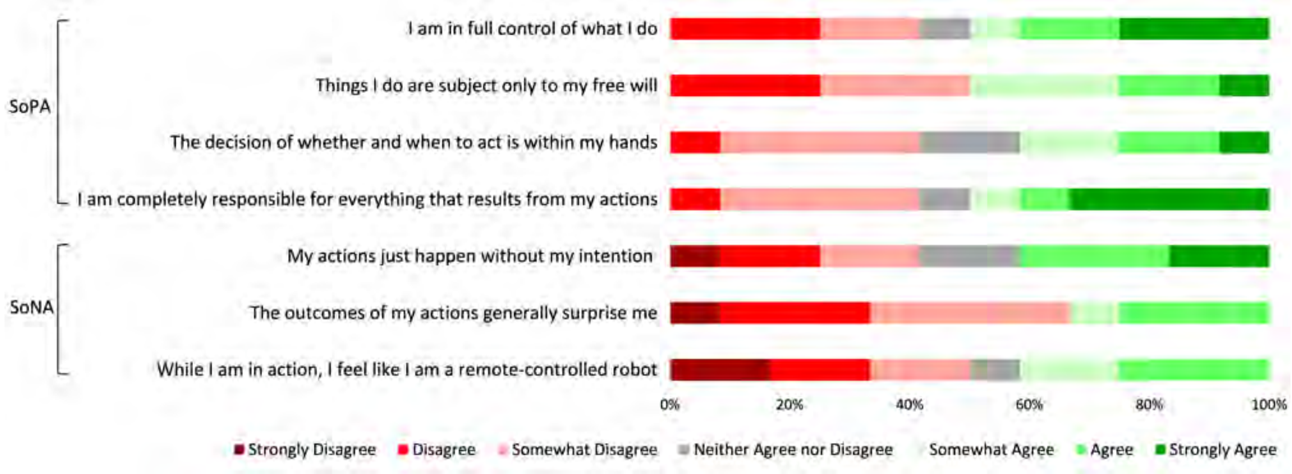


Figure 4.7: Participant responses to the Sense of Agency Scale.

Figure 4.7 shows the participants' responses to the Sense of Agency Scale. I found a significant difference in the SoNA score, in which the SoNA of Wi-Fi Twinge (M = 11.25, SD = 4.90) was higher than the baseline (M = 7.25, SD = 3.65), V = 66, p = 0.037 (Figure 4.8). The comparison of SoPA (M = 17.58, SD = 6.57) and SoA (M = 30.33, SD = 10.09) with the baseline (SoPA: M = 20.25, SD = 4.41; SoA: M = 37, SD = 6.98) revealed no statistically significant difference (SoPA: p = 0.146; SoA: p = 0.064). This means participants reported higher levels of negative agency in this study compared to the baseline.

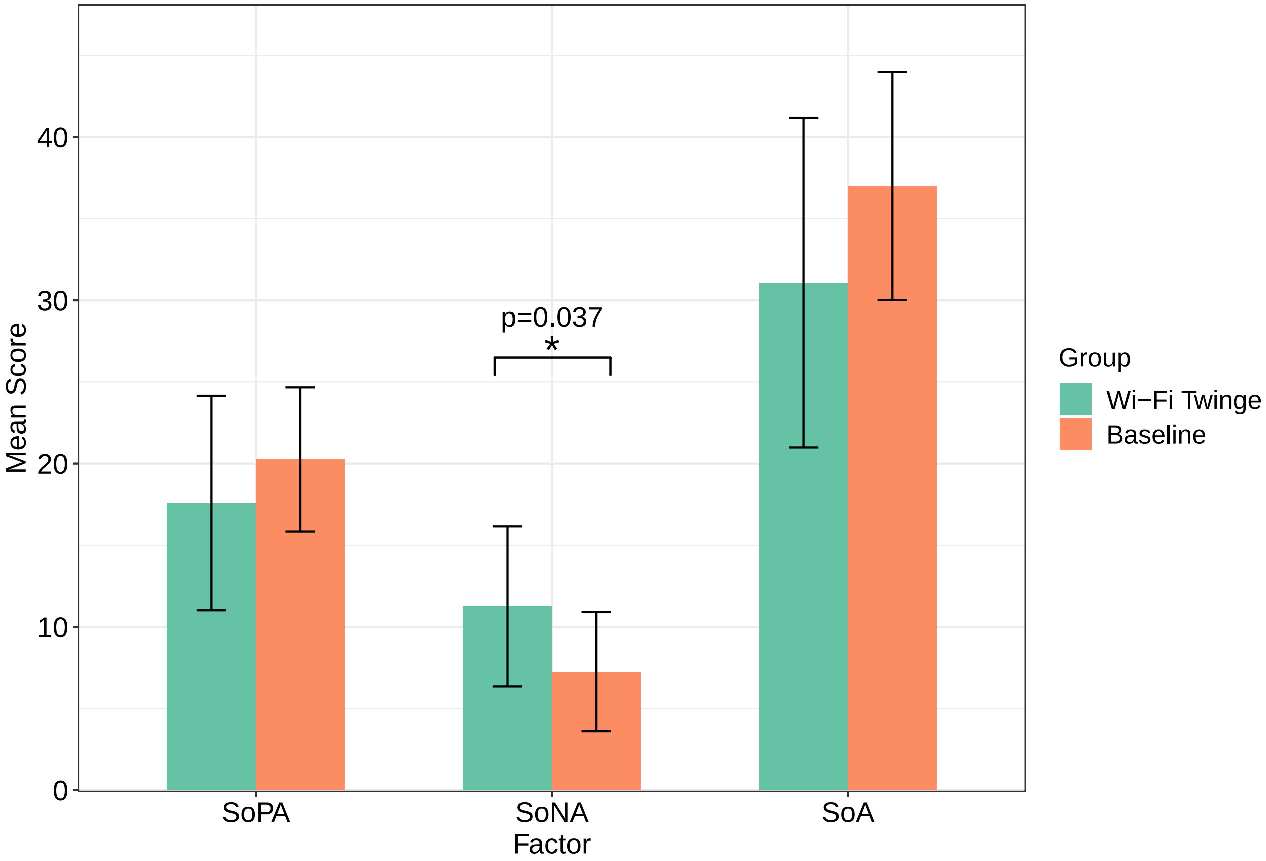


Figure 4.8: The average score of the Sense of Agency Scale (SOA) and its subscales (SoPA and SoNA) compared with the baseline. Error bars represent one standard error of the mean.

4.4.2 Qualitative analysis

Overall, participants reported that the concept and experience of Wi-Fi Twinge were "*fascinating*" (P1), "*surprising*" (P9) and "*interesting*" (P11). Participants said they became more aware of their bodies and the surrounding environment by sharing the world with the Wi-Fi signals around them.

The following sections investigate these results further by articulating three themes: Wi-Fi Twinge creates fortunate outcomes out of unfortunate effects; Wi-Fi Twinge facilitates a variety of emotions and sensations over time; and Wi-Fi Twinge facilitates varying degrees of sense of agency.

4.4.2.1 Theme 1: Wi-Fi Twinge creates fortunate out of unfortunate effects

This theme describes how participants interacted with and how they felt unfortunate and fortunate as a result of wearing Wi-Fi Twinge. I first describe sub-themes that indicate that this system was indeed an unfortunate superpower. Then I explain how it was unfortunate, but also how it sometimes could be fortunate.

Physically hindering daily activities: Participants experimented with different day-to-day life activities while using Wi-Fi Twinge, such as cooking (P1, P5, P8), commuting (P4, P6, P10, P12), working with a computer (P2, P9, P11) and watching movies at home (P3, P7, P8), to investigate how different contexts influenced their experience of the system. Participants reported that many of their daily activities were affected by the superpower. For example, P10 said: "*I used it today during commute. I became very slow, and I found it hard to do what I had to do, [so] I couldn't catch the train*". Participants spoke about how their hands, and hence, hand-focused activities were affected by the system. For example, P11 said: "*When I was working on my computer, I couldn't spread my fingers and type certain keys because of [the] finger twitching. And I had the same problem with my phone*". As a result of the influence the system had over the participants' bodies in different contexts, participants modified their behaviour to adapt to the stimulation. Three participants reported that they tried to avoid using the stimulated hand by instead using their other hand. P5 explained: "*I didn't use my left hand a lot and used my right hand more because I couldn't control my fingers*". In addition, three participants indicated that they did not like the superpower, and P5 explained why they would not use the system again: "*I didn't like to lose control. It affects what you do every day, you cannot work, you cannot do your daily stuff*".

Interfering with tasks that require concentration: Two participants reported that the EMS stimulation "*interfered with their concentration to do other tasks*" (P7). In particular, they "*felt distracted because of the stimulation feelings*" (P11). So, unlike the result above about how the EMS stimulation hindered their physical hand actions, these comments articulate how the feeling from a computer-controlled hand can interfere with other tasks cognitively. This highlights that with superpowers can come limitations in another (bodily) area, here, concentration.

Embarrassing in social interactions: One participant reported that they "*wanted to use the system on public transport but felt embarrassed to have weird finger twitches in public*". However, other participants did not receive any comments about the system from bystanders, or mentioned feeling embarrassed wearing it in public. This could be due to minor twitching that is not very visible from afar.

Changing the way people think of Wi-Fi: Two participants mentioned that they started to realise "*how densely our world is now surrounded by Wi-Fi signals, it's almost everywhere*" (P12). This suggests that the system helped participants to get a better understanding of their surrounding environment. Furthermore, the word "*dense*" suggests that the system made them more aware of how Wi-Fi signals can affect their lives within it, as they now have to live in a world shared between them and the wireless signal. P10 was not only more aware of the Wi-Fi signals but also deduced that they can be a threat to their wellbeing: "*[…] the fact that my house is full of signals, which is not good*". This led P10 to express concerns about their children's safety in their home: "*I feel so worried about those signals around me, too many signals. I have kids, and I feel so worried about them because some people are talking about the impact of this signal on the body and brain. And there is no scientific study on that. I feel not okay with all these signals around me*". In this instance, I interpreted P10's concerns to be referring to the belief that too much Wi-Fi exposure (both over time and intensity) can be detrimental to one's health, even though current scientific evidence does not support this concern [15]. This quote suggests that this system made P10 more worried about how safe their children are in their homes as they became more aware of the ubiquity of the signals in their homes. I postulate that the bodily nature of this system could have fuelled that physiological reaction, i.e., fear, especially if I compare it to checking the signal strength with an app on a mobile phone, for example.

Rekindling an appreciation of the hands: Three participants reported that losing some control of their hands made them "*realise the importance of their hands*" (P11). This realisation was the result of becoming aware, thanks to the system, "*how difficult it is to not be able to control your hand*" (P5). P11 explained that the system made them think of Parkinson's disease and empathise with the "*difficulties and hardships of Parkinson's patients*".

Encouraging people to escape Wi-Fi: Wi-Fi Twinge not only made people more aware of the ubiquity of Wi-Fi signals but also implicitly encouraged people to take action. Participants reported that they were sometimes distracted by hand movements and tingling in their arms, which interfered with their work, making them move to another location with fewer Wi-Fi signals. For example, P11 said: "*Sometimes the stimulation was too strong, I felt so annoyed and couldn't work. So, I decided to stop work and went to the park to escape it*".

4.4.2.2 Theme 2: Wi-Fi Twinge facilitates a variety of emotions and sensations over time

This theme describes participants' various emotions and sensations over time as a result of interacting with Wi-Fi Twinge.

Negative physical sensations and emotions fuel each other: All participants felt numbness as a result of involuntary muscle contractions. P7 also reported a feeling of weakness: "*In addition to numbness, there is also a sudden feeling of weakness in the arm, as if the arm suddenly lost strength*". Four participants mentioned that they felt slight muscle soreness and fatigue sometimes after the stimulation if they used a high-intensity stimulation. For example, P11 said: "*My fingers were so stiff and needed to relax for a while after the experiment in the last two days*". It seems that continuous EMS use affects bodily composition. P8 tried to explain the reason for their fatigue: "*30 minutes [of] stimulation is a lot, and after that, I feel a little bit of fatigue in the fore-*

arms, but it was not annoying". It appears that electrical muscle stimulation may lead to some degree of muscle overuse, but there are no other serious symptoms, and arm fatigue resolves with rest. Five participants reported that their uncomfortable physical sensations led to negative emotions and vice versa. Three of them stated that they felt distracted and angry during the use of the system, for example, P1 mentioned that the system "*sometimes made me annoyed because of the continuous stimulation*". Similarly, P11 said: "*At first, I was surprised, but as time went on, my arms started to hurt, I started to feel very upset, and I was not in the mood to do anything else. Sometimes, when I was in a bad mood, I also got a feeling of more pain, I don't know if it's an illusion or not*".

Changing attitudes towards Wi-Fi Twinge over time: Five participants were surprised by the superpower at first. For example, P9 said: "*It was more of a surprise on the first day*". Another five participants felt "*weird at the beginning*". For example, P5 said: "*The first day, of course, it was weirder, not having control, because I used my left hand and saw my fingers move. I was a bit scared*". In addition, two participants reported that they were "*slightly worried at the beginning that the EMS may cause injury*" (P4) and "*when it comes to the body, I'm a little bit cautious about the electric signals*" (P1). Although these participants had different experiences, their attitudes towards the system changed throughout the study. Six participants discussed how this journey changed them. They spoke about their journey from having initially felt "*weird*" to, over time, getting used to their superpower. For example, P6 said: "*In the first time I tried, the first two minutes, it was uncomfortable and weird. But then I got used to the whole thing. So, I think the more [I] used it, the more I was [getting] used to it, so I could wear it and keep doing other things. And I have forgotten that it was attached to my body*". Two participants also said that after having experienced the system, their concerns were alleviated, and they felt relieved. This highlights that any negative emotions associated with EMS can also go through a trajectory, as previously suggested by Benford et al. (2009). Taken together, it seems that an initially unusual experience quickly turned (usually within three days) into an experience where participants became used to it, even to the point of forgetting that the stimuli were induced by the system and therefore participants have even begun to believe that the superpower is their natural ability.

Changing the way people see the world: As participants began experiencing the stimulation, such as when moving from one room to another with different levels of Wi-Fi signals, they became more aware of their environment through bodily sensations. For example, P12 said: "*I know I am surrounded by Wi-Fi signals but didn't feel it in such a solid way before*". This use of the word "*solid*" is interesting, as it suggests that the system made an abstract concept of wireless signals more tangible, even bodily. This allowed participants to "*feel*" the signal rather than just cognitively comprehend it. The system also changed how participants perceived their environment. Interestingly, P12 said: "*It changes a way of sensing the surrounding environment, from vision to feeling*", which suggests that participants seeing their environment now moved to "*feeling*" the environment. Furthermore, it made participants think about what they usually do not think about. For example, P4 said: "*It does raise my awareness to pay attention to the Wi-Fi strength in my surroundings, which is something I rarely think about*". P5 explained: "*When I was walking in the street, I never paid attention to the structure of the buildings. But when I was wearing the system and passing the buildings, I felt their Wi-Fi signals and started guessing if there was Wi-Fi inside*". It appears that the system helped participants not only gain a greater awareness of their surrounding environment but also changed the ways they see the world.

Heightening awareness of the self: Three participants commented that the system helped them heighten their awareness of their bodies. For example, P6 said: "*I think [I am] more aware of my body because I was concentrating on that [reaction]. So, it was like feeling my spirit, cleaning my body*". This suggests that the system made them more aware of their body more generally. Meanwhile, the use of the word "*spirit*" suggests that the system might have helped participants develop a stronger understanding of their body and mind as well. This speaks to the prior theory that highlights that bodily technology can facilitate self-awareness (Benford et al., 2021). Furthermore, one participant reported that the system made them reflect on their free will, that is, how much in control of their lives they are in general. For example, P1 said: "*[I became] more conscious about how in control I am*".

4.4.2.3 Theme 3: Wi-Fi Twinge facilitates varying degrees of sense of agency

This theme describes how participants perceived who is in charge of their behaviour in terms of both initiating the action and controlling it.

The system initiates actions: All participants reported that they felt that the system initiated muscle movement rather than themselves. Specifically, P9 spoke about consciousness: "*I can tell whether it is my own consciousness or the effect of the device. These two are completely different*". This suggests that Wi-Fi sensing was not considered as their own ability, but something owned by the system. In addition, participants mentioned that their sense of initiative was affected by the presence of the system. For example, P10 stated that this was the case "*because I can see the machine*". P3 explained that the relay also had an impact: "*The device will make a clicking sound and some cables, so it is very clear that the stimulation came out of this device*". However, this was different if participants were not paying attention. P11 said: "*At the beginning, I thought of the system, because I saw it and felt it. But sometimes when I didn't pay attention to it, I felt my body create that movement*". This suggests that participants experienced the superpower sometimes as something separate from their body, possibly exacerbated by the form factor and relay noise; however, if not paying attention to it, they believed it was "*them*" who could sense Wi-Fi.

Regaining control of the hand: Participants held varying opinions about who controls their body and hand movements. Five participants reported that they were in control of their bodies and movements, even though their fingers were contracted involuntarily. P4 said: "*I was able to either bring them under control or avoid using them for the task I wanted to perform*", while P9 said: "*When the stimulation occurs, my muscles are also contracting, but the contraction is not enough to exceed my willpower*". However, willpower can be disturbed by other tasks, thereby affecting the user's ability to control the body. For example, P9 mentioned that they needed conscious control of their body: "*Without paying attention to controlling the hand, I feel that the movement of the hand is completely controlled by it*". Similarly, P2 said: "*Sometimes, it gives a false impression that my hand is completely under my control. But that's not true. My hands still move involuntarily*". It seems the control of the body was not fixed and may fluctuate in different contexts. P8 echoed this notion and explained: "*While I was not using my hand and didn't want to use it, definitely the device is controlling the hand, in the sense of controlling the movement of the hand, specifically flexion. While I was not using it, but I wanted to use it, I felt in control like I was able to fight with the stimulation and I was able to take control again*".

However, six participants reported that the system controlled their hands. For example, P1 said: "*I feel like it was controlling my hand. The device controls my body, it's not me*". P5 emphasised the influence of stimulation intensity: "*Especially when there was a stronger signal, I couldn't control my hand. I tried to keep my hand and my fingers straight, but I couldn't. It was a strong signal, so it's hard to fight it*".

4.5 Discussion

In this section, I discuss my findings, derive design tactics for future superpower systems, and discuss limitations and future research work.

4.5.1 Unfortunate effects of Wi-Fi Twinge

Measures of the subscale Sense of Negative Agency showed a significant difference when participants used Wi-Fi Twinge compared to the baseline. This result suggests that participants experienced a significant increase (55.17%) in the sense of negative agency when they had the Wi-Fi sensing superpower, indicating that participants felt significantly less control over their bodies, and felt more helpless, which speaks to the unfortunate effect of the system. This result aligned with the goal of my study design, as my motivation was to investigate an unfortunate superpower with unfortunate results: involuntary muscle contractions and finger movements, which led to a lack of control over some parts of the body and resulted in a dramatic increase in the Sense of Negative Agency. However, the loss of control in the hands was relatively small compared to the whole body, and the tingling sensation and finger movements were relatively mild. As a result, participants still had the ability to control most of their daily behaviour and take responsibility for their actions. Thus, it may explain why Wi-Fi Twinge had a smaller effect on the participants' Sense of Positive Agency and overall Sense of Agency scores.

My finding that “Wi-Fi Twinge facilitates varying degrees of sense of agency” confirms that loss of body control affects the sense of agency and suggests that users’ perception of the initiator of the action also affects the sense of agency. Participants reported that they saw their hands being moved passively by the machine and therefore perceived the initiator of the hand movements to be the system, thus indirectly reducing their sense of control over their bodies and affecting their sense of agency. It also reflected the technological mediation and human-technology relations in post-phenomenology (Borgmann, 2019; Ihde, 1990; Verbeek, 2008). Wi-Fi Twinge is considered a mediator that influences the way participants perceive and engage with the surrounding environment, and as an extension of the human body, enabling them to sense Wi-Fi signals beyond their own capabilities.

Moreover, participants mentioned that the physical characteristics of the Wi-Fi Twinge system (such as cables, size and sound) strongly influenced this feeling, suggesting that the Wi-Fi Twinge system was experienced as an external device rather than a part of the body. This perception is referred to as the sense of bodily ownership and describes the feeling that the system is a part of the body (Mueller et al., 2021, 2022, 2023). These findings suggest that bodily ownership is a critical determinant in deciding whether or not a technology enables a person to experience superpowers, and as I mentioned earlier, using a person’s own physiology can be a part of what makes it a superpower. Therefore, these results suggest that in addition to employing the user’s own physiology as an interface, the technological components of the system must also be obscured or subtle for users to experience the system as an innate superpower.

Taken together, the sense of agency and sense of bodily ownership permeate almost all experiences and are very important elements in examining the experience of superpower systems (Blanke & Metzinger, 2009b; Braun et al., 2018). For example, Mueller et al. (2021) used them as a lens to design the bodily integration framework, which describes the design of human-computer integration systems in which the human body and computational machine are coupled in a bidirectional actuation. They categorised EMS systems as “Possessed-Body” with a low bodily agency and a high bodily ownership. However, as with the theme “Wi-Fi Twinge facilitates varying degrees of sense of agency”, participants were roughly evenly split on the question of who controlled the hand movements, suggesting that participants’ sense of agency when using Wi-Fi Twinge was partially influenced by the unfortunate side effects, which is consistent with the SoAS results, where the sense of agency score was slightly lower than the baseline, but not significantly different from the baseline. In addition, through the previous analysis, I recognised that the perception of action initiators and hardware features increases the system’s sense of presence, resulting in participants’ sense of bodily ownership being at a low degree. The results show that the Wi-Fi Twinge has a moderate sense of agency and low bodily ownership, and can be considered to fall between the “Chauffered-Body” and “Tele-Body”. These findings suggest that when users become aware of involuntary movements in their bodies, they are aware that they are not the initiators of the power, and that the movements are not driven by themselves, but they retain the willpower to counteract these movements and believe that they are in control of their bodies.

4.5.2 Changes from sensation to cognition

Three participants admitted that they did not like the superpower because of its negative effects. All participants reported that while the superpower enhanced their perception of Wi-Fi, it also caused negative emotional and behavioural effects. This suggests that a superpower, an enhanced capability in one part of the body (sensory), might lead to decreased capability in another part of the body (hand). This confirms the prior theory on the augmented human, which said that a superpower is often a trade-off, where strengthening one part of the body through technology could limit another part (Nanayakkara, 2023).

However, as per the theme “Wi-Fi Twinge creates fortunate out of unfortunate effects”, participants reported that when the discomfort sensation was within their acceptable range, they became more aware of their surrounding environment because of the physical stimuli they received. Particularly, users could infer the surrounding environmental features and get implicit guidance from their sensations. For example, P5 said that they started guessing if there was Wi-Fi in the buildings they passed. These findings suggest that unusual physical sensations may trigger deeper cognitive thinking, making people think about things they would not usually think about, and see the world differently than before.

Moreover, participants reported that they became not only more aware of the surrounding environment but also gained a renewed appreciation of their hands. The EMS stimulation caused involuntary hand movements, reducing participants' bodily control, thus, increasing emphasis on their hands. This appeared to promote empathy by allowing participants to feel physical sensations they had never experienced before and to understand the feelings of people with hand-twinge symptoms. It aligns with prior theories on the potential of embodied systems: research has found that embodied systems can be used to build empathy and compassion (Hirt & Beer, 2020; Jütten et al., 2018; Slater et al., 2019). For example, researchers have used augmented body suits to mimic vision, hearing and movement impairments to educate students about the experiences of people with disabilities (Levett-Jones et al., 2018; Qureshi et al., 2017). This confirms the prior theory that through interacting with sensory-altering systems, the ability to understand and empathise with the feelings of others may be strengthened (Dyer et al., 2018; Hirt & Beer, 2020; Wilding et al., 2023). This embodied experience, rather than an abstract understanding enabled by text or speech, could make people more engaged and immersed in the environment, thereby increasing their empathy with specific groups.

Similarly, in the second theme, “Wi-Fi Twinge facilitates a variety of emotions and sensations over time”, participants reported that Wi-Fi Twinge helped them focus on their bodies and heightened their awareness of their bodies. This finding confirmed that embodied interaction through the user's own physiology could facilitate bodily awareness (Patibanda et al., 2017), which is important because bodily awareness can improve mental and emotional well-being, as, for example, utilised in the recovery of trauma and as therapy for people with autism (Van der Kolk, 2014).

Taken together, these findings suggest that the uncertainty and unpredictable negative side effects of superpowers can physically and cognitively interfere with people's daily lives. These unfortunate effects may disrupt people's activities and concentration; however, people can adapt and cope effectively if these negative effects are kept within reasonable limits. At the same time, these unfortunate effects inspired the participants to harness their willpower to control their superpowers, leading to an enhanced awareness of self and strengthening the connection between their bodies and the surrounding environment.

4.6 Informing the framework

The results and discussion of the Wi-Fi Twinge case study informed the development of the Superpower Experiences Framework. The insights gained from this case study highlighted that physical discomfort, environmental awareness, and, most importantly, agency are critical factors to consider in the design of superpower systems intended for everyday life. Participants' interactions with Wi-Fi Twinge highlighted how involuntary bodily sensations triggered by external Wi-Fi signals can be translated into embodied experiences that influence users' sense of agency.

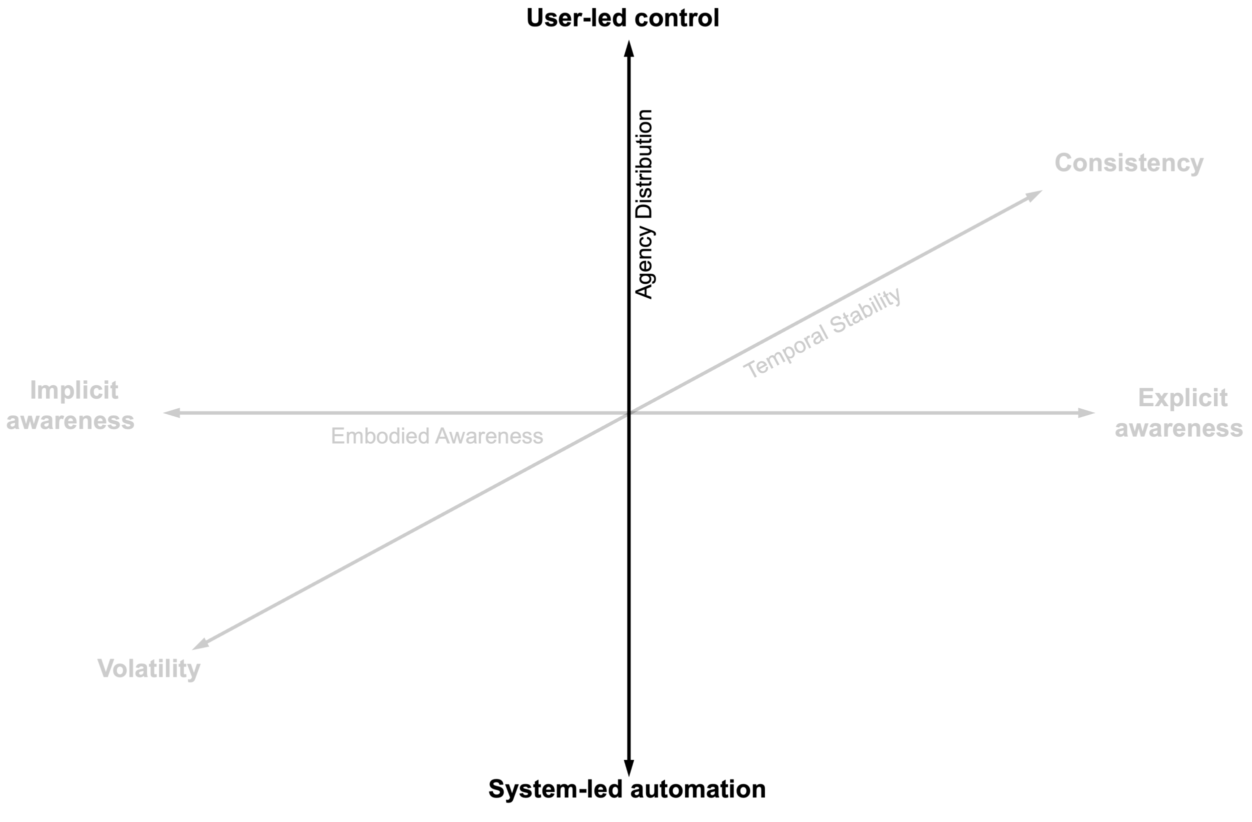


Figure 4.9: First dimension of the superpower experiences framework: Agency Distribution.

Participants' experiences demonstrated that agency is not a fixed attribute but a dynamic and context-dependent continuum. At times, users felt they could regain control over their hand movements, while at other times, they felt completely controlled by the system. This variability suggested the importance of agency as a key factor influencing users' acceptance and engagement with superpower technologies, thus led me to position agency as one dimension in the Superpower Experiences Framework (Figure 4.9).

4.7 Conclusion

In summary, the Wi-Fi Twinge study served as a foundational investigation, focusing on augmented perception as sensory feedback represents an inherently tangible and direct layer of human experience. The study also demonstrated the need to investigate superpower systems that extend beyond external perception to internal processing. Consequently, the next chapter presents EmoPals, a case study exploring the interplay of bodily agency, cognition, and emotion to understand how augmented cognition can create new forms of superpower experiences.

Chapter 5

Case Study 2: EmoPals

Figure 5.1: EmoPals explores how to design cognition superpowers: if one user is happy (left), the brain-computer interface senses this and sends electrical muscle stimulation commands to the other user's face to make them smile (right), even over a distance.

This chapter details my second case study, which investigates superpower experiences aimed at exploring augmented cognition through the design and deployment of "EmoPals" (Figure 5.1). This system uses brain-computer interfaces (BCI) and electrical muscle stimulation (EMS) to extend human cognitive interpretation, enabling two users to share emotional cues by experiencing each other's emotions through facial expressions. By turning internal cognitive states into external, embodied signals, EmoPals opens up new ways for users to perceive, interpret, and reflect on their own and each other's emotions, highlighting how cognitive augmentation can transform interpersonal understanding.

5.1 Associated Publication

This chapter builds upon two publications: a video showcase paper highlighting the design of the system and a full paper detailing the findings of a study.

- Siyi Liu, Barrett Ens, Nathan Arthur Semertzidis, Gun A. Lee, Florian Mueller, and Don Samitha Elvitigala. 2025. “My Happiness Makes You Smile”: Towards Understanding Telepathic Superpower Design via Brain-Muscle Interfaces. In Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA ’25). Association for Computing Machinery, New York, NY, USA, Article 907, 1–2. https://doi.org/10.1145/3706599.3721340. Video
- Siyi Liu, Barrett Ens, Nathan Arthur Semertzidis, Gun A. Lee, Florian Mueller, and Don Samitha Elvitigala. 2025. “My Happiness Makes You Smile”: Beginning to Understand Telepathic Superpower Design Via Brain-Muscle Interfaces. In Proceedings of the 2025 ACM Designing Interactive Systems Conference (DIS ’25). Association for Computing Machinery, New York, NY, USA, 3455–3472. https://doi.org/10.1145/3715336.3735699. Video

5.2 System Design

EmoPals, an amalgamation of “emotion” and “pal” for friend, is a novel wearable wireless networked system that uses EEG-equipped baseball caps for emotion sensing and EMS electrode pads on the face to actuate matching facial expressions between two people, even over a distance.

5.2.1 Sensing component

The sensing component (Figure 5.2) consists of an OpenBCI Cyton board (“Cyton Board”, 2021) connected to eight Ag/AgCl dry comb electrodes embedded inside a baseball cap and two reference ear clips. The electrodes are in direct contact with the scalp and are placed according to the 10–20 electrode positioning convention (Homan et al., 1987; Jasper, 1958), with the following locations selected: Fp1, Fp2, F3, F4, T3, T4, P3, and P4. The

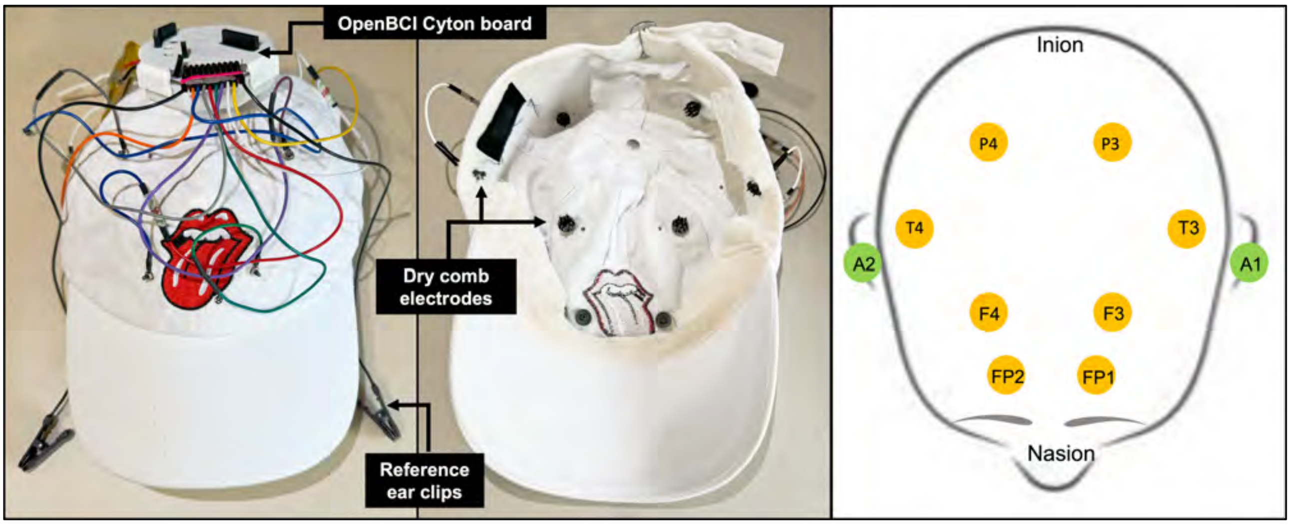


Figure 5.2: The left image shows the sensing component of EmoPals. The middle image shows the inside of the baseball cap with black dry comb electrodes reading EEG data. The right image illustrates EmoPals's electrode configuration mapped onto the international 10 - 20 EEG electrode positions. Positions in yellow indicate the positions of EEG electrodes. Green indicates the positions of the ground and reference EEG electrodes.

baseball cap was chosen due to its tight and adjustable fit to encourage stable electrode contact with the scalp.

Electrode locations and signal processing were chosen according to the SEED dataset collection (Duan et al., 2013; Zheng & Lu, 2015), i.e., the dataset I used to train the emotion classifier (see below). Previous studies have shown that these locations outperform other locations for emotion classification (Duan et al., 2013; Zheng & Lu, 2015). The EEG data was streamed via Bluetooth to a Raspberry Pi and then processed and categorised by a custom Python script using the “brainflow” Python API (Parfenov, n.d.).

The raw EEG signal was sampled at a rate of 250Hz, first filtered through a 0.3 - 75Hz Bessel bandpass filter, with an additional 50Hz Butterworth filter for removing ambient electronic noise. To further mitigate environmental noise and myoelectric artefacts, a “bior3.9” wavelet denoising filter was employed. After filtering and denoising the signal, the power spectral density (PSD) was calculated for each channel using the “Welch method with a Hamming windowing” function. The band powers for bandwidths 1-4 Hz (delta), 5-8 Hz (theta), 9-13 Hz (alpha), 14-30 Hz (beta), and 31-50 Hz (gamma) were calculated from the PSD for each channel individually. Band power values were binned in eight-second moving windows and fitted to a support vector

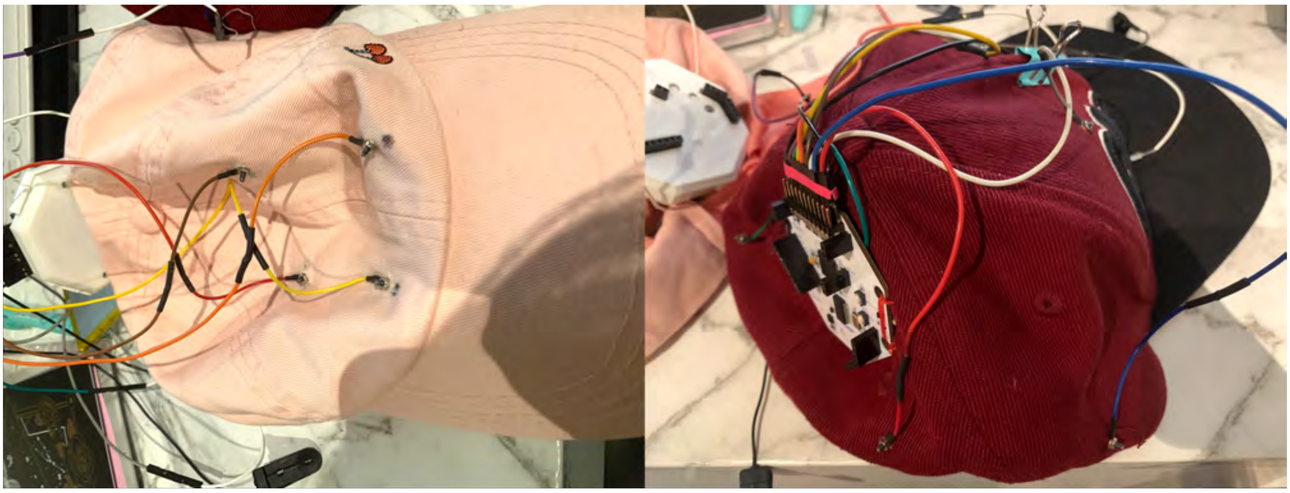


Figure 5.3: The exploration of EEG-equipped baseball caps.

machine (SVM) classifier to infer the participant's emotional state as positive, neutral or negative. This study's goal was not to build the most accurate classifier, but instead to reach a trade-off between accuracy and speed, with my system requiring a reasonably fast classifier that does not require too many resources to allow for real-time classification in a wearable form factor. SVM is a commonly used classifier in emotion recognition based on physiological signals, and it has been effective in EEG classification due to the spatial properties of the EEG dataset (Kamble & Sengupta, 2023; Semertzidis et al., 2023). The kernel function helps to categorise the data and reduces the computational complexity by converting the low-dimensional data into high-dimensional data. The classifier was trained with the SEED dataset following the data processing procedures previously mentioned, yielding a classification accuracy of 78.82%. Once the current emotional state was recognised, this result was automatically uploaded to the cloud database MongoDB Atlas (MongoDB, 2023) via a secure link for the actuating component.

5.2.2 Emotion classifier calibration

I found that the EEG emotion classifier was not consistent with participant self-reported experiences in a pilot study, although it achieved high accuracy when fitted to the SEED dataset. I investigated the data and found that the differences came from body movement during everyday activities, as participants in the SEED dataset were seated throughout with no body movement (Duan et al., 2013; Zheng & Lu, 2015). Therefore, I calibrated the emotion classification for the system by recruiting the general population to train the model in everyday contexts. Participants were recruited from advertisements on my lab's mailing list and social media accounts. I used the same method as in the SEED dataset to elicit emotions with audiovisual stimuli in the form of movies. I selected movie clips from the "Open Library for Affective Videos (OpenLAV)" (Israel et al., 2021). The database offers 188 movie scenes that were rated by 422 participants on 10 classification criteria. For each of the three emotions (happy, sad and neutral), I selected a total of 10 minutes of movie clips.

10 participants (5 men, 5 women, none non-binary and none self-described) aged between 23 and 34 years (M = 28.2, SD = 3.05) took part, and each participant watched all the selected film clips. I equipped them with the BCI device and ensured an optimal fit of the electrodes close to the scalp and in direct contact with the skin. Participants were encouraged to freely move in a quiet room in front of a screen on which the chosen movie clips were shown, mimicking their daily activities such as drinking water, standing up and sitting down. I first presented a neutral movie clip to establish a baseline. After that, I showed happy and sad movies in a random order. After each movie clip, participants were given a 2-minute break.

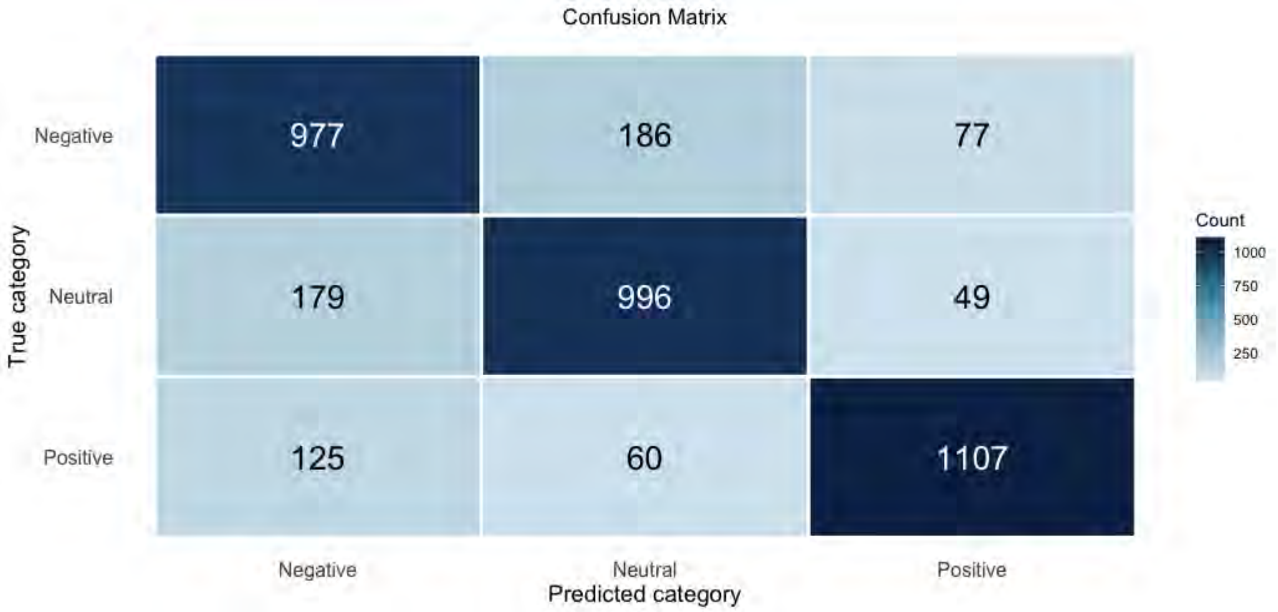


Figure 5.4: The confusion matrix of the emotion classification model.

I collected all participants' EEG data and fed this data and its labels into the SVM emotion classifier. Each participant's data was categorised into two sets: a training set and a testing set. 70% of the dataset was utilised for training purposes, and the remaining samples were for testing purposes. After the calibration, the average classification accuracy was 82.00% (SD = 9.78%, Precision = 82.08%, Recall = 81.95%, F1 Score = 81.99%). The confusion matrix of each category of emotion is shown in Figure 5.4.

5.2.3 Actuating component

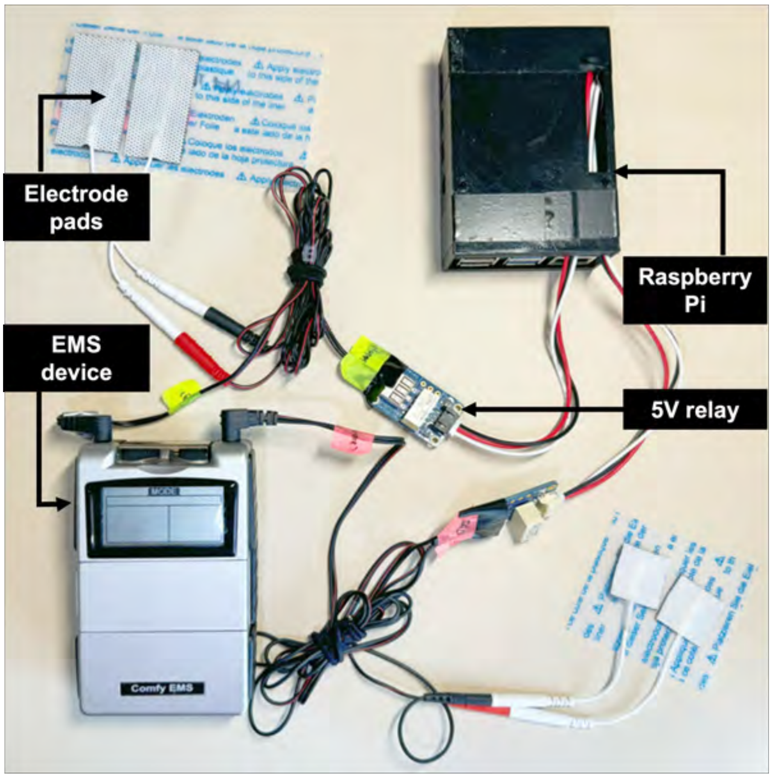


Figure 5.5: The actuating component. The black box houses the Raspberry Pi microcontroller, connected to the EMS device via two relays with two electrode pads. Rectangle electrodes (top left) were used to stimulate a smile expression. Square electrodes (bottom right) were used to stimulate a sad expression.

I chose EMS to actuate facial expressions as the output of the system rather than relying on audio or visual feedback, as I aimed to provide users with an embodied output where emotional feedback is not only observed but physically felt. By stimulating the facial muscles directly, EMS can create tangible, internalised emotional responses that might offer a more immersive and nuanced interaction. Unlike audio or visual feedback, EMS activates the user's own physiology to form a direct link between emotional states and bodily awareness, possibly more akin to a superpower experience, I believe, and provides a unique physical sense of emotional presence that audio or visual feedback may fail to replicate.

To achieve this embodied output, the actuating component consisted of an EMS device and two 5V relays (Figure 5.5). The relays were connected to the Raspberry Pi microcontroller, while the EMS device was battery-powered and connected to 4 electrode pads (2 pairs). These 2 pairs of electrode pads vary in size to fit different facial muscle groups and deliver stimulation to the user's chin and cheeks respectively. Based on pilot testing, I decided to use a constant EMS pulse width of 200 µs and a pulse rate of 100 Hz. The Raspberry Pi continuously fetched the emotional states of the other user from the cloud database and then controlled the relay to close the circuit between the EMS machine and the electrodes associated with the desired facial expression.

The placement of the electrode pads was critical to target each muscle accurately and was selected according to the nerve position on the human face (Figure 5.6). Two rectangular electrodes (5cm x 2cm) were placed around the Zygomatic branches and the Buccal branches to stimulate the cheek muscles to generate a smiling facial expression. Two square electrodes (2cm x 2cm) were placed around the Marginal mandibular to depress the angle of the mouth to generate a sad facial expression.

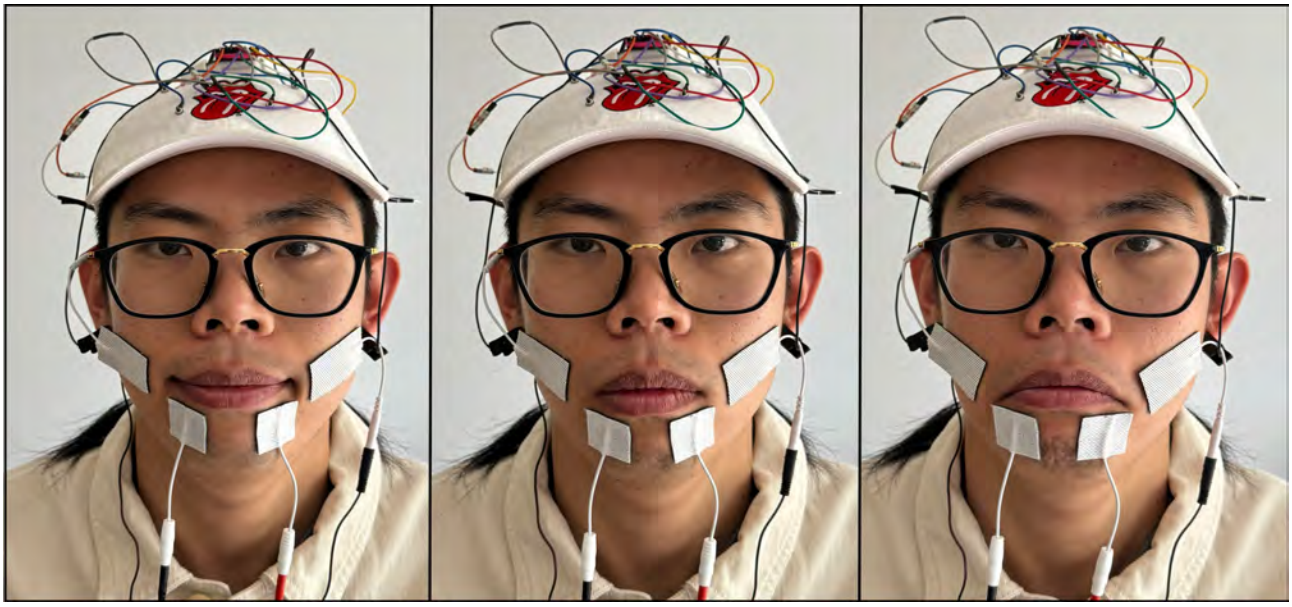


Figure 5.6: A user wearing EmoPals: The left photo shows a positive expression made with EMS, the middle photo shows a neutral expression (no EMS fired), and the right photo shows a negative expression.

Table 5.1: Demographics of participants

Group	Relationship	Location	Participants	Age
Group1	Friend	Co-location	P1 P2	29 30
Group2	Colleague	Remote	P3 P4	27 29
Group3	Partner	Co-location	P5 P6	30 31
Group4	Partner	Co-location	P7 P8	27 28
Group5	Colleague	Remote	P9 P10	25 26
Group6	Friend	Remote	P11 P12	32 32

5.3 Study

I conducted a 5-day field study to understand the user experience of EmoPals.

5.3.1 Participants

Twelve participants (5 men, 7 women, none non-binary and none self-described) were recruited, aged between 25 and 32 years (M = 28.83, SD = 2.29). Participants were recruited in pairs, including intimate couples, friends and colleagues (Table Table 5.1).

5.3.2 Study procedure

The participant pairs received an instruction document before the study, including how to operate the system, how to wear the baseball cap and adjust the position of the EEG electrodes, and where to place the four EMS electrode pads on their faces. I also provided them with a video containing these instructions for reference at home. Each group was asked to wear the system for 30-40 minutes daily over 5 continuous days. The system was set to turn off automatically after 40 minutes to protect them from muscle fatigue.

On the first day of each pair's study, I guided the participants to calibrate and set up the system. Participants were first asked to make smiling and crying facial expressions to determine the optimal position of the EMS electrodes. Then, I attached the electrodes to their faces. Next, I checked the placement and calibrated the amplitude of the EMS current. Under my guidance, participants slowly increased the intensity of the stimulus by turning the dial on the EMS device themselves until the desired intensity was reached, when the angle of the participant's mouths appeared to be visibly raised or lowered. Each participant was given three minutes to familiarise themselves with the stimulation. Photographs were taken of the intensity settings and electrode positions and then given to the participant for later reference. I informed each participant that they could readjust the intensity settings.

After the calibration, the study began. Each pair was required to wear the system concurrently but without constraints in regards to being co-located. Participants notified me by video call when they were prepared to wear the system so that I could remotely assist in adjusting the placement of the system and monitor the data flow to ensure that the system was operating properly. There were no prescribed tasks, as I aimed to understand the user experience in everyday life situations. Participants were instructed that they could use the system at any time of the day and anywhere, whether working, studying, entertaining, etc. I also instructed participants to "simply go about your daily activities as usual".

5.3.3 Data measurement

Participants were asked to complete the Sense of Agency Scale and the Sense of Body Ownership survey before the first use of the system and after each use. The Sense of Agency Scale (SoAS) is divided into the Sense of Positive Agency (SoPA), including feeling in control of one's body, mind and environment, and the Sense of Negative Agency (SoNA), which includes the feeling of being existentially helpless, not under control. The survey has been validated with good psychometric properties (Hurault et al., 2020). The Sense of Bodily Ownership survey was revised based on Grechuta et al. (2019) to fit the study by changing the question from the hand to the face. After each use, participants were also asked to complete a digital diary in survey form, recording the activities they did, when they wore the system, how they felt while wearing the system, how they communicated with their partner and whether they were co-located or apart during use. They could refer to these diaries in the interviews to recall their experiences.

At the end of the 5-day study, participants were asked to participate individually in a semi-structured interview that lasted approximately 30 minutes, allowing them to share their individual thoughts and perceptions without the influence of others. The interviews included 16 questions about participants' interactions and communications with their partner, potential physical and emotional effects. Questions that I asked were, for example: "Did the system influence your interaction with other people? Did it influence your emotions? When using the system in your everyday life, who do you think is in control, you or the system?" I considered calibration differences by asking what the EMS experience was like and encouraging participants to demonstrate how they used the system, including the intensity settings and electrode pad positions used.

5.3.4 Data analysis

As the Sense of Agency Scale and the Sense of Bodily Ownership Survey are ordinal in a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree), I performed non-parametric Wilcoxon signed rank tests of the mean scores for SoAS and the SoO over the 5-day study compared with the baseline. The Sense of Agency Scale has three factors, sense of positive agency (SoPA), sense of negative agency (SoNA), and total sense of agency (SoA) score, and thus I tested the mean scores of each factor to the baseline. The baseline data were results of the Sense of Agency Scale and the Sense of Bodily Ownership Survey that participants filled out before using the system, in which participants directly responded to their sense of agency and bodily ownership in everyday life.

The interviews were audio-recorded and transcribed for qualitative analysis. Reflexive thematic analysis (Braun & Clarke, 2006, 2019a) was used to analyse the interview data and identify themes by distilling and articulating meaning from the data. In total, the analysis identified three high-level themes.

5.4 Results

In this section, I detail the results yielded from the analysis of participants' responses to the Sense of Agency Scale and Sense of Bodily Ownership survey and describe three high-level themes that I derived from the analysis of the interview data.

5.4.1 Quantitative results

Figure 5.7 shows the quantitative results. The left figure shows the results of the Sense of Agency Scale. All three factors show significant differences, in which the SoPA of EmoPals (M = 22.53, SD = 5.11) was lower than the baseline (M = 35.33, SD = 6.93), W = 78, p = 0.003, the SoNA of EmoPals (M = 28.23, SD = 4.14) was higher than the baseline (M = 18.42, SD = 5.82), W = 4, p = 0.007, and the total SoA of EmoPals (M = 50.30, SD = 7.54) was lower than the baseline (M = 72.92, SD = 12.26), W = 78, p = 0.003. This means participants reported lower levels of sense of agency with EmoPals than at the baseline. The right figure shows the participants' responses to the Sense of Bodily Ownership Survey. The comparison of the mean score of sense of bodily ownership of EmoPals (M = 3.94, SD = 0.61) with the baseline (M = 3.61, SD = 0.41) revealed no statistically significant difference (W = 13, p = 0.061). This means that the EmoPals did not significantly affect the sense of bodily ownership.

Figure 5.8 illustrates the change in mean scores on the Sense of Agency Scale over five days. SoPA scores start at 22.00 on Day 1 and show minor fluctuations, gradually increasing to 25.78 on Day 5, indicating a growing sense of positive agency over time. In contrast, SoNA scores remain relatively stable, ranging between 27.125 and 30, suggesting a consistent perception of negative agency throughout the study. The SoA scores show a notable upward trend, starting at 49.00 on Day 1 and reaching a peak of 56.78 on Day 5 (because of the increased SoPA score and decreased SoNA score), suggesting an overall increase in participants' sense of agency with the system over time.

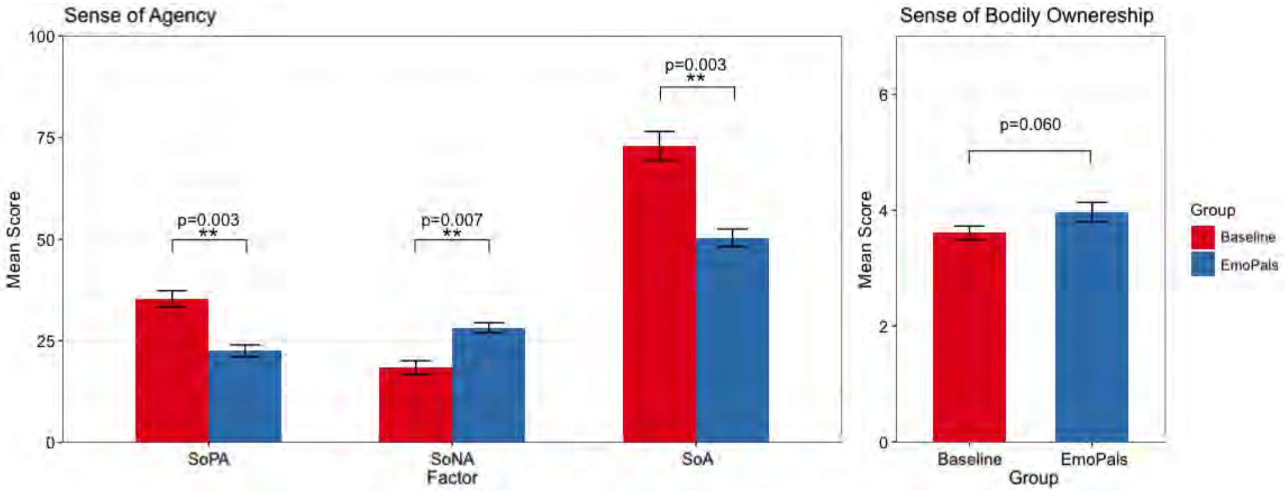


Figure 5.7: Results of participants' responses to the survey. The left figure shows the mean score of SoPA, SoNA and total SoA compared with the baseline. The right figure shows the mean score of the Sense of Bodily Ownership Survey compared with the baseline (Error bars: one standard error of the mean/ $**$: $p <= 0.01$).

5.4.2 Qualitative results

Overall, all participants reported that they felt a "superpower" thanks to EmoPals. This experience was "*fascinating*" (P7), "*exciting*" (P6) and "*beyond expectation*" (P11). Three themes emerged: experiencing physical and emotional changes, strengthening connections through shared experience, as well as understanding emotional awareness through interactions. For each theme, I identify sub-themes categorised as "fortunate," "unfortunate," or both, in parentheses. This categorisation indicates whether the user experience perceived by participants in each sub-theme was predominantly positive, negative, or both.

5.4.2.1 Theme 1: Experiencing physical sensations and emotional changes

In this theme, participants discussed their experiences of novel physical sensations and emotional changes brought on by the system. The theme has four sub-themes: exploring new physical sensations; influencing emotional states; amplifying negative emotions; and regaining control of the body.

Exploring new physical sensations (fortunate & unfortunate): The system introduced participants to a range of novel physical sensations because of involuntary muscle contractions and unexpected facial movements. Participants

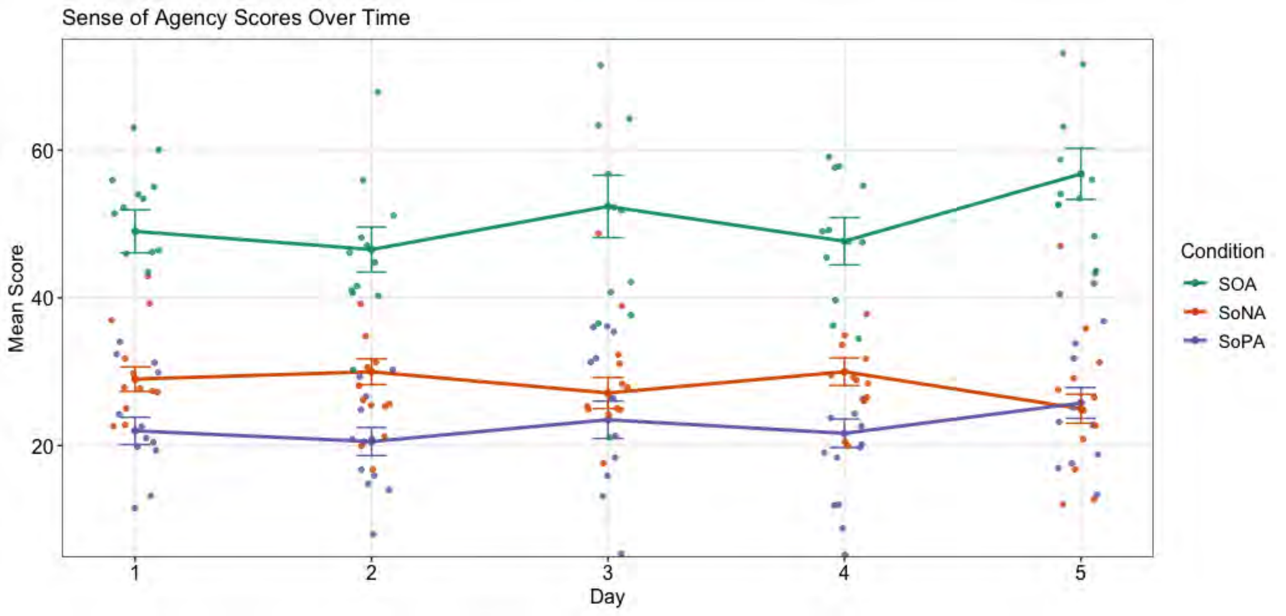


Figure 5.8: Mean scores of participants' responses to the SoAS (Error bars: one standard error of the mean).

reported that EmoPals allowed them to "*feel like having a telepathic superpower, because these [physical sensations] came from my own body, not an external device*". These experiences were both "*fascinating*" (P7) and "*novel*" (P9), with four participants feeling excited as well as curious about EmoPals. One of them was P9, who said: "*I didn't know what would happen, so every new sensation felt like a discovery and I enjoyed the process.*" Other participants used words like "*strange*" (P1), "*tingling*" (P3), and "*shock*" (P8). Four participants expressed a "*fear of this superpower because of the physical sensations*" (P1). P4 said: "*My facial muscles were forced to stretch, which was strange for me, and made me feel like a different person.*" P3 added: "*It was like an invisible hand was pushing on my face, controlling my expression, and it made me feel nervous and worried.*" Over time, the initially unusual sensations became more familiar to the participants, who became accustomed to the system's induced facial expressions, allowing them to integrate these sensations as part of their everyday lives. For example, P6 said: "*Over time, towards the end, I think it lined up with me, so I felt my facial expression was more natural, and I felt more superpowers as well.*"

Influencing emotional states (fortunate): Participants experienced various facial expressions across different activities and emotions while using EmoPals.

Figure 5.9: A participant uses EmoPals to share their emotions while cooking.

The system facilitated the transmission of facial expressions, which influenced the emotional states of the participants. For example, P5 said: "*I felt some happiness when the system stimulated a smile on my face because I knew my partner was happy at that moment.*" Participants reported an affective echo effect, where the actuation of an emotional response in the receiver triggered an actuation in the original sender. For example, P3 explained that the system is a feedback mechanism between the expression and emotions of two people: "*Especially when I'm looking in the mirror, I can see my muscles lifting, and I also smile, not only because of my muscle feelings but also because of my funny facial expressions, and then my partner said they felt the happiness from me*".

Amplifying negative emotions (unfortunate): Five participants reported that the system seemed to amplify negative emotions or even evoke new emotions, blending physical sensations with emotional reactions. They explained that system-induced facial expressions not only heightened their awareness of the other's negative emotions but also amplified their own negative feelings through physical sensations. For example, P12 said: "*When my partner had sad feelings, I felt pain in the area below my mouth. This pain makes me feel another negative emotion, not just the sadness I got from my partner.*"

Participants also felt emotional overload when the telepathic superpower introduced conflicting feelings or too many feelings at once. P1 explained: “*The electrical stimulation itself led to some negative feelings, so when the system generated stimulation, it influenced my own emotions immediately, even if I was happy before.*” This experience also led to reflections on the nature of their own emotions. P6 elaborated: “*It became blurred between what I was feeling and what I thought I should be feeling. I began to doubt whether it was my emotions or if the system was affecting my emotions.*”

Regaining control of the body (fortunate & unfortunate): Participants reported how they explored the concept of control through EmoPals. Five participants said that their activities were interrupted by the system “*especially when facial expressions were accidentally triggered*” (P4), and they “*had to stop chatting for a bit*” (P12). Participant’s attention was also distracted by EmoPals: “*When I was focused on doing something, the stimulation always pulled me away from what I did. And then maybe my body may continue to do it, but my mind has already detached and wandered away*”(P10). Participants reported that they learned how to adjust their responses, following the system’s control in some activities that do not require much personal facial expression control, such as reading and working. For example, P5 stated: “*When I did activities that didn’t require facial expressions, such as reading a book, I just gave up control and let the system control my expressions so that I could focus on the book.*” Seven participants reported that they were in control of their faces, even though their facial expressions were contracted involuntarily. P9 said: “*If I don’t want electrical stimulation to make my facial movement, I think I could prevent it, and I have the opposite force to make it not move.*” Furthermore, P11 explained that familiarity with their body can help them control their body: “*I can feel very clearly which part of the muscle has been forced, so I know what part is created by me and what part is created by the system.*”

The system’s intensity also affected the balance of control between the body and the system. Participants reported a negative correlation between the intensity of EMS and the degree of control, i.e., “*the higher the intensity, the greater the pain, the more negative emotions and distractions and the less control over [the] body*” (P12). P3 explained: “*Within the normal range of intensity, I can control myself and control whether to smile or pout. But if the intensity is very high, I lose control and am not able to control myself.*”

5.4.2.2 Theme 2: Strengthening connections through shared experience

In this theme, participants discussed how the shared experience influenced their emotional understanding, sense of connection and social communication. The theme has three sub-themes: deepening emotional bonds, facilitating empathy toward each other, and amplifying social discomfort.

Enhancing emotional closeness (fortunate): Nine participants indicated that the system facilitated emotional communication with their partners. They reported that actuated facial expressions offered more opportunities to discuss their emotions and therefore facilitated communication around emotions, whether questioning or caring (Figure 5.10). For example, P2 said: "*When my partner's face moved, her attention would turn to the system and she started asking me about my emotions*". Additionally, participants found that real-time emotional feedback helped to enhance the clarity and depth of communication. Seven participants reported that the emotional exchange without words created an additional dimension of interaction, deepening their emotional bond with each other. For example, P7 said: "*When I saw my partner's facial expression matching my emotions, it made me feel more connected and assured that we were on the same page. It was a new way of feeling close.*" Participants noted that they felt a deeper emotional connection in a more direct and embodied way. Therefore, they thought that the system positively impacted relationships, regardless of the kind of relationship they were in. For example, P5 stated: "*Using the system allowed me to feel closer to my partner than text or voice alone, as we could share feelings without needing to say them verbally, which is very useful in long-distance relationships.*" P10 explained: "*This superpower is like a heartbeat, you can feel that other people are there with you, accompanying you, and feel the same way*". These experiences highlight a potential influence of the system on enhancing emotional closeness and facilitating richer emotional communication in real-time without the constraints of traditional communication methods.

Facilitating empathy (fortunate): Seven participants mentioned that the system facilitated the sharing of emotions regardless of physical distance, enabling them to feel enhanced empathy. For example, P9 said: "*When I was really happy and enjoyed my dinner, I felt my friend was sad from the superpower. So, I just wanted to ask what happened, and after he explained the reason,*

Figure 5.10: Two participants communicated using EmoPals at the same location.

like struggling with work, I also felt very stressed and became upset as well.” The sensations and synchronised facial expressions helped participants understand their partner’s inner thoughts: “*My partner is the kind of person who remains untouched even after being told how others feel. So, I think this superpower can help people improve their empathy ability, making them more understanding of others*” (P7). This empathy-building potential allowed participants to explore unfamiliar emotions together and build empathy in ways they had not anticipated. P4 mentioned that the system even elicited care for others’ feelings: “*I am a bit cold with other people and do not pay attention to their inner emotions. I think this system triggered my curiosity about others, and with it, I wanted to know others’ feelings, emotions and thoughts and I can easily understand that from the system, from my facial expressions*”.

Amplifying social discomfort (unfortunate): Five participants reported moments of social discomfort as their facial expressions were influenced by the system, so they used the system only at home. P6 explained: “*It is harder to do that among people since I don’t want to show strange faces to others.*” P4 worried that wearing the system in public would be embarrassing: “*I did the study at the lab for the first two days, and I was trying to avoid contact with other people except for my partner to avoid embarrassment.*” The sharing of emotions also led to a sense of vulnerability as the system could expose emotions: participants reported that they became more aware of how emotional changes were visible to their partners, and they sensed a loss of control over how they appeared to their partners. For example, P2 said: "*I felt exposed like my emotions were out there even when I didn't want them to be.*" However, P7 stated that they would wear EmoPals if the social environment was "*relaxed and familiar*", and it could "*even trigger some happy moments*". P10 attempted to use the system in public but refrained due to concerns about the reaction of others: "*I wanted to use the system when [I] picked up the parcel and wanted to show it to the delivery person, but I felt it was too bold and worried it might scare them.*"

5.4.2.3 Theme 3: Understanding emotional awareness through interactions

In this theme, participants reflected on their emotional awareness and the impact of their emotional expressions across varied interactions. Three subthemes were identified: increasing awareness of emotional responses; elevating relationships; and facial expressions compromising privacy.

Increasing awareness of emotional responses (fortunate): EmoPals appeared to encourage participants to reflect more on their emotional states, leading to increased self-awareness. Nine participants noted that the experience motivated them to think about how their emotional expressions might impact others or be interpreted differently depending on the context, leading them to reconsider their emotional presentation and prompting deeper self-reflection. For example, they were curious about how their inner thoughts reflected their emotions and how they appeared on their partner's face. P5 said: "*I was curious if my thoughts would cheat me and how long my emotions would last, so I kept testing it on my partner's face. I tried to watch some funny videos to see if my partner's facial expression turned into a smile, and then observed how long that expression lasted, which represented how long I'd been happy*". The system also encouraged participants to be more aware of their emotional influence on others, fostering an increased understanding of social interactions. For example, P7 shared: "*Seeing my partner's reactions made me more aware of how my emotions affected others and how their emotions changed. I realised that sometimes my negative emotions may be taken out on him*".

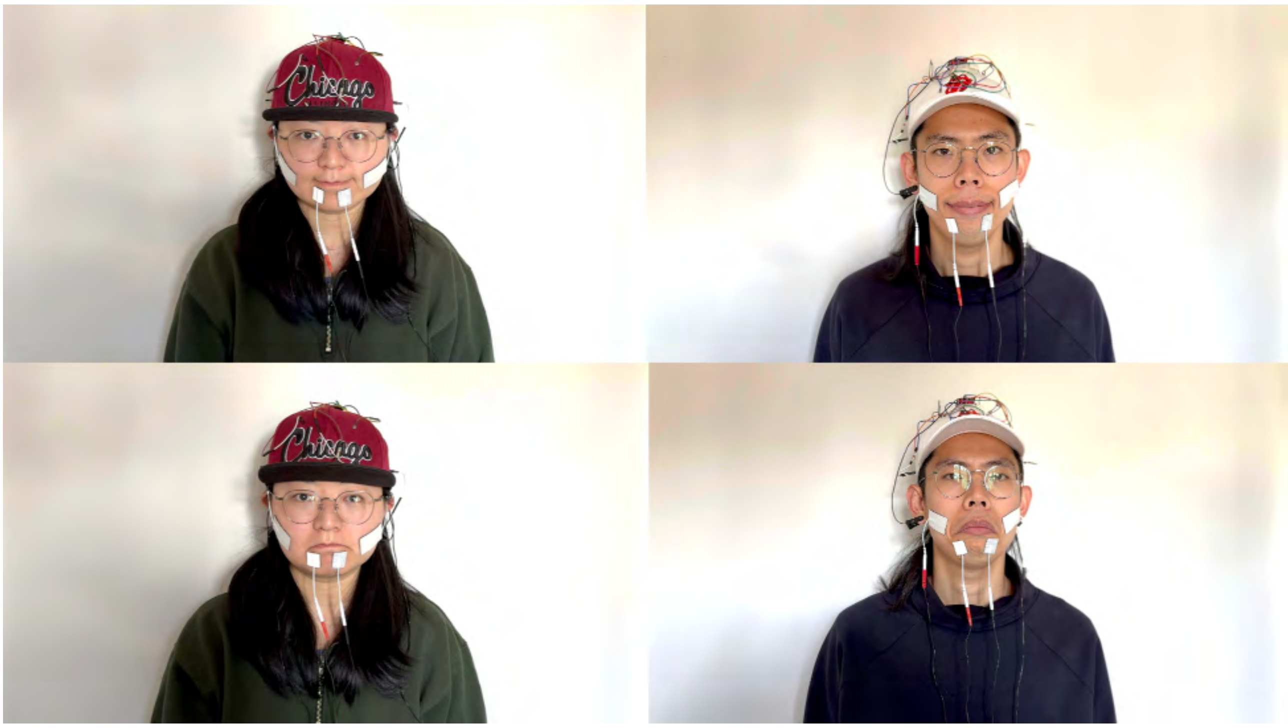


Figure 5.11: EmoPals connects two people through their facial expressions even over distance.

Elevating relationships (fortunate): Participants reported how EmoPals helped them elevate their relationship with the other person. EmoPals's influence on their facial expressions and emotional states was perceived differently depending on whether they were colleagues, friends or partners. For instance, in collegial relationships, EmoPals allowed colleagues to be aware of each other's emotional states while maintaining professional distances. P9 explained: "*I could tell that he was upset and didn't want to open up to me. So, I didn't bother him anymore and let him calm down.*" In friendships, emotional awareness encouraged a closer bonding, as friends were more likely to express concern and could better understand each other's feelings. Participants explained that they cared about their friend while "*respecting each other's boundaries to maintain the friendship*" (P11). In intimate partnerships, the system deepened emotional intimacy by facilitating a more open exchange of feelings. Partners showed a heightened concern for each other's emotions and were often able to infer reasons without explicit communication. For example, P8 reflected: "*When I used the system with my partner, they immediately sensed my sadness, asked me what was wrong, and even guessed the reason behind my feelings before I had the chance to explain*". This increased emotional awareness in intimate relationships allowed for more empathetic interactions and helped participants feel understood, ultimately strengthening their emotional bonds.

Facial expressions compromising privacy (unfortunate): Eight participants reported that facial expressions could reveal hidden emotions. P9 talked about their colleague's emotion: "*I could sense that the other participant was feeling sad, but whenever I asked, he would always say 'nothing' and act normal. Although he said everything was fine, I could tell that he was upset and didn't want to open up to me.*" In addition, eight participants mentioned that it appeared that they were responsible for the emotional expression of the other and themselves, resulting in an additional burden. For example, P6 noted: "*I usually don't care much about my facial expressions, but with this superpower, I started to care about problems when interacting with others because I am now responsible for the facial expressions of two people.*" Participants reflected on the degree to which the system compromised their sense of privacy. P1 explained: "*If I have too many negative emotions, it may affect my friend's interactions with others. They may react incorrectly to others, [which] may lead to a misunderstanding.*" This raised concerns about the loss of agency over one's emotional boundaries and the potential for unintentional disclosure of sensitive feelings. In contrast, two participants expressed a preference for this kind of revelation, because they could get to know others better. For example, P11 said: "*When the topics come to the interesting thing, I can feel my experiment partner is very interested and excited about that topic, and the emotions were very continuous compared to our normal conversation*".

5.5 Discussion

EmoPals allowed me to understand the design of telepathic superpowers that augment emotional communication through technology. The results highlight that while telepathic superpowers could strengthen deeper connections and heighten empathy, they also pose challenges to agency and emotional privacy and self-expression. These insights reveal design challenges that go beyond technical performance, prompting broader reflection on the ethical dimensions of augmentation. Through EmoPals, I do not attempt to offer conclusive answers but rather present an exploratory case that informs new design recommendations for future investigations on superpowers in HCI research.

5.5.1 Emotional contagion: Bridging self and others

Participants expressed that, through the system, they can mirror and feel their partner's emotions through embodied experiences (theme "enhancing emotional closeness"). This finding appears to confirm the theory of emotional contagion, in which one's emotions are transmitted among individuals unconsciously by observing others' emotional expressions (Dimberg & Thunberg, 2012; Hatfield et al., 1993; Yoshida et al., 2021). I extend this theory by demonstrating that emotional contagion can also occur through indirect physical sensations, mediated by interactive technology, broadening the understanding of how emotions are shared. This work suggests that superpowers that support embodied affective experiences facilitated by physical sensations could create deeper emotional connections, even in non-visual or long-distance contexts. This highlights the potential of using physical sensations to amplify emotions and foster deeper interpersonal bonds. For example, telepathic superpowers could be designed for therapy, such as improving emotional regulation in relationships or assisting people with difficulties in emotional expression, thereby expanding the boundaries of how superpower designs can mediate human connections.

However, such heightened emotional contagion is not always positive. Negative emotions, such as frustration or anxiety, are also amplified and can lead to emotional overload (theme "amplifying negative emotions"). This finding aligns with Hatfield et al. (1993), who argued that emotional contagion can have both bonding and overwhelming effects. My research extends this argument by illustrating how the amplification of negative emotions via embodied interactions through superpower design can intensify emotional experiences beyond traditional face-to-face communication.

In addition to facilitating interpersonal connections, the superpower also affected participants' self-awareness and inner feelings. Participants reported heightened emotional awareness, not only reflecting the emotions of their partner but also experiencing their own emotions more deeply through the feeling of facial expressions. Through physical manipulation of facial expressions, the internal emotional states are affected, which extends prior research on the Facial Feedback Hypothesis (Adelmann & Zajonc, 1989; Izard, 1971; Tomkins, 1962) by exploring how EMS-induced expressions affect emotional experiences. While previous research has demonstrated that only natural, voluntary facial expressions affect emotions (Coles et al., 2022; Folk & Dunn, 2024), this study's findings demonstrate that EMS-induced, involuntary facial expressions can also affect emotional experiences. This phenomenon could be attributed to participants' cognitive awareness of the emotional cues being conveyed. Participants explicitly recognised that EMS-induced facial expressions represented their partner's emotional state, which appeared to amplify the emotional contagion effect. By connecting involuntary facial expressions to the emotional meaning conveyed by the system, participants were able to internalise and experience emotions naturally. This study reveals the role of cognitive awareness in emotional contagion, which aligns with prior findings that individuals tend to experience emotions more intensely when they are aware of the emotional context of facial expressions (Dimberg et al., 2000). This finding suggests that the interaction between physical sensations and cognitive awareness could be a valuable tool for designing superpower systems that facilitate emotional understanding and empathy.

5.5.2 Telepathic bodies: Exploring “Körper” and “Leib” in affective interactions

The concepts of “Körper” and “Leib” can help understand the affective interaction within telepathic superpower experiences. Mueller et al. (2018) use two German terms - “Körper” and “Leib” - to distinguish between different perspectives on the body. The “Körper” refers to the material, external and objectified physical body, including facial expressions. The “Leib” refers to the subjective and lived body - how we experience our bodies subjectively. Traditionally, during unmediated human interactions without technological augmentation, such as face-to-face conversations, one's “Körper” is affected by one's own “Leib” and then affects the other's “Leib” (Figure 5.12A). For example, feeling joy (“Leib”) might naturally result in a smile (“Körper”), which, in turn, evokes emotional resonance in the other person by affecting their “Leib”, making them feel happy.

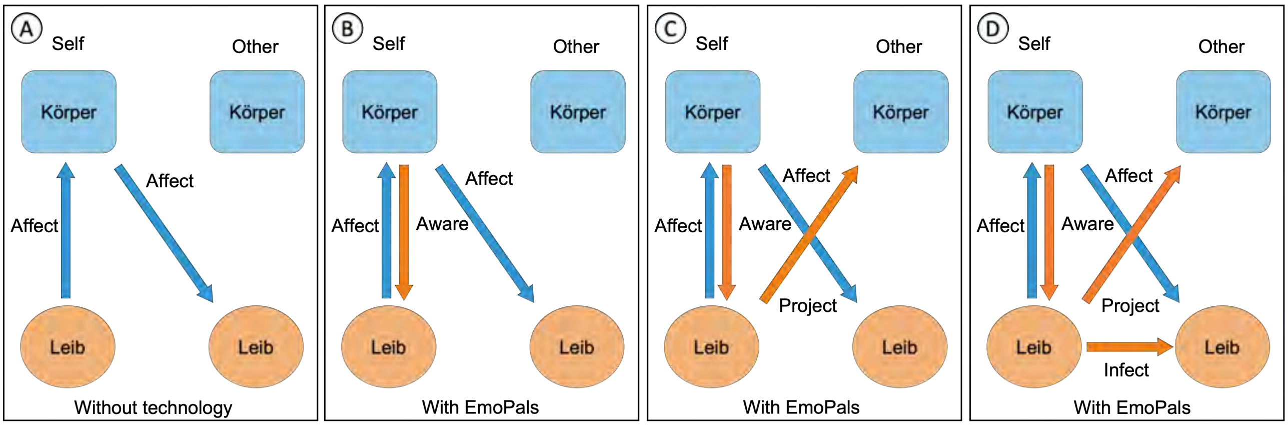


Figure 5.12: The relationship of Körper-Leib with and without EmoPals.

The study suggests that EmoPals expanded the interaction between "Körper" and "Leib" by altering both the external and internal experiences of emotions. When superpower systems such as EmoPals are used, one's "Leib" can become aware of a changed "Körper" through bodily awareness (Figure 5.12B). For example, EmoPals used EMS to induce facial expressions such as a smile, directly altering the user's external body state ("Körper"). This manipulation from the external environment allows the user to be more aware of their bodily changes ("Leib"). Participants described that they experienced these externally induced emotions in their inner bodies, including the physical sensation of stimulation, which changed their perception of their emotional states.

With EmoPals, one's "Leib" states can be detected and projected onto the other's "Körper" (Figure 5.12C) by conveying facial expressions. This process can evoke empathetic responses, and facilitate the infection of emotions from one's "Leib" to the other's "Leib" (Figure 5.12D). Participants reported being more curious and concerned about their partner's emotions when communicating remotely, as the absence of visible emotional triggers heightened awareness of transmitted emotions. This finding suggests that telepathic systems appeared to enhance emotional transparency by enabling emotions to be transmitted directly through multiple channels. These emotional dynamics highlight how telepathic systems can expand traditional routes of emotional interaction, creating novel feedback loops that involve both the user and their partner. By expanding the framework, the investigation not only extends the theoretical understanding of "Körper-Leib" but also provides designers with insights into how they can harness this relationship between "Körper" and

“Leib’’ by creating systems that amplify the positive effects of emotional interaction from emotional awareness, projection or infection.

5.5.3 Sense of agency and ownership: Balancing control and adaptation

The results from the Sense of Agency Scale indicated a decrease (31.02%) in participants’ sense of agency when using the EmoPals compared to the baseline condition. Specifically, participants experienced a significant decrease (36.23%) in the sense of positive agency and a significant increase (53.26%) in the sense of negative agency, suggesting that participants felt their facial expressions were being controlled by external forces, which aligns with my design intention to explore both positive and negative side effects. This loss of control reflects the challenge of designing superpower systems that interfere with bodily actions without undermining users’ sense of agency. EMS exacerbated this loss of agency, indicating that superpower design must be carefully considered to balance the system’s influence and the user’s control.

When examining the SoAS trend over the five days (Figure 5.8), participants’ mean scores of SoA fluctuated, with scores showing a slight decrease early on and then an increase later in the study. These trends indicate that participants’ sense of agency was not constant but rather increased over the study. The increase in SoA scores later in the study suggests that participants developed coping mechanisms and became more familiar with the system, which helped them regain some sense of agency. This finding aligns with prior research on EMS (Patibanda et al., 2021, 2024): while EMS may initially diminish the user’s sense of control, a longer-term experience might lead to an adaptive process where users regain some control over the body as they figure out how to adapt to the intensity of the stimulation. This adaptive process demonstrates that the loss of agency may be a short-term effect, suggesting that the gradual introduction of the system can help users adapt to the experience of superpowers, thereby mitigating initial negative side effects.

Furthermore, it is noticeable that in the theme “balancing control with system influence”, 58.33% of participants (seven out of twelve) reported retaining control over their facial expressions even when stimulated, suggesting that the Sense of Agency Scale (based on an average over the 5 days) may not fully reflect the participants' agency. For example, participants reported that the level of control is affected by EMS intensity; higher intensity settings resulted in a greater loss of agency, while lower intensities allowed participants to feel more in control. This confirms the bodily integration framework argument that EMS systems facilitate the "Possessed-Body" user experience (Mueller et al., 2021) because users can feel as if an external force possesses their body and controls their facial expressions. However, the fluctuations in SOA and retention of control reported by participants suggest that the sense of agency with such systems is not solely determined by the loss of control. Rather, it is influenced by a variety of factors, including the intensity of the stimulation, the length of time it is used, and the individual's adaptations over time.

In contrast, measures of Sense of Bodily Ownership revealed no significant differences. This result suggests that participants felt their bodies belonged to themselves even when external forces influenced their faces. The SoO measure was commonly used to evaluate the rubber hand illusion (Botvinick & Cohen, 1998), in which participants may feel ownership over a hand that is not physically theirs due to synchronised visual and tactile stimuli. In the study, however, there were no such conflicting sensory inputs; participants were fully aware of their own facial expressions being manipulated, maintaining a strong connection to their physical bodies. This result can be explained through the lens of "Körper" and "Leib" (Mueller et al., 2018). Participants experienced their facial expressions ("Körper") influenced by the system but did not perceive a detachment from their subjective selves ("Leib"). Participants still possessed their own bodies, felt the stimulation on their bodies and saw their expressions in the mirror or through partner feedback. This continuity of physical self-awareness may help to reinforce their bodily ownership, as participants were not confronted with an external "other" but rather experienced their own body in an augmented form. Interviews revealed that participants perceived the telepathic ability as a superpower of their own abilities rather than a takeover by an external device (theme "exploring new physical sensations"). This result suggests that by maintaining bodily ownership, superpowers can augment bodily experience without alienating users from their physical selves, even when experiencing external influences.

5.5.4 Ethical transparency: Protecting emotional privacy

Participants expressed concerns regarding emotional privacy when using the system (theme “facial expressions compromising privacy”). They reported feeling uncomfortable due to the disclosure of their emotions through involuntary facial expressions. These findings align with prior research (Dingler et al., 2017) that indicated that the use of technology to mediate emotional communication could introduce ethical challenges, particularly concerning the unintended disclosure of intimate emotional states. This study extends these findings by revealing that the automation of emotional expressions in telepathic superpowers not only mediates emotions but also complicates the user’s ability to manage their emotional self-presentation. As Howell et al. (2016) pointed out, biosignals could introduce interpretive ambiguity in social contexts. Similarly, the facial expressions induced by EMS in the study could be interpreted ambiguously, complicating how emotional signals are individually and socially understood.

Building upon Goffman’s theory of self-presentation (1956), I extend the argument that individuals manage their emotional expressions to control the impressions others form of them. According to Goffman, individuals perform differently depending on whether they are on the “front-stage” or “back-stage” of their social interactions. The “front-stage” is where people present themselves in ways that align with social expectations and norms, often involving careful control over their emotional expressions. In contrast, the “back-stage” represents spaces where individuals can relax and express themselves freely without concern for audience expectations. The involuntary emotional expression as a result of the superpower design forced participants to behave “front-stage” even in “back-stage” contexts, which may strip them of the privacy and freedom associated with intimate personal spaces. The self-presentation is disturbed when users are unable to regulate their emotional expression to fit the stage they are on. For example, when in a professional setting, a user might want to suppress emotions like sadness or frustration, but the system’s automation could inadvertently reveal these emotions, leading to potential discomfort or reputation risk. Thus, the emotional transparency provided by the system extends beyond visibility and creates an imbalance between the front-stage and back-stage presentation of self, raising concerns about the invasion of emotional privacy.

Furthermore, the findings reveal that the system's enforced emotional transparency conflicts with the autonomy available in "back-stage" settings. When the system automates emotional expressions, the opportunity for users to manage their emotional states and adapt them to the social context diminishes, which may undermine the sense of self-presentation across different environments. This suggests that involuntary expression can disrupt the management of emotional expression in social situations in ways contrary to expectations. Participants reported feeling exposed and vulnerable in social situations (theme "amplifying social discomfort"). This disruption of the self-presentation process can destabilise the boundaries between "front-stage" and "back-stage" behaviour, as individuals may not be able to separate the emotional experiences they wish to keep private from those that they automatically share with others. The enforced "front-stage" display of others' emotions could even raise ethical tensions akin to "tele-puppetry", where individuals are manipulated into performing another's "back-stage". This echoes concerns raised in "ChameleonMask" (Misawa & Rekimoto, 2015a, 2015b), where a person acts as a surrogate for another, displaying behaviours dictated by the remote user. However, in contrast to "ChameleonMask", where personal identity is overridden, participants in this study retained their facial expressions and agency over nonverbal cues outside the emotional feedback, creating a hybrid performance where external emotional influences blend with the individual's own presence. This partial overlay may introduce a more subtle and implicit form of manipulation that raises concerns about authenticity, consent and emotional autonomy, prompting reflection on where the self ends and augmentation begins.

Additionally, this study engaged with Goffman's concept of "audiences", where individuals perform differently depending on who is observing them (Goffman, 1956). The system acts as an implicit observer and influencer, programmed to detect and trigger emotional expressions based on the user's emotional state. Participants needed to reconcile their own emotions with those dictated by the system, which may amplify or distort their expressions. This dual audience introduced additional complexities; for example, if the system triggers a smile when the participant cries, the participant may struggle to align their own feelings with the external demands of both human and non-human observers, potentially leading to emotional dissonance.

5.6 Informing the framework

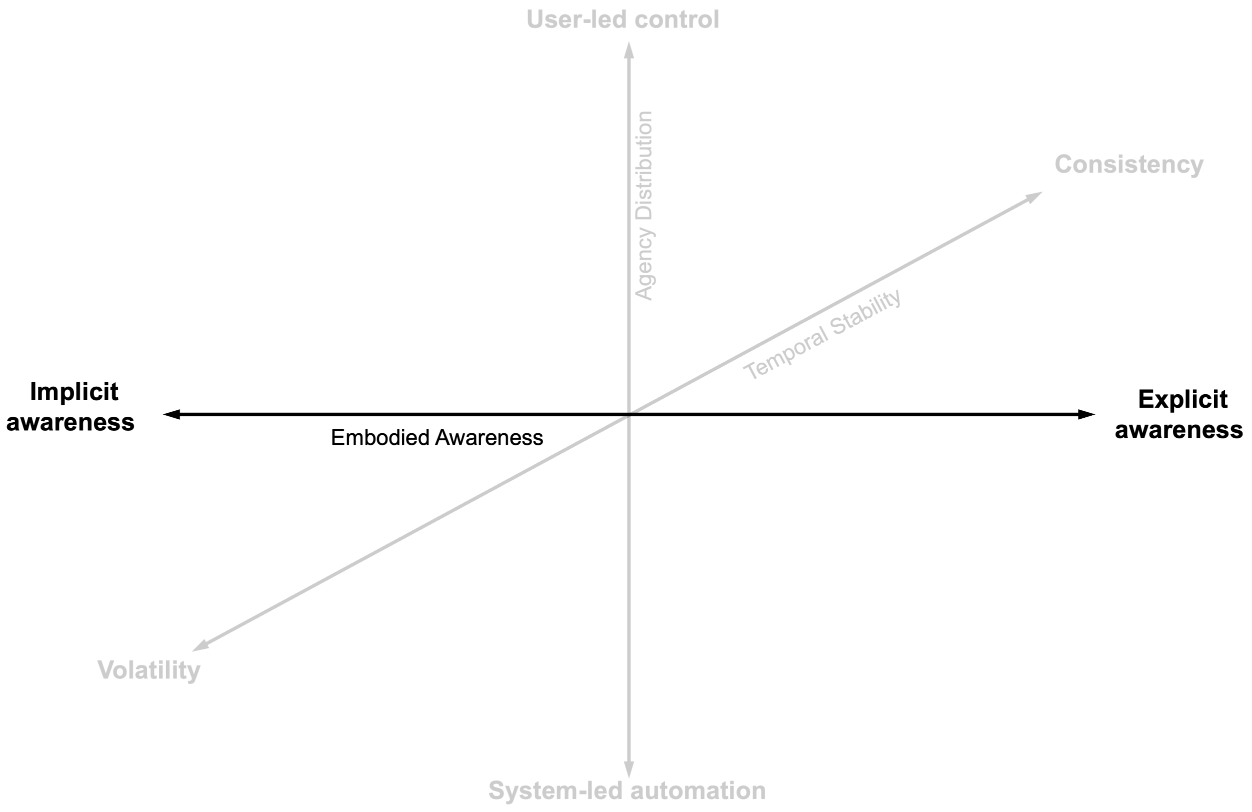


Figure 5.13: Second dimension of the superpower experiences framework: Embodied Awareness.

The EmoPals case study contributes to the framework by highlighting the role of awareness of superpower influence: I call it “embodied awareness of superpower” (Figure 5.13). EmoPals externalised users’ internal states through expressive behaviours in wearable devices. This externalisation creates a heightened awareness of the system’s influence, prompting users to reflect not only on their own mental states but also on how these states are being perceived and communicated to others.

The decision to include embodied awareness of superpower influence as a dimension of the framework is driven by the recognition that the superpower experience depends not only on the functionality of the system, but also on how visible and interpretable its influence is to the user. When users become consciously aware of being augmented, their relationship with the system may change. They may begin to question its accuracy, interpret its output as feedback, or even use it to manage how they are perceived by others. In such cases, heightened awareness does not reduce user engagement or control; rather, it can deepen the user's interaction with both the system and their own cognitive and emotional processes. Therefore, the EmoPals study suggests that the awareness of the influence of superpowers is critical to understanding how superpowers are experienced and integrated into everyday life.

5.7 Conclusion

In summary, the EmoPals study explored the internal dimension of augmentation, identifying embodied awareness of superpower as a critical factor in how users reflect on and integrate their cognitive states. However, the scope of human augmentation extends beyond perception and cognition; it also involves action and physical control of the human body. Consequently, the next chapter presents Flytrap Hand, a case study focused on augmented action, exploring the dynamics of shared agency and physical execution.

Chapter 6

Case Study 3: Flytrap Hand

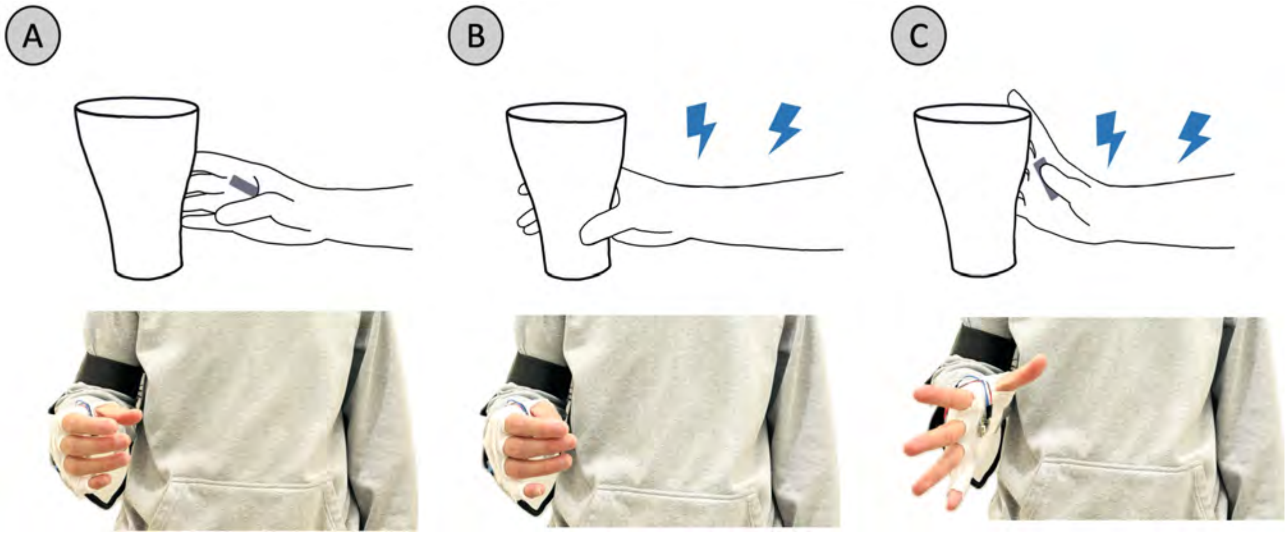


Figure 6.1: Flytrap Hand: when the user's hand approaches an object (a), the system triggers the user's fingers to contract and grasp the object with increased speed (b), the object is released when the user raises their little finger or after a random amount of time has passed (c).

This chapter details my third case study, which investigates superpower experiences aimed at exploring augmented actions through the design and deployment of "Flytrap Hand" (Figure 6.1). This system integrates distance sensing and EMS to extend human grasping capabilities, enabling faster and automated gripping when the hand approaches objects. By partially transferring hand control from the user to the system, the Flytrap Hand allows users to experience bodily actions that occur beyond their conscious intention, blurring the boundaries between voluntary and involuntary movement. Through this experience, the study examines how augmentation action can evoke both empowerment and discomfort, hesitation, and loss of control, revealing tensions between performance, agency, and trust in technologically augmented action.

6.1 Associated Publication

This chapter builds upon two publications: a video showcase paper highlighting the design of the system and a full paper detailing the findings of a study.

- Siyi Liu, Barrett Ens, Nathan Arthur Semertzidis, Gun A. Lee, Florian Mueller, and Don Samitha Elvitigala. 2025. Flytrap Hand: Towards Understanding Dark Patterns of Physical Augmentation via Electrical Muscle Stimulation. In Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA ’25). Association for Computing Machinery, New York, NY, USA, Article 913, 1–2. https://doi.org/10.1145/3706599.3721344. Video
- Siyi Liu, Barrett Ens, Gun A. Lee, Nathan Semertzidis, Florian Mueller, and Don Samitha Elvitigala. 2026. Towards Understanding The Design of (Un)Fortunate Superpowers Through A Flytrap-Inspired Hand Augmentation. In Twentieth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’26), March 08–11, 2026, Chicago, IL, USA. ACM, New York, NY, USA, 17 pages. https://doi.org/10.1145/3731459.3773299. Video

6.2 System Design

Flytrap Hand enables users to automatically grasp and release objects. This design allows exploring how augmenting human action through EMS can simultaneously empower users and introduce complex trade-offs around bodily control. This section details the design motivation, hardware components and interaction mechanisms.

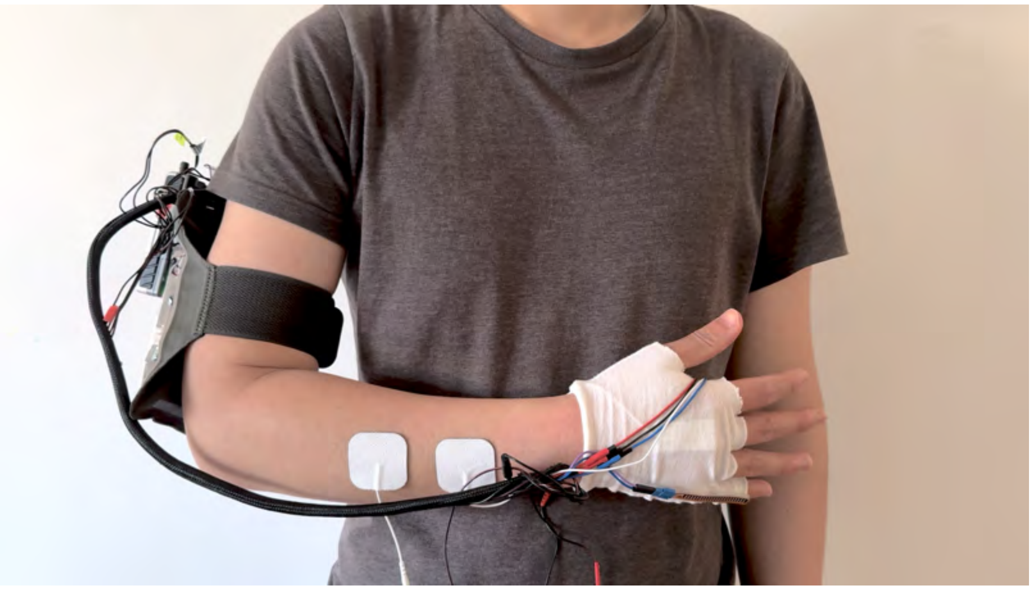


Figure 6.2: A participant wears the Flytrap Hand prototype.

6.2.1 Design motivation

The Flytrap Hand was designed to investigate how physical augmentation can simultaneously enable and constrain the user. Motivated by the Venus flytrap, a plant whose leaves automatically close when triggered (Forterre et al., 2005; Yang et al., 2010), I transformed this reactive mechanism into a wearable augmentation system that closes the user's hand when an object enters a predefined sensing range. By intentionally incorporating bodily automation and loss of control, the design treats discomfort and ambiguity as design materials (Benford et al., 2012) to question the assumption that "superpower" capabilities are inherently beneficial, prompting reflection on control and autonomy in augmentation experiences, following principles from critical and speculative design (Bardzell & Bardzell, 2013; Dunne & Raby, 2013).

6.2.2 Hardware components

The Flytrap Hand (Figure 6.3) consists of a glove embedded with a time-of-flight distance sensor (Adafruit Industries, 2024) and a flex sensor (SparkFun Electronics, 2024a), connected to a SparkFun RedBoard micro-controller (SparkFun Electronics, 2024b), controlling a dual-channel EMS device (The Clinical Source, 2024). The distance sensor detects the distance between objects and the hand, and the flex sensor measures the bending angle of the little finger.

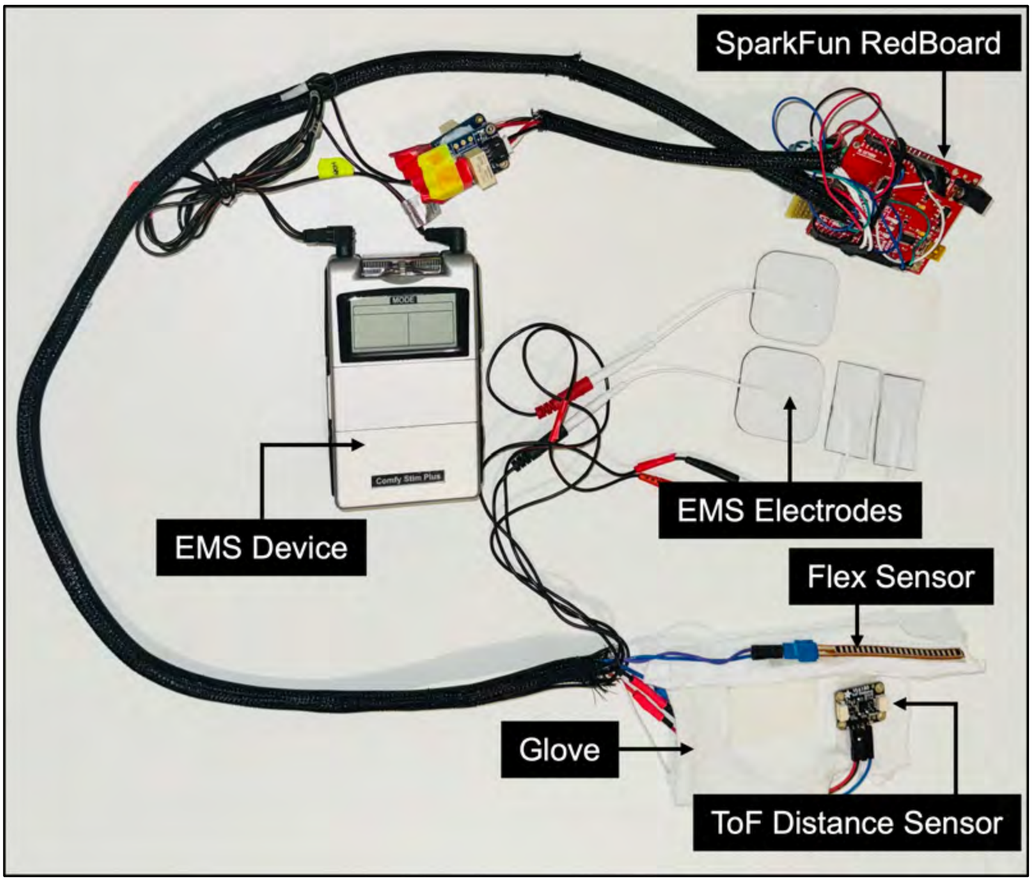


Figure 6.3: Flytrap Hand system.

Two rectangular EMS electrode pads (4cm x 2cm) are attached to the lumbrical muscles (palmar side) and dorsal interosseous muscle (dorsal side) between the second digit and third digit to flex fingers to generate a tripodal grasp gesture (Figure 6.4). Another two square EMS electrode pads (4cm x 4cm) are placed around the extensor carpi ulnaris and extensor digitorum muscles to stretch the wrist and fingers into an open-hand gesture. When the user's hand comes near an object but is not yet holding the object, the distance sensor detects proximity (typically within 4–8 cm, corresponding to the reachable space of the participant's fingers) and sends the signal to the micro-controller, which immediately triggers the EMS to activate the stimulation of the hand muscles so that the hand would automatically grasps the object. This reduces the delay (below 5 ms) between the user's intention to grip an object and the actual grip. A pilot study (N = 4, M = 28.00, SD = 5.48) demonstrated improved grip reaction times, with faster grip speeds (M = 140 ms) than without the system (180 ms), as measured by a slow-motion camera. Although the sample size was small, the pilot provided reliable mea-

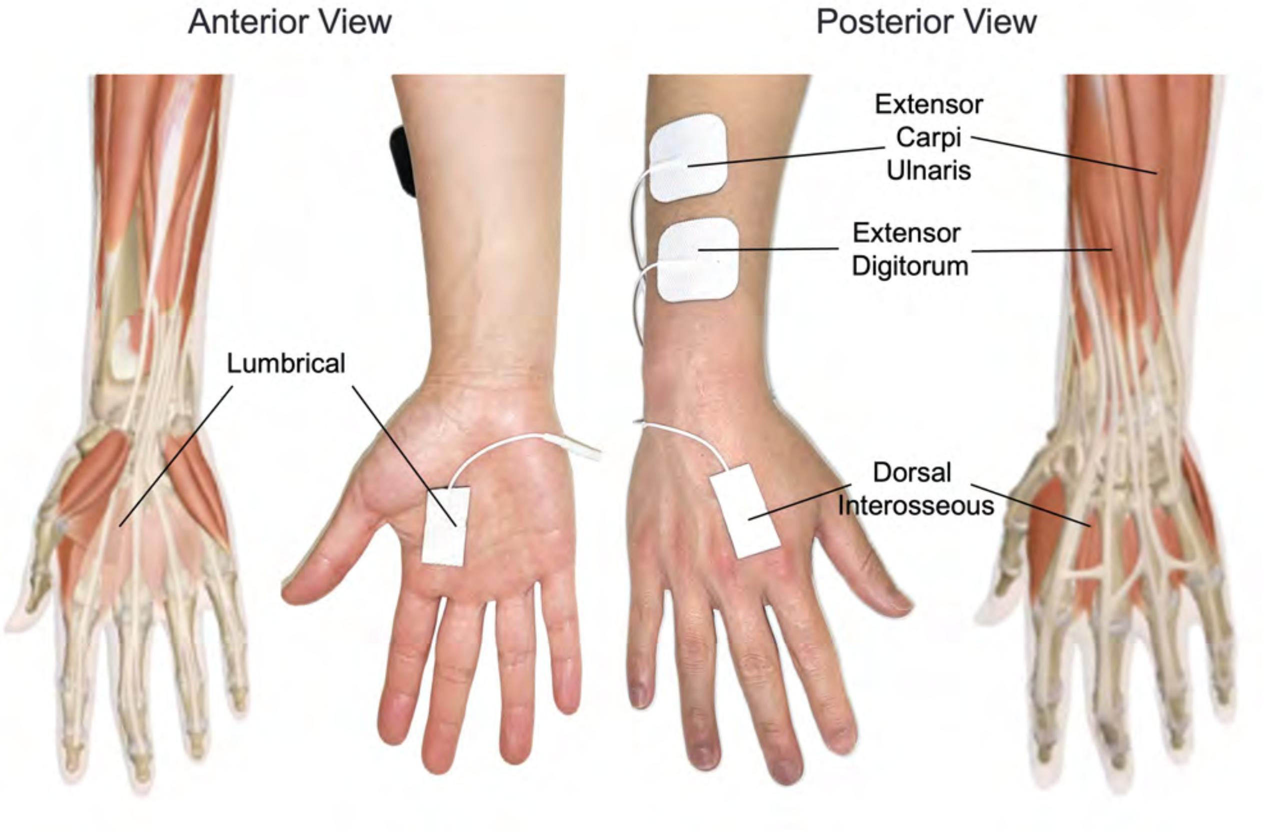


Figure 6.4: The placement of the EMS electrode pads.

surements of reaction dynamics primarily influenced by hardware and neuromuscular response. Despite minor individual variation, the consistent improvement in reaction times and minor delay established a stable temporal profile. These findings align with preemptive action research (Kasahara et al., 2019), ensuring the reliable temporal behaviour of the Flytrap Hand system.

6.2.3 Grasp gesture selection

A grasping gesture refers to the physical movement or positioning of the fingers and hand to hold or manipulate an object, which is a fundamental action in human-object interaction, relying on both the biomechanics of the hand and the sensory feedback received during the action (Cutkosky et al., 1989; Feix et al., 2009). In the Flytrap Hand prototype, a grasping gesture is controlled by EMS to induce specific hand movements. Selecting an appropriate grasping gesture is key to providing the user with a fast-grasping superpower that enables them to manipulate objects naturally at faster speeds, while accounting for the biomechanical limitations of the EMS.

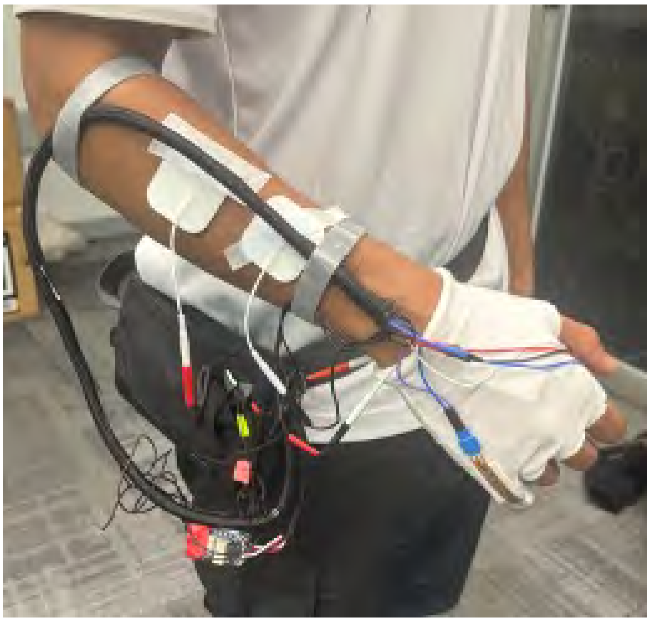


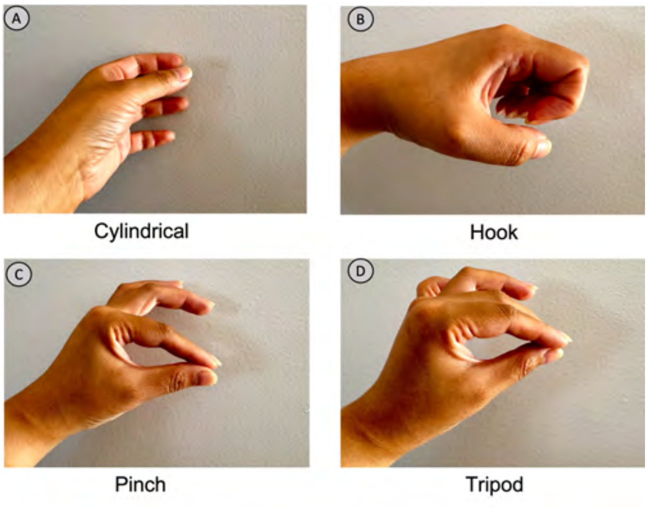
Figure 6.5: A person wearing the Flytrap Hand system in a pilot user study.

Grasp types can be broadly categorised into precision grasps (e.g., pinch grasp, tripod grasp) and power grasps (e.g., cylindrical grasp, hook grasp) (Cutkosky et al., 1989; Feix et al., 2009; Yang et al., 2015). Power grasps primarily engage large extrinsic muscles, making them easier to activate with EMS but less suitable for precise object manipulation (Nishida et al., 2017). Conversely, precision grasps rely on intrinsic hand muscles, enabling finer control for handling small objects. For the Flytrap Hand, I selected the tripodal grasp as the primary gesture after evaluating four grasp types (Figure 6.6). The tripodal grasp is characterised by the opposition of the thumb with the index and middle fingers. This grasp offers a balance between stability and dexterity, making it suitable for manipulating a variety of everyday objects while preserving a natural hand posture (Feix et al., 2015).

6.2.4 Releasing mechanisms

A key design challenge was enabling users to release their grasp reliably, as EMS can sustain muscle contraction indefinitely when active. I implemented two contrasting release mechanisms that embody different trade-offs between user agency and system automation.

The first mechanism I call “randomised time control”, where the system deactivates EMS on the hand and activates the EMS on the forearm to forcibly



Cylindrical
Hook
Pinch
Tripod

Figure 6.6: Types of grasp gestures considered and experimented with in this study.

release the grasped object after a randomly determined duration (which is determined by the task requirement). Users have no control over when the release occurs. This design deliberately reduces user agency to explore the emotional and cognitive effects of involuntary movement, simulating an adversarial superpower experience where the system overrides the user's bodily control. The unpredictable, involuntary release can cause discomfort, distrust, and a sense of bodily alienation, thus probing the "dark side" of augmentation and the unintended negative effects of superpowers.

I call the second mechanism "body control", where the system senses through the flex sensor if the user lifts their little finger, and turns off the EMS on the hand and turns on the EMS on the forearm, thereby forcing the palm to open. This design restores partial user agency by allowing the release to be initiated by the user's action, yet it introduces an unfamiliar gesture that may require a learning curve. This mechanism shifts the challenge toward motor adaptation and cognitive load, offering a contrasting lens on the trade-offs between agency, usability, and bodily comfort.

6.3 Study

I conducted a within-subjects, counter-balanced mixed-method study to understand the user experience across three conditions:

- Randomised Time Control: Grasping and release occur at randomised intervals.

- Body Control: Grasping is triggered when participants perform a specific gesture (lifting the little finger).
- Baseline: No EMS stimulation where the system remains turned off during both the grasping and releasing actions.

6.3.1 Participants

Twelve participants (5 men, 6 women, 1 non-binary and none self-described) were recruited, aged between 18 and 45 years (M = 25.67, SD = 7.70). Participants were recruited through advertisements on my lab's mailing list and social media accounts. Participants were screened to exclude any history of muscle disorders, prior injuries affecting the upper limb, or negative experiences with EMS to prevent confounding effects. Four participants had used EMS before. Nine participants were right-handed.

6.3.2 Tasks

Participants performed each task twice in each condition. The first task was an object relocation task (Figure 6.7a). This task simulates everyday object manipulation to explore how the system's automatic grasping influences user control. Participants were asked to relocate eight everyday objects, including pens, plastic containers, boxing gloves, sponges, paper cups, squeeze balls, charging cables, and tissue boxes, between designated points on a table and the floor, three meters away, as quickly as possible. These objects were chosen to represent a range of common shapes and grasp challenges, enhancing ecological validity. Participants could choose their own order, reflecting natural prioritisation strategies. The time taken and accuracy of the relocation were recorded. Accuracy was measured by counting the number of times an object was placed in a marked location without being dropped in the process.

To further probe the tension between augmentation and user agency under cognitive load, participants also performed a dual-task (Figure 6.7b). This combined a cognitive task with a movement task. The cognitive task, taken from prior work, was the *n-back task*, which is commonly used to measure

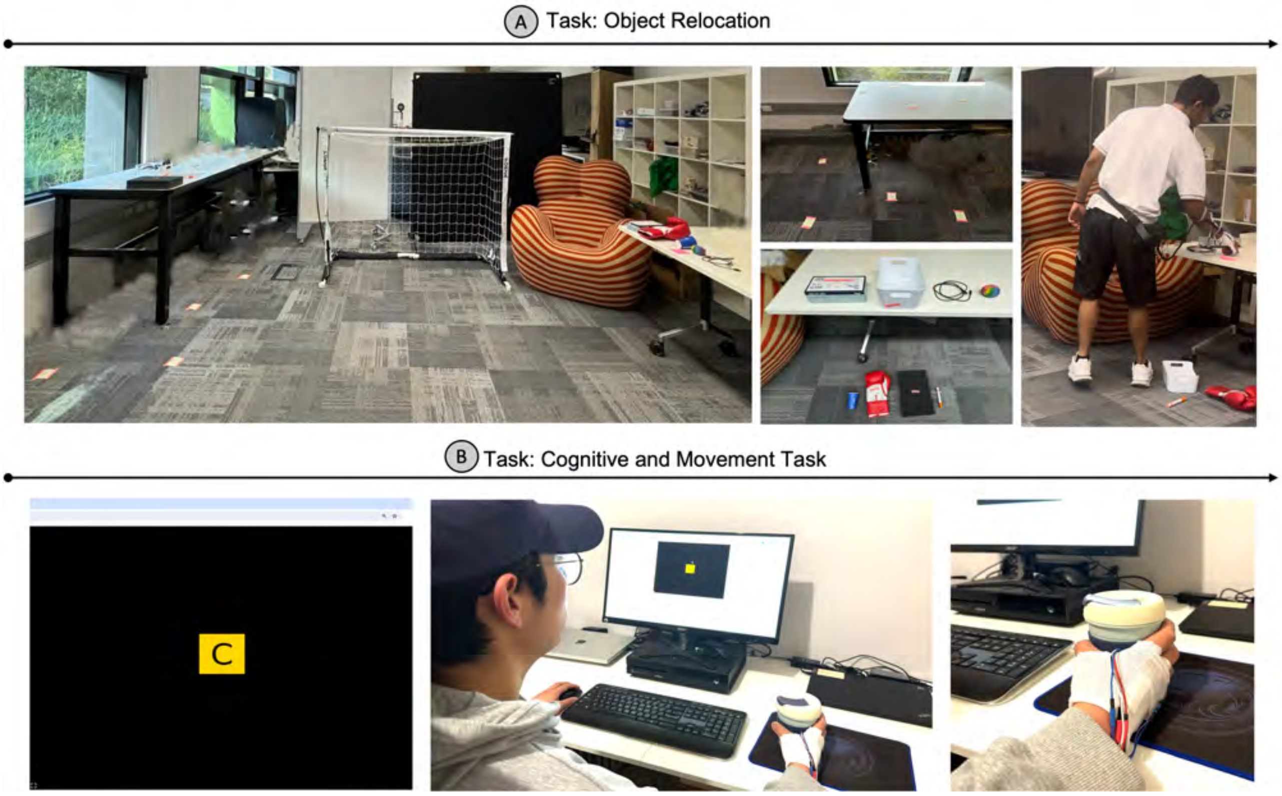


Figure 6.7: The process of tasks for each condition and results of task performance. A: object relocation task; B: cognitive and movement task simultaneously.

working memory (Jaeggi et al., 2010; Kane et al., 2007; Miller et al., 2009). The participant was presented with a sequence of letters on a screen (randomly chosen from A, B, C, D, E, H, I, K) one by one, and they needed to click the mouse if the current letter was the same as two letters ago (left of Figure 6.7b). A total of 25 letters were presented for 760 ms each at 2000 ms intervals. The movement task was a repetitive object manipulation task often used to analyse cognitive load under split attention (Longo et al., 2018; Nith et al., 2024). The participant was asked to pick up and put down a plastic coffee cup with an audio cue at 10-second intervals played over a speaker (right of Figure 6.7b), simulating repetitive manual tasks like clearing a table or packing a bag. This dual-task is designed to capture how augmented control interacts with attention and coordination by simulating real-world challenges such as managing devices or tools while thinking or conversing. The accuracy of the n-back task (proportion of letters clicked correctly) and the error rate of the movement task (proportion of times the participant missed or forgot to grasp or release the coffee cup) were recorded.

This design balances ecological relevance (everyday objects, real-world multitasking) with experimental control, allowing for systematic analysis of how superpower grasping affects agency and task performance.

6.3.3 Procedure

After signing a consent form, participants were introduced to the system. I then helped participants attach the electrodes to the dominant hand and forearm. I prepared a pair of gloves to fit both hands. Calibration for EMS was performed for each pair of electrodes. Participants were guided to slowly increase the intensity of the stimulus until the desired intensity was reached to observe hand movement. A constant EMS with a pulse width of $200\,\mu s$ and a pulse rate of $100\,Hz$ was adopted based on repeated pilot testing. Next, I assisted participants in putting on and calibrating the distance sensor and flex sensor. This calibration ensured that the tripod grasping gesture was triggered within the reach of the participant's finger in order to grasp the object at the appropriate time. Additionally, participants were asked to move their little fingers to calibrate the flex sensor so they could open their hands and release objects. Participants were given at least three minutes to familiarise themselves with the system. In the randomised time control condition, each grasp lasted 300–700 ms, with releases occurring at randomised intervals. In contrast, in the body control condition, grasp onset was contingent on the participant lifting the little finger. Stimulation intensity was controlled by the participants themselves, allowing them to stop EMS at any time to prevent prolonged stimulation or accidental grasps. Participant-specific offsets were calibrated to account for individual differences in hand size and muscle activation thresholds, ensuring consistent stimulation intensity and timing accuracy across participants.

Participants performed two tasks, each twice, under three conditions in a counterbalanced order to reduce order effects. At the end of each condition, I administered the "Sense of Agency Scale" (Hurault et al., 2020; Tapal et al., 2017), the "Sense of Bodily Ownership Questionnaire" (Grechuta et al., 2019) and the "Unweighted NASA-TLX Questionnaire" (Hart, 2006; Hart, 1988). Afterwards, participants were asked to fill out the overall preferences questionnaire. I then conducted a semi-structured interview (Adams, 2015; Kallio et al., 2016) that lasted approximately 30 minutes. The interview included 14 questions about participants' interactions with the system, potential physical and psychological effects, and their reflections on control, agency, and overall perceptions of each release mode. For example, participants were asked: "How did each of the two modes make you feel?", "Did you experience any discomfort or loss of control?", and "In what situations, if any, would you find such a system useful?"

6.4 Findings

I used a repeated-measures analysis of variance (RM ANOVA) to analyse normally distributed data, with generalised eta-squared as effect sizes. A paired t-test was conducted as a post-hoc analysis to identify significant differences. I used a Friedman test to analyse questionnaire data and non-normally distributed data in a within-subjects design. A paired Wilcoxon signed-rank test was used for the post hoc analysis. To address multiple pairwise comparisons, the significance threshold for both parametric and non-parametric tests was adjusted using the Bonferroni correction (Armstrong, 2014). Qualitative interview data were audio-recorded and transcribed for qualitative analysis. Reflexive thematic analysis (Braun & Clarke, 2006, 2019a) was used to analyse the interview data and identify themes by distilling and articulating meaning from the data.

6.4.1 Task performance

Figure 6.8 shows the performance data of the relocation task. An RM ANOVA on task completion time (TCT) revealed a significant difference (F(2, 22) = 13.55, p < 0.001, η^2_G = 0.355). Post-hoc Bonferroni-corrected t-tests (Armstrong, 2014) revealed that the baseline (M = 53.30s, SD = 6.34) was significantly faster than randomised time control (M = 72.10s, SD = 16.70, p < 0.05) and body control (M = 72.30s, SD = 12.30, p <0.01). However, there was no significant difference between the randomised time control and body control. For object placement accuracy, a Friedman test found no significant differences (W = 0.05, $\chi^2(2, N = 36)$ = 3.16, p = 0.21) across the randomised time control (M = 95.83%, SD = 3.08), body control (M = 96.88%, SD = 4.21) and the baseline (M = 98.43%, SD = 2.83).

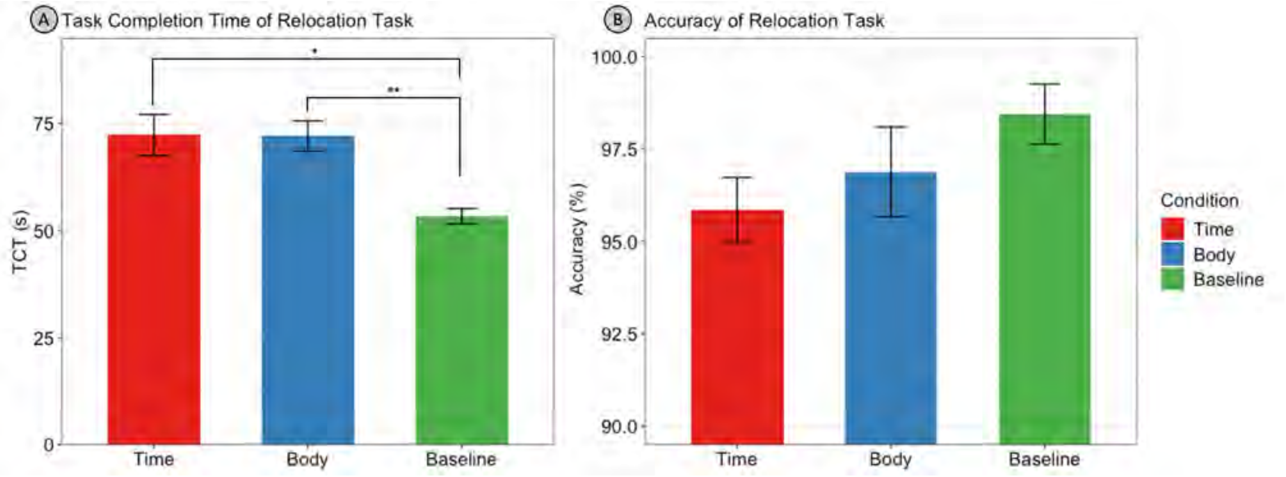


Figure 6.8: Results of participants' performance for the relocation task, including (a) task completion time and (b) accuracy (Error bars: one standard error of the mean/ $*$: p <= 0.05 / $**$: p <= 0.01).

Figure 6.9 shows the performance data of the dual (cognitive and movement) task. I measured movement task error rates using a Friedman test, which revealed a significant difference ($\chi^2(2, N = 36)$ = 7.48, p = 0.024, W = 0.11). Post-hoc Bonferroni-corrected pairwise Wilcoxon signed rank test showed a significant difference (W = 4.5, p = 0.007) between the baseline (M = 21.53%, SD = 9.70) and randomised time control (M = 13.19%, SD = 10.33), but no significant difference was found for body control (M = 18.75%, SD = 11.85). Cognitive task accuracy, analysed via RM ANOVA, showed no significant differences (F(2, 22) = 1.85, p = 0.18, η^2_G = 0.027) across the randomised time control (M = 46.79%, SD = 31.94), body control (M = 37.42%, SD = 29.86) and the baseline (M = 48.75%, SD = 31.39).

6.4.2 Sense of agency

I measured the sense of agency using the 7-point Likert scale Sense of Agency Scale (SoAS) (Tapal et al., 2017), comprising Sense of Positive Agency (SoPA) and Sense of Negative Agency (SoNA) factors (Figure 6.10). Higher SoPA indicates stronger body control, while higher SoNA reflects greater helplessness. A Friedman test revealed significant differences in overall SoA ($\chi^2(2, N = 36)$ = 17.17, p = 0.0002, W = 0.26). Post-hoc Wilcoxon signed rank tests revealed that the baseline (M = 77.00, SD = 12.01) was significantly different from randomized time control (W = 0, p = 0.008, M = 43.50, SD = 9.31) and body control (W = 1, p = 0.009, M = 51.50,

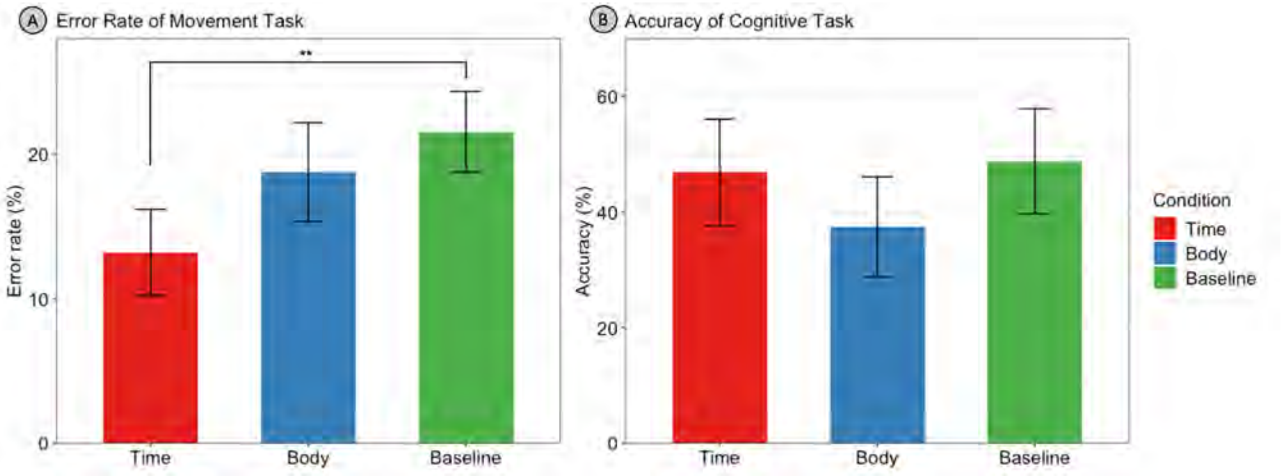


Figure 6.9: Results of participants' performance for the dual task, including (a) error rate of the movement task and (b) accuracy of the cognitive task (Error bars: one standard error of the mean / $**$: p <= 0.01).

SD = 7.83). Similar results were observed for SoPA ($\chi^2(2, N = 36)$ = 18.67, p = 0.00008, W = 0.28) and SoNA ($\chi^2(2, N = 36)$ = 14.91, p = 0.0006, W = 0.23), with both time (SoPA: W = 0, p = 0.008, M = 21.08, SD = 6.49; SoNA: W = 4.5, p = 0.012, M = 16.42, SD = 9.29) and body control (SoPA: W = 0, p = 0.008, M = 24.00, SD = 6.34; SoNA: W = 4.5, p = 0.023, M = 28.50, SD = 6.11) conditions showing significantly lower SoPA and higher SoNA compared to the baseline (SoPA: M = 37.42, SD = 5.55; SoNA: M = 16.42, SD = 9.29).

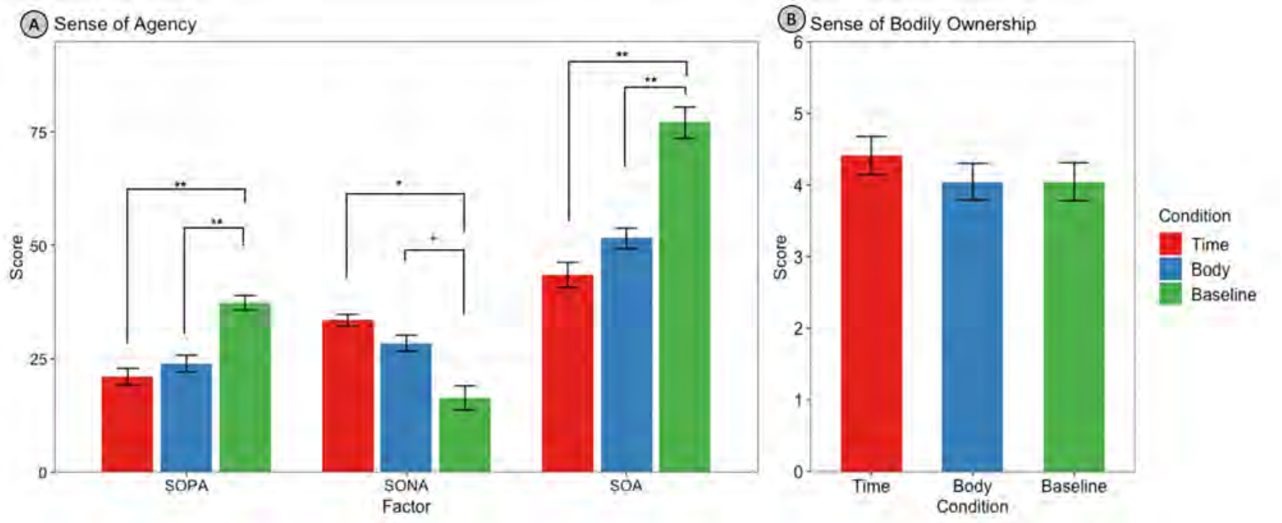


Figure 6.10: Results of participants' responses to (a) sense of agency and (b) sense of bodily ownership questions (Error bars: one standard error of the mean / $*$: p <= 0.05 / $**$: p <= 0.01).

6.4.3 Workload

The NASA-TLX Questionnaire results showed no significant difference in overall workload across conditions (Figure 6.11). However, the *frustration-level* was significantly different ($\chi^2(2, N = 36)$ = 6.69, p = 0.03, W = 0.10) across three conditions. A Post-hoc analysis showed a significant increase (W = 52, p = 0.013) in randomised time control (M = 48.30, SD = 23.30) compared to the baseline (M = 27.90, SD = 24.10).

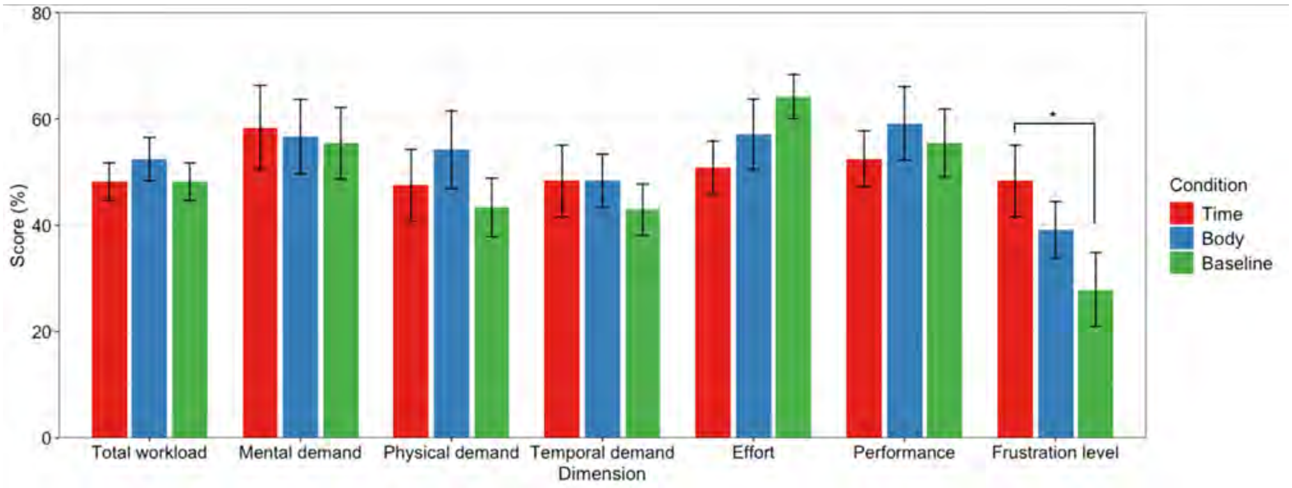


Figure 6.11: The NASA Task Load Index score for each condition (Error bars: one standard error of the mean / $*$: p <= 0.05).

6.4.4 Sense of ownership

The “Sense of Bodily Ownership Questionnaire” was revised based on Grechuta et al. (2019) with an ordinal 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). I calculated the average score and conducted a Friedman test (Figure 6.10). The test did not reveal a statistically significant difference ($\chi^2(2, N = 36)$ = 3.27, p = 0.20, W = 0.06) between the randomized time control (M = 4.05, SD = 0.85), body control (M = 4.41, SD = 0.89) and the baseline (M = 4.05, SD = 0.88).

6.4.5 User preferences

Two-thirds of participants (N = 8) preferred body control over randomised time control. Overall system performance was considered satisfactory. Seven participants rated their overall experience as positive, while three remained neutral. Six participants reported that they believed the system improved their reaction time. Eleven participants expressed appreciation for the system's ability to automatically grasp and securely hold objects, indicating general satisfaction with its functionality.

6.4.6 Interviews

The analysis identified three themes that demonstrate the complexities of experiencing a superpower with Flytrap Hand: (1) perceived benefits and challenges of superpower, (2) changes in agency and system acceptance, and (3) psychological and behavioural adaptations. Participant quotes are labelled according to the coding scheme. "Qx.y" denotes the y-th illustrative quote under Theme x (e.g., Q1.1 is the first quote under Theme 1). Each quote is further labelled with the participant ID and condition: P# (R/B), where R indicates randomised time control and B indicates body control.

6.4.6.1 Theme 1: Perceived benefits and challenges of superpower

Flytrap Hand introduced a complex mix of benefits and challenges, with participants appreciating the efficiency and reduced physical exertion, while they also experienced difficulties in task execution, control, and adaptability.

Experiencing the superpower of increased speed: While the Flytrap Hand system did not consistently boost raw task performance, users reported qualitative improvements such as feeling faster and more confident, and perceiving tasks as easier to execute. These subjective experiences illustrate that superpower experiences encompass more than measurable outcomes, including cognitive and perceptual enhancements. Eight participants reported experiencing a superpower with the system. P6 (R) said: *"It felt like something out of a sci-fi movie. It made my hands close and open on their own. It was crazy. I felt like I had superpowers"* (Q1.1). One of the most often reported benefits of Flytrap Hand was the speed enhancement in object interaction. Many participants found that Flytrap Hand enabled them to grasp objects more quickly than they would manually, allowing them to act with greater efficiency. P2 (R) shared: *"It helped me pick up objects quicker than I usually would"* (Q1.2). This ability to automatically initiate a grip as soon as an object was detected reduced the need for conscious decision-making, which some participants perceived as *"saving them time"*(P4 (B), Q1.3). For example, P1 (R) reflected:*"For grabbing things in a hurry, it worked very well"* (Q1.4). Participants highlighted that this enhanced speed could be particularly beneficial for sports or activities requiring quick reflexes, such as catching or dribbling a ball. P8 (B) noted: *"I think it's very useful in sports if you need to catch or grab something quickly"*(Q1.5). This quick response could also be seen as a benefit in unexpected situations, such as reacting to falling objects or intercepting moving objects. P11 (R) described: *"This system helped me react quicker, perhaps allowing me to pick up the dropped item directly"* (Q1.6).

Reducing physical exertion: Participants appreciated being able to grasp objects without fully engaging their hand muscles, which they found helpful in scenarios involving repetitive grasping. For example, P3 (R) said: *"The system made gripping objects very easy, and I didn't have to think about it, which was great"* (Q1.7). Five participants *"felt relieved"* (P4 (B), Q1.8) by this reduction in effort. Furthermore, by minimising the need for fine motor control, participants could focus on other aspects of the task. For example, P5 (R) stated: *"When I was doing the dual task [cognitive and movement together], I could focus more on the task of memorising the letters"* (Q1.9). In addition, seven participants suggested that such a system might be useful for people with limited hand strength or conditions such as arthritis, as it could assist with grasping. For example, P10 (B) speculated: *"I thought it would help people with weak hands. It does the grasping for you, which is very helpful for people with diseases that affect hand function, and it can even help practice grasping"* (Q1.10).

Complicating task execution: Participants reported that the system's automation also introduced new difficulties in task execution. Five participants reported that while the system sped up the grasping process, it sometimes acted prematurely, leading to disruptions. For example, P7 (R) said: *"Sometimes it grabbed too early [...] so I had to adjust my hand gesture later"* (Q1.11). Seven participants noted that unintended grasping could lead to dropped objects and excessive force, which required additional effort to compensate for these errors. P5 (R) described this experience: *"I had to deal with items falling out or waiting for the hand to open, which slowed things down"* (Q1.12). For some participants, these disruptions outweighed the anticipated efficiency gains, as they had to spend more time correcting unintended actions, which led to a longer task completion time and complicated the task. For example, P9 (B) said: *"The hand action was fast, but if it reacted at the wrong time, it actually made things harder instead of easier"* (Q1.13).

6.4.6.2 Theme 2: Changes in agency and system acceptance

Flytrap Hand introduced an unconventional form of control that may lead to an unexpected misalignment between thought and action, thus challenging the user's sense of agency and affecting their overall acceptance of and trust in the system.

Feeling of external control over actions: Two-thirds of participants expressed discomfort with the system acting beyond their control. This feeling arose because the system automatically activated grasping based on proximity sensing rather than conscious active engagement. Five participants described this as a loss of control or forced control by the system, as their hands moved without their explicit authorisation. P12 (R) reflected: *"It wasn't me making the decision to grab. It just happened"* (Q2.1). Furthermore, the EMS-driven automation could trigger actions before users consciously decide to act, leading to a sense of cognitive lag. For example, P6 (B) described: *"My brain was still thinking [...] but my hand had already started closing around it"* (Q2.2). This phenomenon of external control had mixed effects. Some participants felt that it facilitated quick responses, while others expressed unease about the loss of bodily control. P3 (R) noted: *"I wasn't sure whether it was me controlling my hand or if the system was acting on its own"* (Q2.3). It appeared that this effect could lead users to perceive themselves as passive observers rather than active agents in their own actions.

Conflict between intentions and actions: Participants also experienced moments where their intentions and the system's actions were misaligned, even within the same condition. Three participants described a cognitive disconnect in which the system initiated action before they fully formulated their intentions, thus disrupting their action-perception loop, rather than simply feeling like the system was taking over in the body control condition. P5 (B) explained: *"Even if sometimes I know I want to pick something up,* *my thoughts are interrupted when my hands move faster than my brain commands"* (Q2.4). This misalignment also led to hesitation in performing tasks. Some participants reported a newfound uncertainty in their interactions with objects, as they were unsure when the system would engage in the randomised time condition. P9 (R) reflected: *"I had to pause before reaching for things because I wasn't sure if the system would start at the right moment"* (Q2.5). This hesitation was not only a reaction to external control but an adjustment strategy where users had to actively change their actions to cope with the system. Furthermore, three participants reported that once they became familiar with the system, they could *"anticipate the system activation"* (P7 (B), Q2.6) and adjust their hands accordingly. For example, P2 (R) said: *"After a few rounds, I started to time my movements to match the system's stimulation, and it felt more natural"* (Q2.7).

Fluctuating trust in the system: Participants reported that their trust in the system fluctuated depending on predictability. Unpredictable actions, such as grasping or failing to release objects at unintended moments, caused four participants to doubt whether they could trust the system. P4 (B) illustrated this trust difference by contrasting different control mechanisms: *"In the body control mechanism, I can control the release action with my finger, which is predictable, so I have relatively more trust in the system compared to the randomised time control mechanism"* (Q2.8). For some participants, the system's inconsistency was an occasional inconvenience, while for others, it fundamentally influenced their willingness to engage with the system. For instance, P1 (B) remarked: *"The system is impressive, but I would not fully trust it and rely on it in everyday life"* (Q2.9). P9 (R) expressed frustration over its unpredictability: *"If you're trying to get something done, you'll get frustrated with how it sometimes messes up"* (Q2.10). Despite these concerns, not all participants considered unpredictability as inherently negative. For example, P5 (R) found it a novel and playful experience: *"It felt like a game sometimes. I need to figure out when it would grip and when it would release. It wasn't always bad, just different"* (Q2.11).

6.4.6.3 Theme 3: Psychological and behavioural adaptations

The Flytrap Hand prototype influenced not only how participants performed tasks but also how they adjusted their behaviours, perceived their own actions, and considered the long-term consequences of augmentation.

Experiencing mixed emotions from excitement to anxiety: Participants reported a wide range of emotions, from excitement to stress and anxiety. Despite initial fears, participants found the Flytrap Hand's automated actions to be novel and entertaining once they became *"accustomed to the system"* (P8 (B), Q3.1). The experience was *"intuitive"* (P2 (B), Q3.2) and made them feel less uncomfortable after becoming familiar. In particular, participants with prior EMS experience adapted more smoothly and confidently. However, participants also mentioned that they felt anxiety when they realised that the release of the system was unpredictable. P1 (R) expressed it like this: *"I felt like I'm always preparing for my hand movements. It makes me nervous because I didn't know exactly when it would start"* (Q3.3). Furthermore, four participants reported feeling tired at the end of the relocation task as they had been focusing on the system and their own gestures, resulting in negative emotions such as *"overload"* (P10 (R), Q3.4), *"stressful"* (P3 (B), Q3.5) and *"exhausting"* (P11 (B), Q3.6).

Concerns about dependency and loss of bodily ability: While participants enjoyed the benefits of rapid grasping, they also raised concerns about potential reliance on augmentation: They asked whether any long-term use might reduce their innate reflexes over time or weaken their hand's function to perform tasks without technology. For example, P7 (R) expressed: *"If I use this all the time, will my brain stop sending those signals as quickly? Will my reaction speed decrease?"* (Q3.7) Some participants assumed that their bodies might quickly adapt to the change and become dependent on the system. P6 (B) explained: *"I noticed that after using it for a while, I started expecting my hand to move automatically"* (Q3.8). In addition, rapid grasping can also lead to hesitation in hand movements as it might conflict with participants' intentions. P9 (B) reflected: *"I felt hesitant because I didn't know if I should let the system do it or if I should take control"* (Q3.9).

Context-dependent acceptance: Participants reported that their acceptance of their superpower was highly related to the environment. Some participants valued faster hand movements in task-oriented scenarios, while some participants reported that they felt distracted or unnecessary to use this ability in their daily activities. P12 (B) described a moment of frustration: *"I do feel like it's a superpower, but I don't think it would be useful in my daily life. I still want to do things in a natural way rather than using devices to speed things up"* (Q3.10). Our participants suggested that many daily activities require deliberate and controlled hand movements, while sudden and rapid grasping may feel unnatural and sometimes seem awkward in social situations. P5 (R) described worries in public: *"If I use it in front of other people, I would worry about the impact on others, whether it would scare them, whether I was overreacting"* (Q3.11). As a result, some participants preferred context-sensitive control, allowing them to selectively activate the augmentation rather than have it automatically work in all situations. P4 (B) suggested: *"I want to turn this on only when I actually need it. In everyday life, I don't think I want my hand to move faster than normal"* (Q3.12).

6.5 Discussion

This section discusses the findings in relation to prior work, especially regarding how the physical augmentation led to superpower experiences but also revealed insights into negative side effects that significantly influenced user experience, including aspects such as agency, task efficiency, and emotional response. By integrating the quantitative and qualitative findings, I am able to reveal complex trade-offs between performance enhancement and reduced control at play.

6.5.1 Balancing performance gains and cognitive costs

The results reveal a trade-off between speed-oriented performance gains and the cognitive costs of reduced agency. Quantitative analysis showed that participants' Sense of Agency (SoAS) scores were significantly lower when using the Flytrap Hand, consistent across both Randomised Time Control and Body Control modes. This reduction aligns with prior HCI research on body-actuated interfaces, where automation can diminish the user's perception of being the author of their actions (Knibbe et al., 2018a; Patibanda et al., 2021, 2022). The thematic analysis supported these findings, where participants described the system as "acting before my brain decided" (Q2.2) and "taking over" (Q2.1), which at times created frustration and hesitation. While such automation improved grasping speed (Q1.2, Q1.5) and reduced physical effort (Q1.7), it also disrupted the alignment between intentions, motor commands, and sensory feedback (Pacherie, 2008), increasing cognitive load and adversely affecting engagement (Q1.11, Q1.12, Q2.4, Q2.5). Although Flytrap Hand reduced certain task errors, it inadvertently led to a feeling of reduced personal control, highlighting the central challenge of balancing automation with agency in superpower experiences.

Mueller et al. (2020a) describe such interaction as a mix of *fusion* and *symbiosis*. *Fusion* occurs when human and machine functions blend seamlessly so that the technology feels like an extension of the self. *Symbiosis* preserves a distinction between user and system so that agency can be shared between them. The results suggest that Flytrap Hand leans toward *fusion*, with users feeling that the system sometimes overrode voluntary action (Q2.1, Q2.2). While this could enhance performance efficiency (Q1.2, Q1.3, Q1.4), it also contributed to frustration when unexpected activations occurred (Q1.11, Q1.12, Q1.13). In contrast to traditional assistive devices that typically function as tools, the Flytrap Hand appeared to actively modulate users' actions, potentially blurring the boundary between assistance and control (Q2.5, Q2.6), contributing to a sense of cognitive ambiguity (Q2.3).

This blending of human and system action sometimes produced a misalignment between user intentions and technological assistance, reflected in higher NASA TLX frustration scores. Such misalignment can generate cognitive dissonance, a psychological state in which one's actions diverge from internal expectations (Pacherie, 2008). Involuntary movements that occurred without conscious initiation can further create discrepancies between intention and sensory feedback (Q2.4, Q2.5), leading to confusion about action ownership, as well as hesitation and resistance in initiating actions.

Importantly, participants' experiences within the same condition were not uniform. Several reported alternating moments in which the system's activation felt aligned with their intention to grasp, creating a sense of fluent coordination, followed by episodes when the stimulation preceded or lagged their intended movement, producing discomfort and loss of control (Q2.2, Q2.4). This indicates that the subjective user experience was also influenced by the temporal alignment between system response and motor intention, which has been examined in preemptive action research (Kasahara et al., 2019). These findings suggest that agency in superpower experience also depends on the dynamic coupling between human motor planning and technological actuation, rather than on static condition parameters alone.

In summary, this study extends previous theories by demonstrating that while automation can bring performance gains, it also introduces complex cognitive and experiential trade-offs. These findings raise questions about how superpower augmentation reshapes users' perceptions of agency and emphasise the need for future research to explore ways to engage with this, such as adaptive strategies that could mediate the benefits of superpower experiences while preserving user agency. Such trade-offs invite further ethical examination of the boundaries of shared control, especially when user intentions are partially overridden.

6.5.2 Ethics of shared and ambiguous agency

Interviews revealed that perceptions of reduced agency were neither static nor absolute. Participants described moments where the system's automated action felt seamlessly aligned with their intentions (Q2.7) and others where control was abruptly lost (Q2.1, Q2.3). This fluctuation created a "grey zone" of shared control (Clark, 2010; De Vignemont & Fourneret, 2004; Ihde, 2002; Limerick et al., 2014) in which user and system jointly shaped actions, challenging traditional clear distinctions between self and other, voluntary and involuntary action (Gallagher, 2000; Jeannerod, 2003; Synofzik et al., 2008a). Such ambiguity complicated responsibility attribution, particularly when the system autonomously acted on behalf of the user and the outcomes diverged from intentions (Q2.3, Q2.5, Q2.9), raising questions over whether the user, the designer, or the system bears responsibility (De Graaf, 2016; Etemad-Sajadi et al., 2022; Ostrowski et al., 2022).

This finding also suggests that ambiguity can be intentionally crafted to shape these experiences. The randomised time control mechanism introduced unpredictability in the release timing, which some participants experienced as engaging and playful (Q2.11) and others as discomforting and frustrating (Q2.1, Q2.3, Q3.9). This aligns with the concept of ambiguity as a design resource proposed by Gaver et al. (2012, 2003). With the Flytrap Hand, the ambiguity was primarily informational (Hallnäs & Redström, 2001), where users received inconsistent cues for when an object would be released, compelling them to interpret the system's behaviour and reconsider their relationship with it. By embracing these forms of ambiguity, augmentation systems might engage users more deeply and turn discomfort or uncertainty into catalysts for reflection, prompting users to confront and reflect on their ethical perceptions about physical augmentation, including agency and capability (Boehner et al., 2008).

From the proportionality ethics perspective (Brey, 2012; Vallor, 2016; Verbeek, 2011), I believe that the ethical question is not whether negative effects should be eliminated, but whether they remain within acceptable limits relative to their reflective value. This study's results seem to point to three ethical evaluation criteria, which can be seen as a starting point for future investigations. Firstly, system actions should align with user intentions frequently enough to preserve trust and autonomy. Secondly, discomfort must remain proportionate, reversible, and within safe physical and psychological limits. Thirdly, reflective value should outweigh potential long-term risks such as dependency. These ethical criteria could provide a foundation for understanding (un)fortunate superpowers.

6.5.3 Contrast between enhancing inherent and introducing new abilities

Superpower experiences can either enhance inherent human abilities, such as with Flytrap Hand and SpiderVision (Fan et al., 2014), or introduce entirely new ones, such as Wi-Fi Twinge and VibraHand (Kim et al., 2024) showed. By contrasting their positive and negative effects, I can begin to understand how each type uniquely impacts the user experience. Flytrap Hand enhanced inherent grasping ability; however, participants expressed concern that continuous reliance on the Flytrap Hand's grasping might lead to a gradual deterioration of their natural reflexes and motor control (Q3.7, Q3.8, Q3.9). These risks are particularly salient when amplifying a user's inherent ability, as it may erode natural motor skills over time. In contrast, VibraHand introduced a novel sensory ability without threatening existing skills. While it could trigger confusion or negative emotion, study participants focused on integrating it into daily life, considering it as a beneficial augmentation that complements their natural senses rather than replacing them.

These contrasts suggest that design priorities differ by superpower type. Inherent-ability enhancements might benefit from safeguards against dependency and loss of agency, while new-ability designs could prioritise adaptation and comfort. Recognising these differences might strengthen the understanding of user experiences in superpower design.

6.5.4 Trust, dependency, and long-term use

Participants expressed concerns that prolonged use of Flytrap Hand might lead to dependency (Q3.7, Q3.8). This concern is consistent with previous findings that trust in automated systems is dynamic and context-dependent (De Visser et al., 2018; Lee & See, 2004; Parasuraman et al., 2000). Trust develops through repeated interactions and perceptions of system performance (Lee & See, 2004), and the results suggest that trust is also influenced by the user's experiences and familiarity with the technology. For example, participants with prior EMS experience expressed confidence and adapted more smoothly to the system.

Perceived reliability and predictability were central to maintaining trust (Gulati et al., 2024; Hoff & Bashir, 2015; Wischnewski et al., 2023). Inconsistent automation, such as unexpected grasp or release, reduced willingness to rely on the system (Q2.9, Q2.10), while consistent performance sometimes inflated trust to the point of over-reliance (Q3.7, Q3.8). This also mirrors placebo effects in human augmentation (Villa et al., 2023) that the belief in possessing a "superpower" can amplify perceived performance gains beyond the system's actual contribution. In this study, the misplaced beliefs sometimes led participants to credit the system for successes that were partly their own, potentially undervaluing their own abilities.

These findings highlight that trust evolves through a dynamic interaction of performance outcomes, perceived control, and prior experience. To maintain user trust over time, system behaviours should be easy to understand and align with user expectations. Clear cues and predictable patterns could support a stable sense of control, ensuring that superpower experiences enhance rather than diminish user autonomy.

6.6 Informing the framework

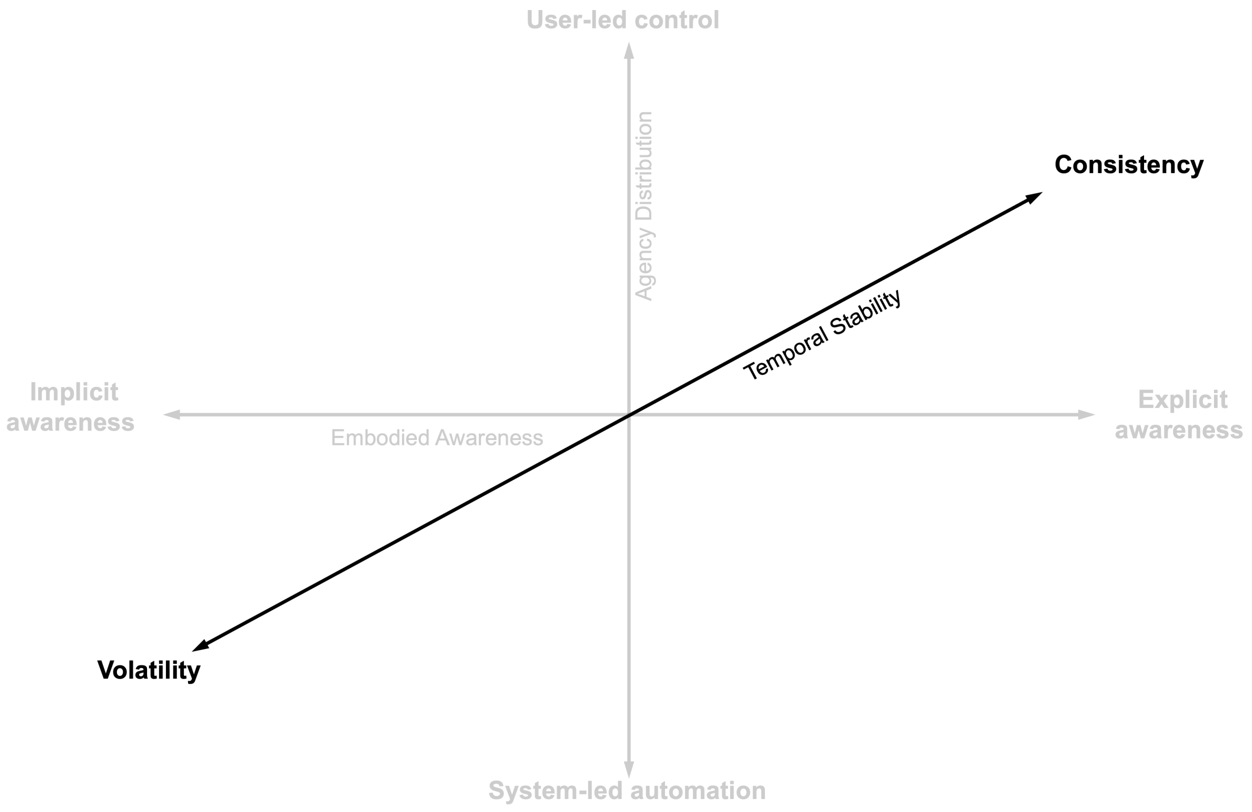


Figure 6.12: Third dimension of the superpower experiences framework: Temporal Stability.

The Flytrap Hand case study contributes to the framework by introducing the concept of temporal stability of superpower experiences, which captures how the user experience fluctuates over time in response to system behaviour and control. The study revealed that the perceived stability of superpower experiences is not constant but dynamically mediated by the interaction between system automation and user adaptation. The two control mechanisms of the Flytrap Hand demonstrated distinct temporal trajectories of stability. In the randomised time control mode, the system determined the duration of grasp and release, producing unpredictable and involuntary actions. Users often described this experience as unstable, as they could not anticipate the system's timing and were frequently caught between fascination and anxiety, where participants felt both assisted and constrained by the system's autonomy. By contrast, in body control mode, users gradually established a rhythmic coordination with the system. Although the system still controls the execution of the opening action, through repeated interactions, participants gradually learned how to initiate actions proactively and adjusted their movements accordingly. This temporal regularity fostered a sense of partnership between human and system, creating a more stable superpower experience that integrated automated actions.

These findings suggest that temporal stability is critical to understanding how superpowers are experienced. When the system behaves inconsistently and unpredictably, the superpower experience remains transient and externally driven, leading to feelings of uncertainty and hesitation. When it becomes temporally stable, users begin to internalise the augmentation as part of their own action repertoire, transforming the superpower into an embodied extension of capability. Consequently, the Flytrap Hand study informed the inclusion of temporal stability as a key dimension in the Superpower Experiences Framework, extending the understanding of superpower experiences beyond immediate sensations of control or awareness. This temporal perspective highlights that the sustainability of augmentation lies not only in its technical reliability but also in its capacity to support coordination between user and system, allowing superpower experiences to become durable and stable forms of augmentation.

6.7 Conclusion

In summary, the Flytrap Hand study investigated the dynamics of augmented action, identifying temporal stability as a definitive factor in how users sustain and internalise superpower experiences. This finding extends the understanding of superpower experiences beyond immediate feelings to include the dimension of time and adaptability.

With the completion of this final case study, the research has now explored the three critical layers of augmentation: perception (Wi-Fi Twinge), cognition (EmoPals), and action (Flytrap Hand). Drawing these empirical insights together, the next chapter presents the Superpower Experiences Framework, a theoretical model designed to understand the positive and negative effects of human augmentation.

Chapter 7

The Superpower Experiences Framework

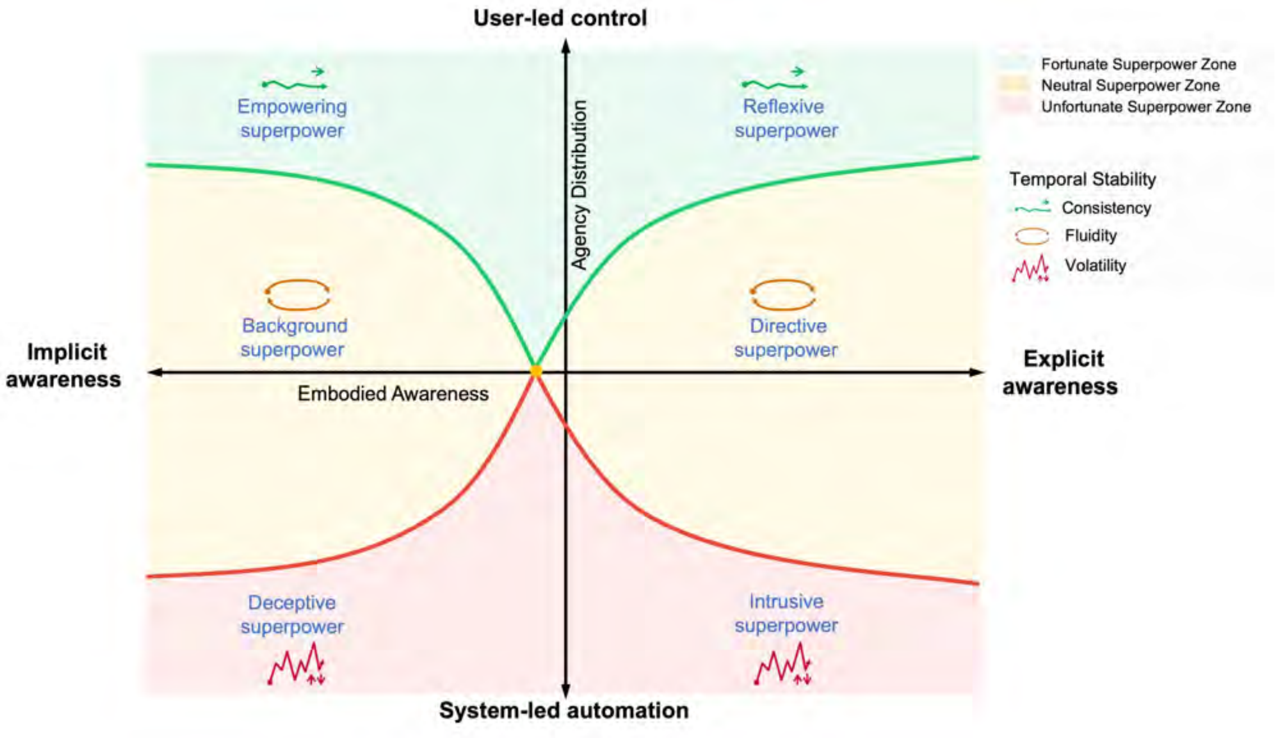


Figure 7.1: Superpower Experiences Framework.

This chapter integrates insights from the three case studies to develop the Superpower Experiences Framework (Figure 7.1). Section 7.1 describes the framework's structure, defining it along three key dimensions: two primary axes that capture awareness and user-perceived agency, and an additional temporal stability dimension representing the consistency of experiences over time. Section 7.2 explains how the experiential space is divided into six distinct experience types, offering a detailed characterisation of each type. Section 7.3 demonstrates how the framework can be applied to analyse and extend the design of superpower experiences through my three case studies. Section 7.4 offers a set of design considerations as part of the framework. Finally, Section 7.5 presents a validation of the framework through a Flytrap Hand field study.

7.1 Framework Dimensions

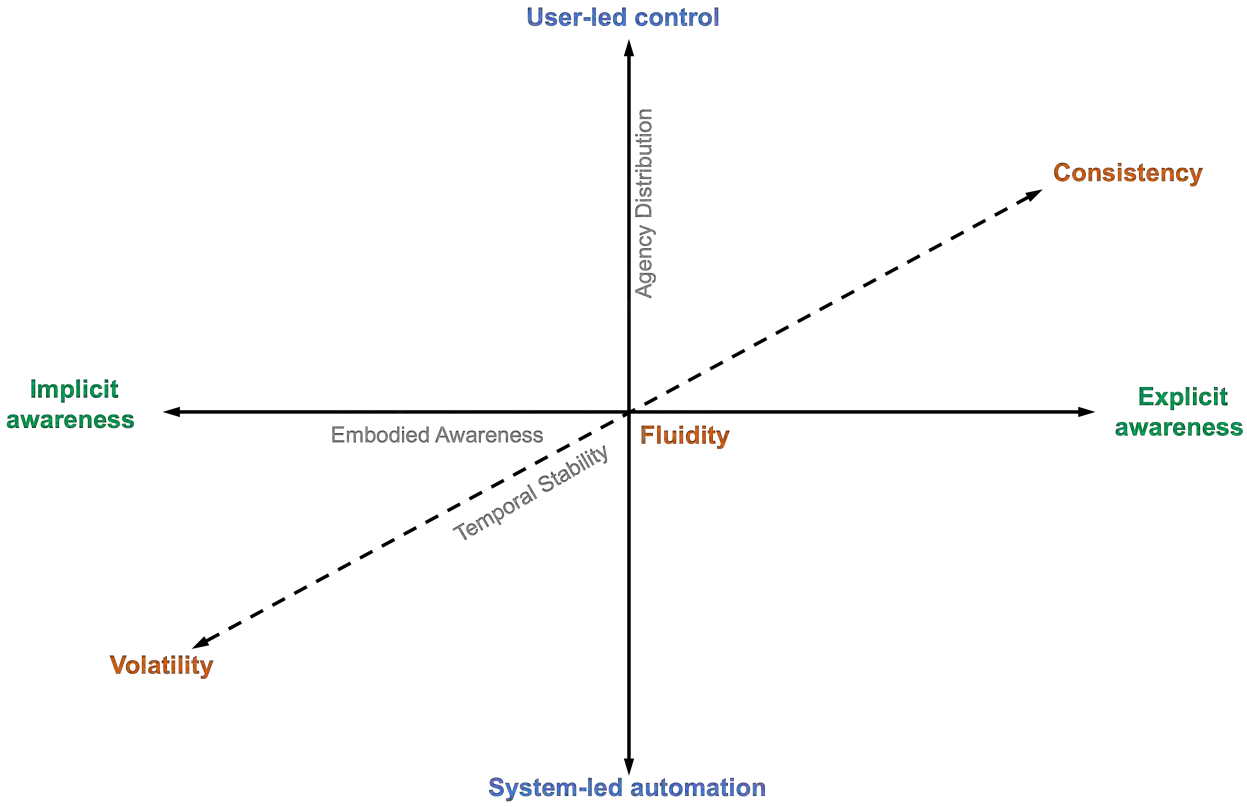


Figure 7.2: Dimensions of the Superpower Experiences Framework: Agency Distribution, Embodied Awareness and Temporal Stability.

The Superpower Experiences Framework is structured along two primary dimensions: Embodied Awareness (X-axis) and Agency Distribution (Y-axis), and an additional third dimension of Temporal Persistence (Figure 7.2). Each dimension is grounded in insights from the three case studies (Wi-Fi Twinge$f$, EmoPals, and Flytrap Hand) and connects to broader discourses in HCI. Together, these dimensions form a design space that maps how an augmented ability is felt and managed by the user. It is important to note that the arrangement of these dimensions across the x, y, and z axes is interchangeable.

7.1.1 Embodied Awareness (X-axis)

The first dimension of the Superpower Experiences Framework concerns the degree of embodied awareness, which refers to the extent to which the influence of a superpower is consciously perceived by the user in their bodily, perceptual, or cognitive experience. This dimension is not simply about whether the augmentation is "noticed" but about how it is taken up by the body, how it is lived through in experience, and how it reshapes the user's sense of agency and self in action.

At one end lies implicit awareness, where the superpower integrates seamlessly into the user's sensorimotor repertoire. In this state, the superpower operates below the threshold of conscious reflection, blending with ordinary experience, and becomes part of what Merleau-Ponty described as the body schema (Merleau-Ponty et al., 2013). The body schema is not a representation of the body (as in "body image") but a pre-reflective, dynamic structure of bodily possibilities, an "I can" that organises perception and action without deliberate thought. For example, when we reach for a cup, we do not consciously calculate angles and muscle movements, as our body schema accomplishes it seamlessly. Merleau-Ponty argued that tools can become incorporated into the body schema through habituation (Merleau-Ponty et al., 2013). For example, the blind man's cane, over time, is no longer perceived as an object held in the hand but as an extension of touch, incorporated into the body.

In the context of superpower experiences, implicit awareness describes this incorporation. When an augmentation fades into the background of conscious attention and begins to "disappear" into action, it functions as an extension of the body schema, in which the user experiences the superpower as a natural extension of their own body rather than an external tool. This is evident in "Wi-Fi Twinge" experiences, where an unfamiliar tingling sensation, initially drawing conscious attention, gradually became a background cue that participants used to orient themselves in space. Over time, the signal resembled a "sixth sense" that integrated into their bodily repertoire, no longer felt as intrusive feedback but as an additional, tacit channel of perception, mirroring the cane's transformation into an extension of touch.

In contrast, at the other end lies explicit awareness, where the modulation of the superpower is acutely noticeable, either because it disrupts bodily expectations or because it introduces novel sensations that draw the user's attention. Explicit awareness can be understood as the body transitioning from a pre-reflective, habitual mode of action into focal, reflective consciousness (Merleau-Ponty et al., 2013), making users acutely aware of how their actions and perceptions are being altered. Consequently, the user may pause to recognise that "this is beyond the capabilities of the everyday body" and consciously adjust, interpret, or reflect on this new sensation.

In superpower experiences, explicit awareness can heighten novelty, wonder, and even critical reflection. Similar to defamiliarisation (Bell et al., 2005), which deliberately disrupts everyday experiences to stimulate reflection and engagement, explicit awareness also invites the user to attend to the strangeness of their own technologically augmented body. For example, "Flytrap Hand" disrupts the flow of action by forcing involuntary grasping, producing a heightened awareness of bodily limits and the system's modulation. Participants reported moments of surprise and even amusement at feeling their hand "move by itself," which amplified the sense of possessing an extraordinary ability, even if it can be unsettling. Explicit awareness can also encourage users to question habitual patterns of interaction. Dunne and Raby (2013) notion of critical design emphasises the importance of designing for moments that interrupt habitual engagement, prompting people to question their assumptions about technology and their body. In the EmoPals study, when users consciously perceived another person's emotions through EMS feedback, this explicit bodily sensation was not only unfamiliar but also raised questions about the boundaries of self and other. The augmentation became a site of reflection, where users reconsidered what it meant to "feel for another" and where agency in emotion resided.

The contrast between implicit and explicit awareness should therefore not be read as a hierarchy of "good" and "bad," but as two ends of a spectrum, each with distinct characteristics. Implicit awareness facilitates fluidity, naturalness, and long-term incorporation into the body schema; explicit awareness fosters novelty, transparency, and critical reflection.

7.1.2 Agency Distribution (Y-axis)

The second dimension (Y-axis) concerns the distribution of agency between user and system, which describes how control over action is shared, shifted, or contested between the user and the system. Agency in this context is not treated as a binary quality that belongs either fully to the human or fully to the machine, but as a dynamic relation that is constantly negotiated in interaction. This dimension captures whether the superpower functions as a direct extension of the user's intentional action, as a collaborative partner, or as an autonomous force that may override the user's will.

At one end of this dimension lies user-led control, where the superpower operates primarily as a tool under intentional human command. In this configuration, users experience themselves as authors of action, with the augmentation functioning as an extension of will that follows the user's decisions closely. The system's role is responsive rather than directive, amplifying what the user has already chosen to do. Here, agency remains firmly anchored in the individual, reinforcing the sense of authorship and ownership over action. The Wi-Fi Twinge study sits towards the user-led end of the agency spectrum, in which participants received tingling feedback correlated with surrounding Wi-Fi signals but could choose how to interpret and act upon it. The system did not enforce action or override their intentions, allowing users to decide whether to ignore, attend to, or use the signal. Over time, the twinge became an integrated "sixth sense" that enhanced spatial awareness while remaining under voluntary control. Participants reported feeling empowered rather than constrained, demonstrating how intentional augmentation can strengthen the user's sense of agency while introducing novel perceptual abilities.

At the opposite end is system-led automation, where the superpower takes control or initiative. Instead of being an extension of the user's will, the system introduces its own logic of operation, sometimes anticipating, constraining, or determining how the user acts and therefore the user experiences themselves as being carried along by automation. Positioned towards the end of system-led automation, the Flytrap Hand exposed participants to involuntary movements such as grasping and releasing, whether in randomised time-based and gesture-based modes. Although participants retained a sense of ownership (“my hand is moving”), provoking surprise and curiosity, the system effectively overrode their voluntary actions and deprived them of agency (“I did not move it”), thereby generating unease.

7.1.3 Temporal Stability

The third dimension concerns the temporal stability of the superpower experience, which describes the evolution and consistency of the experience over time. Whereas the preceding dimensions provide an instantaneous static state of the experience, this dimension introduces a time vector to track the experience’s trajectory. Superpower experiences are not static “things” but dynamic events and processes that unfold through user adaptation, habituation, and contextual interaction. This aligns with HCI research that frames temporality as a design material (Lundgren & Hultberg, 2009; Odom et al., 2018; Wiberg & Stolterman, 2021), emphasising that technologies are lived through time and acquire meaning as they unfold in use. From this perspective, temporality is integral to how users develop trust, competence, and meaning in relation to technology. Over time, augmentations may shift from disruptive to embodied, or conversely, from empowering to fatiguing or alienating. Temporal stability captures how users’ sense of control, bodily familiarity, and expectation continuously evolve during interaction. In this framework, temporal stability is represented through three experiential zones: consistency, volatility, and fluidity.

Consistency represents a temporal mode characterised by stability and predictability. Consistent superpowers exhibit predictable mappings between user action and system response, allowing the user to form stable expectations and develop trust in the interaction. These experiences do not require constant cognitive oversight or renegotiation once familiar patterns have been established. This temporal stability is the critical prerequisite for habitual incorporation as it facilitates the transition from mediated interaction to intuitive embodiment, allowing augmented capabilities to sediment into the body’s sensorimotor repertoire as the technology recedes from conscious attention. This concept aligns with research on long-term interactions and slow technology (Hallnäs & Redström, 2001; Odom et al., 2022), which advocates for designing stable relationships with computational objects that support durable emotional engagement. Temporal consistency enables the formation of predictable rhythms of life, allowing the augmentation to merge with the user's body schema. In Wi-Fi Twinge, this process was evident as the initial strange and attention-demanding tingling sensation gradually evolved into a stable and imperceptible sensation that blends into daily spatial awareness.

Volatility, by contrast, represents a temporal mode that is ephemeral, unstable, or unpredictable. Volatile temporal structures prevent the formation of predictable rhythms, producing experiences that are episodic, interrupted, or dissonant (Adamczyk & Bailey, 2004; Couffe & Michael, 2017; Mark et al., 2008). This volatility relates to HCI's long-standing concerns with interruptions, delays, and lag, which are identified as sources of temporal dissonance or sociotemporal disorder (Bailey et al., 2001; Lindley, 2015). However, volatility may not only be a byproduct of system failure but also a deliberate design strategy aimed at provoking heightened awareness or critical reflection. Flytrap Hand exemplifies this temporal mode in its randomised time control and involuntary EMS activation, which abruptly interrupted bodily flow, preventing habituation and maintaining a heightened sense of uncertainty. The resulting temporal dissonance prompted users to notice the automation's control over their body, exposing the fragility of agency in augmentation.

Fluidity represents a temporal mode that is dynamic, adaptive, and flexible. The fluid experience is neither entirely stable nor entirely volatile; rather, it operates as an in-between state that evolves through continuous negotiation among the user, the system, and the surrounding context (Irani et al., 2010; Wiberg & Stolterman, 2021). This temporal mode often requires conscious, ongoing negotiation and reinterpretation. Temporality here is fluid, reflecting how users and technologies co-adapt through situated interactions. This understanding echoes research on adaptive interaction trajectories, which describes how users and technologies engage in evolving journeys of adaptation across time (Benford & Giannachi, 2008; Benford et al., 2009). Such a perspective aligns with Bødker's view of HCI as a continuously shifting practice in which user experience develops through participation and reinterpretation over time (Bødker, 2015). In EmoPals, for example, EMS feedback linked to emotional states was neither entirely predictable nor chaotic. Users had to continuously adapt their interpretations to evolving emotional cues, maintaining a balance between anticipation and surprise. This adaptive rhythm fostered sustained reflection without collapsing into either full stability or complete volatility, enabling engagement through continuous adaptation.

7.2 Experience Types

The three dimensions of the framework interact to define six distinct experiential types, as illustrated in Figure 7.1. The design space is structured by two primary curves, whose shapes and positions are defined by the temporal modes of consistency, fluidity and volatility. These curves represent the theoretical boundaries between the different temporal stabilities that emerged from my analysis.

The upper curve (in green) represents the threshold for achieving consistency, a temporal mode of stable and enduring integration. This state is achievable under user-led control at both ends of the awareness spectrum: in implicit awareness (as an "Empowering Superpower") and explicit awareness (as a "Reflexive Superpower"). Conversely, the lower curve (in red) represents the threshold for volatilityrequiringral mode of ephemerality and instability. This state is primarily associated with system-led automation at both ends of the awareness spectrum: in implicit awareness (as a "Deceptive Superpower") and explicit awareness (as an "Intrusive Superpower"). The area between these two curves is defined by fluidity, representing a dynamic, adaptive, and flexible temporal mode. Fluidity captures the middle ground between stability and disruption, describing superpower experiences that remain flexible and contextually reconfigurable rather than fixed. Within this space lie the "Background Superpower" and "Directive Superpower", both of which involve forms of temporal negotiation that oscillate between comfort and disruption.

The following sections elaborate on each experiential type and its relations to the case studies.

7.2.1 Empowering Superpower

In the upper-left zone sits a type of experience in which users retain control (user-led agency) and the system operates below conscious awareness

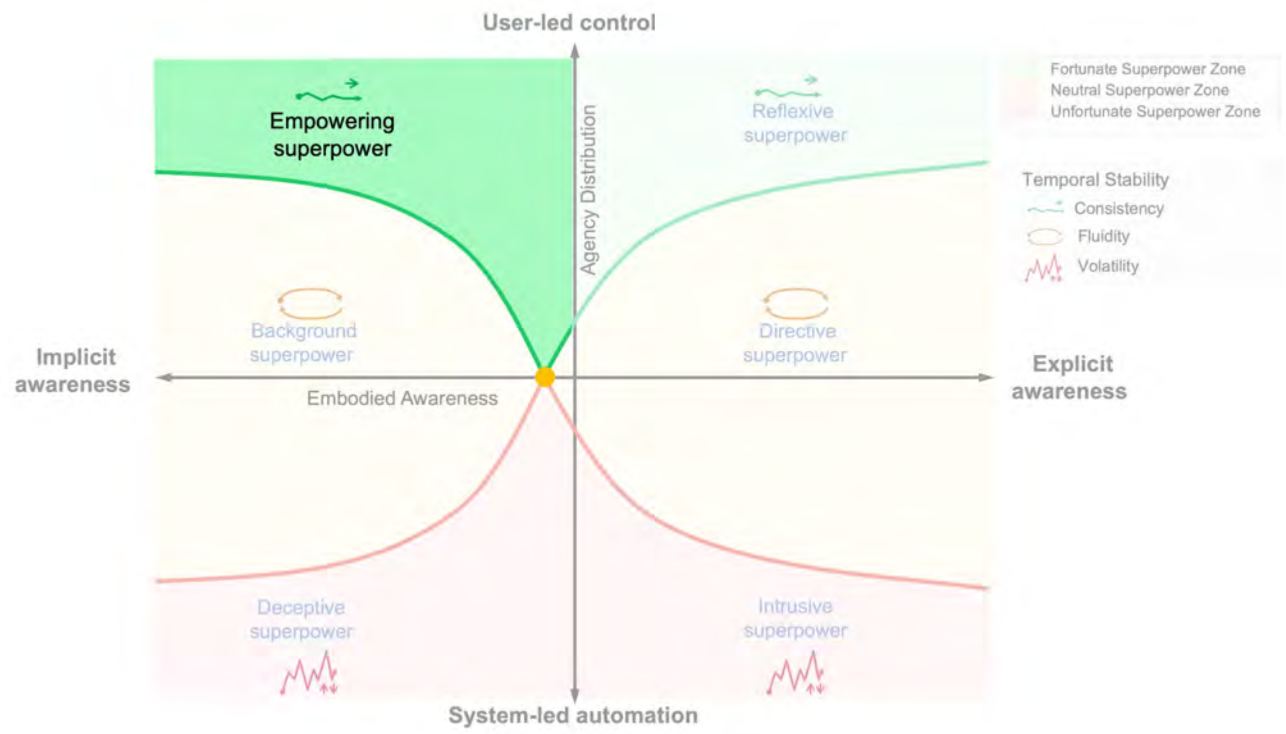


Figure 7.3: The Empowering Superpower.

(implicit awareness), while temporal consistency allows for enduring integration (Figure 7.3). I call this the Empowering Superpower experience because it describes a state in which augmentation strengthens human ability without demanding cognitive effort. The name "empowering" emphasises how control and implicitness converge to maintain a fluent, self-reinforcing experience that feels natural and self-originated. This temporally consistent relation parallels embodiment relations (Ihde, 1990, 2002), in which technology withdraws from focal attention to mediate direct engagement with the world. In this mode, time stabilises action into habit, and the repetition of predictable sensorimotor coupling enables embodied assimilation.

In the Flytrap Hand, this state emerged when participants successfully adapted to the EMS feedback and could predict how the system would grasp objects. After several trials, some participants described moments when "the hand just knows what to do," revealing a form of motor assimilation where the artificial stimulation merged seamlessly with intentional control. Similarly, in Wi-Fi Twinge, when the haptic tingle reliably indicated network strength without distraction, users began treating it as a peripheral sense that enhanced their Wi-Fi sensing capability.

Comparable experiences have been reported in ExoSkin (Gannon et al., 2016), where users gradually internalised haptic feedback from artificial skin until it became a “natural sense,” and in Supernumerary Robotic Limbs (Parietti & Asada, 2016; Prattichizzo et al., 2021; Yang et al., 2021), where trained users treated additional limbs as natural bodily extensions. In this sense, the Empowering Superpower reveals how implicit stability and user-led agency combine to create an enduring illusion of innate ability.

7.2.2 Reflexive Superpower

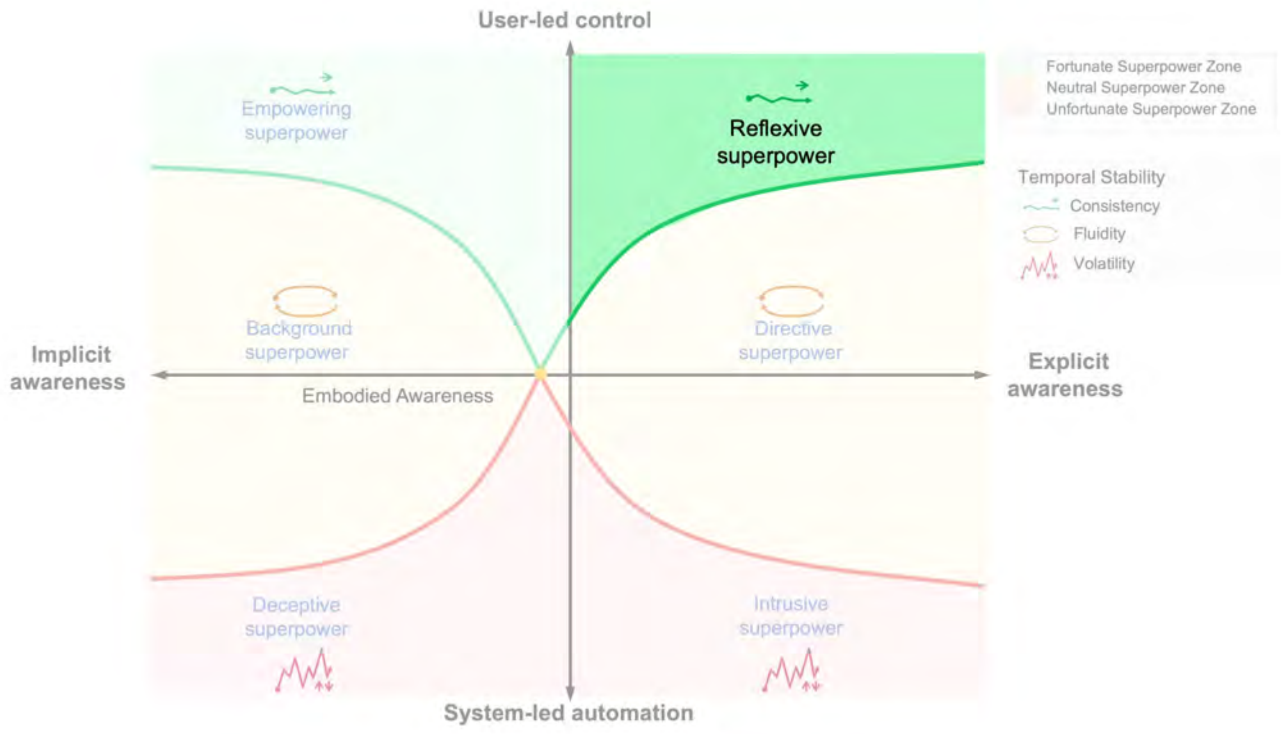


Figure 7.4: The Reflexive Superpower.

In the upper-right zone sits a type of experience in which users retain control (user-led control) and the system remains an object of conscious focus (explicit awareness), while temporal consistency allows for integration over time (Figure 7.4). I call this user experience the Reflexive Superpower because it is defined by a conscious, intentional, and reflective feedback loop between user and system. The term “reflexive” captures both the self-awareness and the self-regulation processes that define this experience type. Reflexive experiences emerge when stability allows users to predict system responses, but awareness remains explicit. Users act, observe, and reflect deliberately on the augmentation, understanding its capabilities and boundaries in a reliable loop.

In EmoPals, participants often reached this state when they consciously adjusted their emotions to influence the partner's emotional mirroring. They became aware not only of how their actions influenced the system's affective responses but also of how the system influenced their own self-expression. Similarly, in Wi-Fi Twinge, when users began to articulate strategies such as "I started guessing and thinking about the building's structure," they were consciously reflecting on the superpower's utility. These examples show how reflexivity stabilises the relationship through thoughtful awareness, integrating augmentation as a tool of reflective experience. Similar findings have been reported in Empathic Interfaces (Prendinger et al., 2004; Van Dijk & Hummels, 2017), where consistent feedback fostered reflection on embodied experiences.

7.2.3 Background Superpower

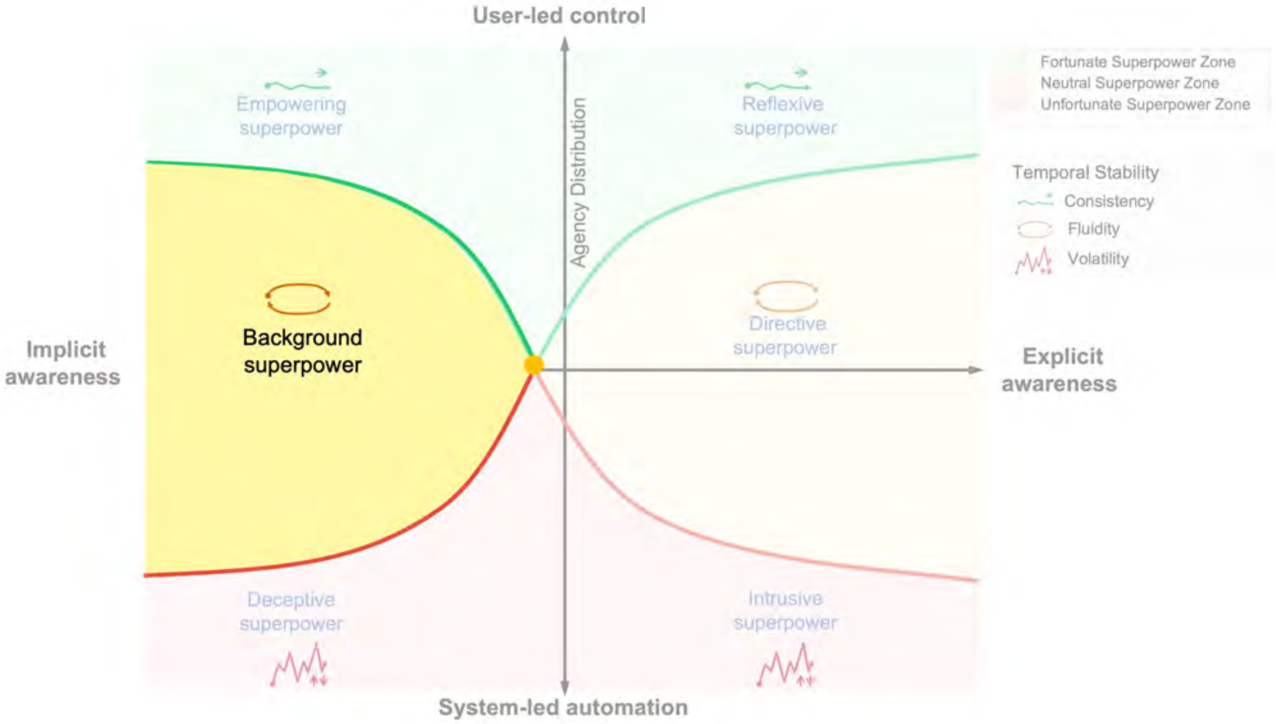


Figure 7.5: The Background Superpower.

In the middle-left zone sits a type of experience in which agency is distributed and the system operates below conscious awareness (implicit awareness), but temporal fluidity requires situated interpretation (Figure 7.5). I call this user experience a Background Superpower because it functions as a peripheral cue that operates in the background of attention. The augmentation recedes into the periphery when unneeded and resurfaces when relevant, reflecting an adaptable and flexible equilibrium where users selectively attend to or ignore the system. Unlike the fully internalised embodiment of the Empowering Superpower, the Background Superpower remains conditionally embodied, where its salience fluctuates depending on context and attentional demand.

In Wi-Fi Twinge, the stimulation that signalled Wi-Fi signal strength gradually faded into the background during ordinary use. Participants reported that, over time, they “stopped noticing it” unless a sudden surge or loss of connectivity occurred. The system’s feedback thus became a situated form of awareness, surfacing only when environmental changes—such as entering a zone with stronger or weaker Wi-Fi—triggered perceptual salience. Users described the stimulation as “a background sense” or “something my body learned to ignore unless it mattered.” In this way, the system oscillated between invisibility and visibility, generating a background rhythm that quietly informed users’ spatial behaviour without requiring explicit engagement. A similar phenomenon was observed in EmoPals, where the emotionally augmented character operated quietly in the periphery of users’ attention. When participants were engaged in other tasks, facial stimulation often went unnoticed, yet these cues became meaningful when users sought emotional reflection or support. This peripheral presence created a temporal elasticity that the system was available but not demanding, facilitating ongoing co-adaptation between user and technology.

Comparable experiences have been reported in Ambient Intelligence and Peripheral Interaction research. For example, Bakker et al. (2015) describe how peripheral interfaces support fluid shifts of attention by remaining available in the background until users intentionally refocus on them. Similarly, systems like Calm Technology (Case, 2015; Weiser & Brown, 1997) and Affective Lamps (Angelini et al., 2015) exemplify technologies that retreat from the centre of consciousness, functioning as quiet background agents that mediate environmental or emotional information. In this sense, the Background

Superpower aligns with such “calm” or “ambient” paradigms but extends them into a superpower context in which peripheral augmentation is not merely informational but also affective and embodied, subtly reshaping bodily perception and spatial decision-making.

7.2.4 Directive Superpower

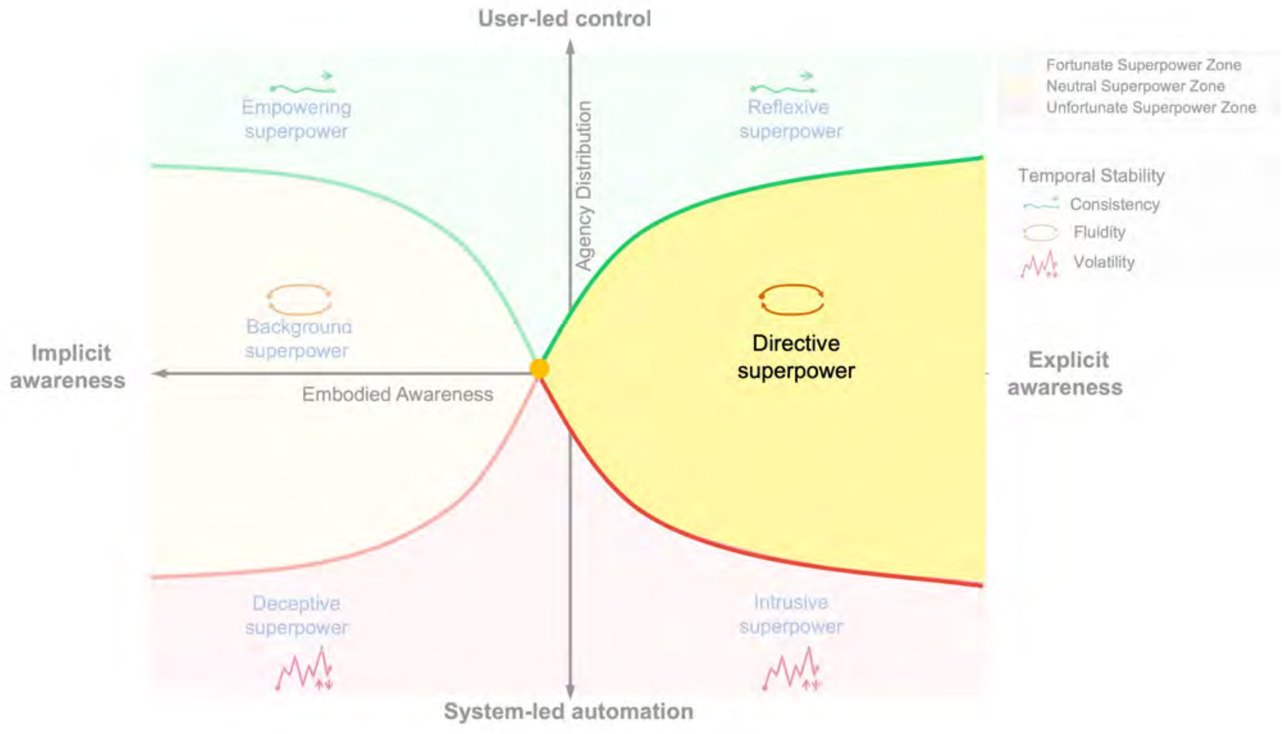


Figure 7.6: The Directive Superpower.

In the middle-right zone sits a type of experience in which agency is distributed, the system is an object of conscious focus (explicit awareness), and temporal fluidity necessitates ongoing negotiation (Figure 7.6). I call this user experience the Directive Superpower because the augmentation in here is not a passive tool but an active guide that directs the user’s attention, interpretation, and reflection by providing cues, prompts, or corrections. Unlike Background Superpowers, Directive Superpowers remain perceptually foregrounded and demand awareness, interpretation, and adjustment. The sense of agency is shared as the user remains aware of the system’s involvement, yet their own action is co-authored, where the system’s guidance becomes a form of scaffolding. The experience is fluid because it unfolds through ongoing negotiation, where the user learns to respond to the system's directives, and the system continuously adjusts its output in response to user behaviour.

This experience was evident in EmoPals. For example, when one user experienced a moment of frustration during a task, the system translated this negative affect into a frown on the other user's face. The receiving participant became explicitly aware of both the system's modulation and its emotional cue, often pausing to interpret it before reacting, either by verbally responding, changing facial expression, or attempting to re-establish emotional balance. Across these exchanges, users reported consciously reading and responding to the system's feedback, forming a triangular relationship among self, system, and partner, while the system operated as an affective director that did not dictate emotion but subtly guided the flow of empathy and response. There were moments of interruption that provoked reflection, but over repeated interaction, participants gradually learned to predict, reinterpret, and even manipulate the system's feedback.

Comparable experiences have been reported in research on adaptive guidance, affective feedback, and co-regulative systems. For example, socially assistive robots engage in ongoing influence over user behaviour through motivational and corrective prompts rather than acting purely autonomously (Feil-Seifer & Matarić, 2011). Similarly, persuasive technology offers frameworks where computers or devices shift attitudes and behaviour through continuous engagement rather than overt control (Fogg, 2002). Intelligent tutoring systems such as AutoTutor (Graesser et al., 2005) present mixed-initiative dialogues and affect-sensitive feedback loops that balance learner autonomy with guided modulation. In these systems, users retain partial agency but are continually shaped by the system's directives, suggestions or affective cues. The concept of Directive Superpower extends such paradigms into human augmentation, where the guiding influence is not only cognitive but embodied, affecting one's perception, cognition, and social relations with others. In this respect, it resonates with Verbeek's (2008) framework of technological mediation, where technology directs moral and perceptual experience by transforming how humans relate to others and the world. In EmoPals, the system not only transmits emotion but also directs its meaning, transforming spontaneous affect into a reflective, technologically co-authored event, highlighting the expressive and instructive nature of Directive Superpower.

7.2.5 Deceptive Superpower

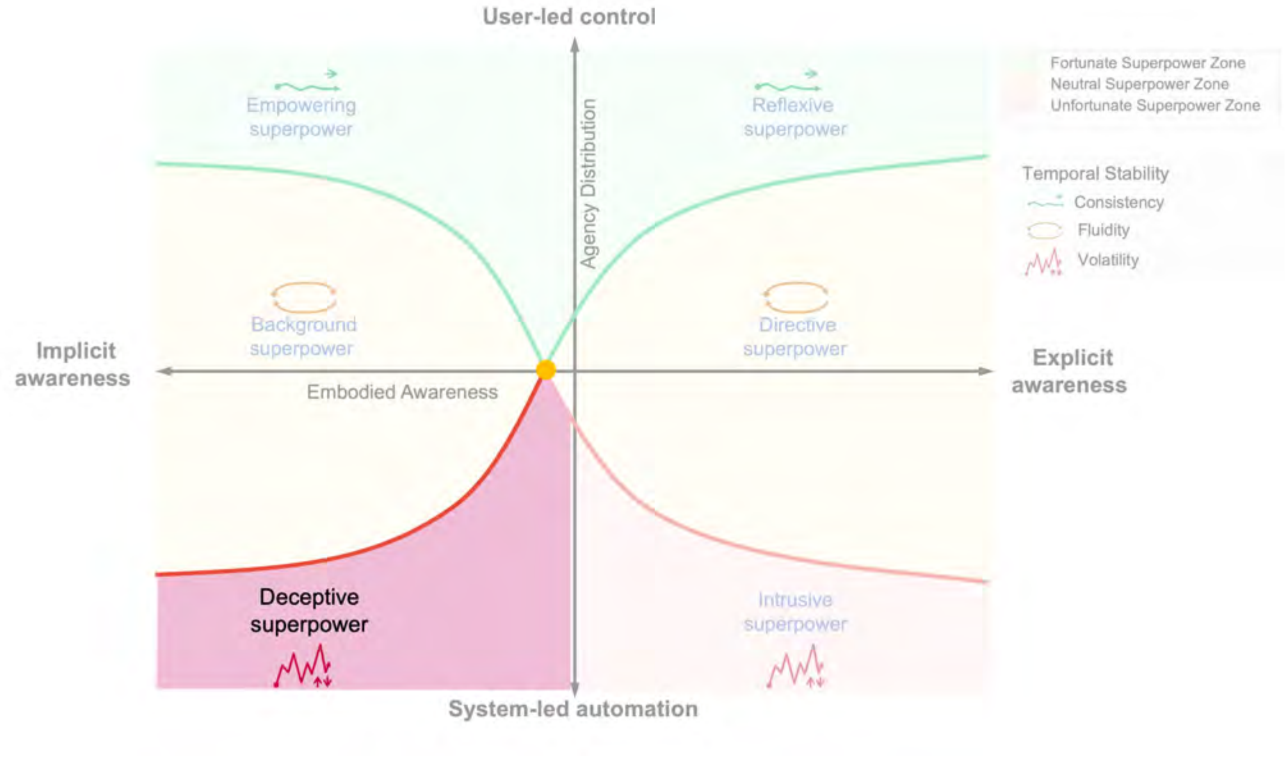


Figure 7.7: The Deceptive Superpower.

In the lower-left zone sit experiences in which the system dominates control (system-led control), operates below the threshold of conscious awareness (implicit awareness), and exhibits temporal volatility that subtly manipulates perception (Figure 7.7). I call this user experience the Deceptive Superpower because the system conceals its manipulation behind seemingly normal or reliable interfaces, prompting users to trust and follow its cues even as they are being misled. The term "deceptive" captures the covert nature of the augmentation, where the effects may be perceived as an unexpected extension of the self. Users may believe they are acting freely, while in reality, their sensations and decisions are being manipulated by the system. This phenomenon aligns with prior discussions of illusory control and deceptive automation. Wegner's (2017) concept of "the illusion of conscious will" provides a theoretical grounding, showing how users often misattribute agency when system outputs align with their expectations.

The deceptive experience emerged in the Flytrap Hand, particularly during the randomised time control setting. Participants occasionally reported that they had learned the system's rhythm or could predict when the hand would open or close. In truth, the timing was entirely random. Participants' cognition imposed patterns and agency where none existed, reflecting an inherent drive to maintain coherence and predictability. This adaptation reveals how humans seek coherence, transforming unpredictable automation into an illusion of self-perceived control. These findings indicate that deceptive experiences arise not only from external manipulation but also from cognitive mechanisms that preserve a sense of self-consistency.

Comparable experiences can be found in speculative and deceptive interaction design research. Research on adaptive interfaces demonstrates that systems that continuously alter input–output mappings or provide opaque, shifting feedback can induce persistent uncertainty about where control resides, leading users to doubt whether actions originate from themselves or from the device (Jameson & Gajos, 2012). Similarly, persuasive technologies, as discussed by Fogg (2002), are designed to influence users' attitudes or behaviours through persuasion and social influence. While intended to produce beneficial outcomes, such mechanisms have also been criticised for their manipulative potential, in which users feel they are making free choices, yet hidden design intentions systematically steer their choices (Jacobs, 2020; Verbeek, 2006). The Deceptive Superpower operates covertly, and its control is effective precisely because it remains implicit, transforming enhanced perception into misperceived truth.

7.2.6 Intrusive Superpower

In the lower-right zone sit experiences in which the system dominates control (system-led control) and is highly perceptible to the user (explicit awareness), where temporal volatility continually disrupts bodily and cognitive flow (Figure 7.8). I call this the Intrusive Superpower because it intrudes upon users' actions and attention, making the system's manipulation unavoidable and demanding. The term "intrusive" emphasises the invasive and sometimes coercive nature of these experiences, in which users are forced into engagement, their control is partially taken away, and their sense of agency is destabilised. This superpower embodies confrontation that sees the body's vulnerability to external command, foregrounding the tension between being augmented and being possessed (Mueller et al., 2023).

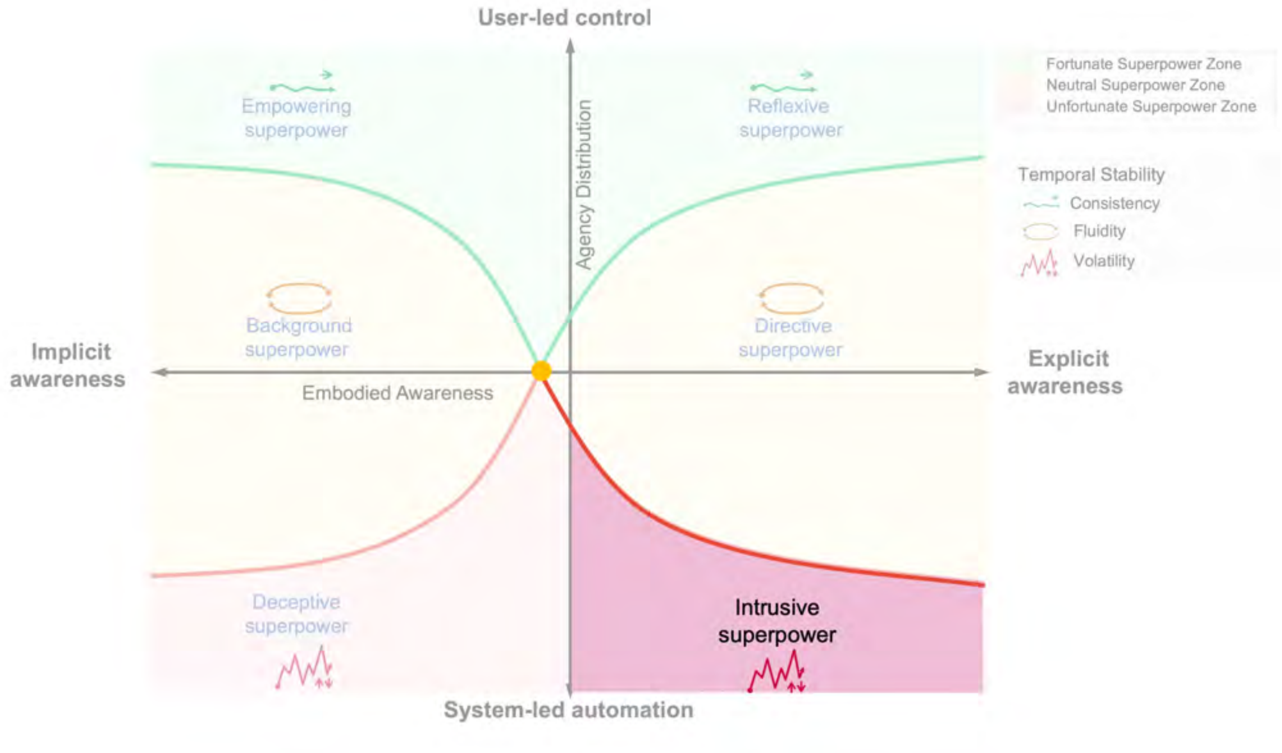


Figure 7.8: The Intrusive Superpower.

In the Flytrap Hand, participants experienced Intrusive Superpowers when EMS-induced grasping or releasing actions occurred unexpectedly. One participant described, *"I froze because I couldn't control my hand. It was doing something on its own."* The explicit awareness of the system's autonomous action, combined with the unpredictability of temporal volatility, generated a strong sense of bodily alienation. The random timing of grasp-release cycles meant participants could never fully anticipate when their hand would act, causing both physiological surprise and cognitive dissonance, producing what several participants described as a *"fight against the system"*. The intrusiveness lies not only in the physical movement but also in the psychological rupture, in which the user's awareness oscillates between fascination with possessing a superpower and the fear of losing control. Similarly, in Wi-Fi Twinge, sudden and unexpected stimuli could lead to moments of disorientation. Participants might instinctively pause or look around to make sense of the source, questioning whether the sensations reflected real environmental changes or system malfunctions. The volatility of these events disrupted the temporal continuity of action, transforming ordinary perception into an intrusive experience.

Comparable experiences have been observed in studies of involuntary actuation. For example, Lopes et al. (2015) examined EMS-driven interfaces where users' hands were moved without volitional intent, creating moments of confrontation that challenged bodily agency. Similarly, PossessedHand (Tamaki et al., 2011) intentionally triggered involuntary motor actions to explore altered agency. In both cases, the system acted as an explicit, intrusive agent whose volatility disrupted users' sense of temporal and bodily coherence, revealing how excessive system guidance can undermine and disrupt empowering relationships. The Intrusive Superpower builds upon these insights by foregrounding the explicit tension between system dominance and bodily self-awareness. When augmentation crosses the threshold of control, enhancement could transform into intrusion, and the superpower turns unsettlingly against its users.

Taken together, these six experiential types constitute a design space of superpower experiences. Crucially, experiences are not confined to a single zone: they evolve, oscillate, and migrate across the framework as users adapt, resist, or reinterpret their augmentations.

7.3 Applying the Superpower Framework

The Superpower Framework offers a means to analyse, interpret, and reimagine augmentation systems through the lens of human experience. This section demonstrates how the framework can be applied to analyse and extend the design of the three prototypes developed in this thesis: Wi-Fi Twinge, EmoPals, and Flytrap Hand. Each case is discussed in two parts: first, how the framework can explain the observed user experience trajectories, and second, how it can extend or reorient future design directions by adjusting control, awareness, and stability.

7.3.1 Case Study 1: Wi-Fi Twinge

7.3.1.1 Explaining Wi-Fi Twinge through the Framework

Wi-Fi Twinge can be understood as oscillating between Deceptive Superpower and Background Superpower, depending on temporal adaptation. Early interactions with Wi-Fi Twinge manifested as Deceptive Superpower experiences as the system generated ambiguous sensations that blurred the boundary between bodily signal and environmental feedback. The Deceptive Superpower experience was characterised by confusion and cognitive conflict in interpreting bodily sensations, with control being dominated by the system, and the generation of feedback being unrelated to the user's intentions. Over time, as users developed interpretive strategies, the control was shared between the user and the system, the pulsation pattern became background and bodily integrated, and the experience transitioned into Background Superpower.

7.3.1.2 Extending Wi-Fi Twinge through the Framework

Using the Superpower Framework, one could envision Wi-Fi Twinge shifting from a Deceptive Superpower experience toward the Empowering or Directive quadrants. In a Directive Superpower configuration, Wi-Fi Twinge could evolve into an adaptive sensory guide that translates network quality into directional cues. For example, rather than delivering diffuse tingling, the system might modulate the intensity and spatial location of stimulation to subtly lead users toward stronger connectivity areas. This change would preserve system-led control while improving interpretability, allowing users to follow the system's guidance as a cooperative partner.

Alternatively, an Empowering Superpower version of Wi-Fi Twinge might offer users direct, customisable control over the output mapping. For example, users could define specific Wi-Fi signal strength thresholds that trigger sensations or adjust the haptic intensity to match their personal sensitivity. This shift toward user-led control and long-term consistency would facilitate the transition from a fluid state of adaptation to a stable, reliable embodiment relation. Over time, this calibrated sense could be incorporated into the user's body schema, allowing the experience to transition into implicit awareness and become an Empowering Superpower.

Conversely, the framework also allows one to explore critical extensions by deliberately amplifying the Deceptive qualities. A speculative Wi-Fi Twinge variant might generate false or delayed feedback, prompting users to question their reliance on machine mediation and their perception of invisible infrastructures. Such an approach would reposition Wi-Fi Twinge as a dark pattern probe for investigating techno-trust and perceptual manipulation. Thus, through the lens of the framework, the system can be deliberately evolved or distorted to explore the experiential gradient between empowerment, direction, and deception.

7.3.2 Case Study 2: EmoPals

7.3.2.1 Explaining EmoPals through the Framework

The experience of EmoPals moves from Intrusive Superpower towards Reflexive Superpower, from strange, discomfort to expert, embodied empathy. The experience originates in the Intrusive Superpower, representing a state of volatility. The forced expressions are explicitly felt but are system-led and not yet understood, creating a temporal dissonance between the user's body and the system's commands. When users are actively trying to make sense of the feedback rather than being subjected to it, the experience progresses to Directive Superpower. Agency is no longer fully system-led but becomes distributed. The system directs the user's emotional expression, and the user, in turn, engages in ongoing negotiation to adapt and reinterpret the meaning of the facial expressions in the context of their social interaction. As negotiation grows, the experience enters the Reflexive Superpower. Agency shifts more toward the user, who is now engaged in active exploration and interpretation, reflecting on how emotions could be technologically mediated. The user can consciously, reliably, and with user-led control use the feedback to understand the other user's emotional state.

7.3.2.2 Extending EmoPals through the Framework

Using the Superpower Framework, one can envision extending EmoPals to an Empowering Superpower. This would involve design choices that facilitate the transition from explicit awareness to implicit awareness. For example, after a period of successful, conscious exploration, the system's feedback could gradually become more subtle, shifting from distinct feedback to a sub-perceptual calm technology. This would allow the user to internalise the cues, transitioning from a state of conscious translation ("I feel them smile") to a pre-reflective, embodied state ("I feel happy"), thereby achieving the goal of an embodied empathy.

Alternatively, a version of EmoPals could be designed to introduce temporal smoothing or contextual feedback delays, allowing emotional cues to surface more gradually and enabling users to reinterpret the meaning of induced expressions. This would reduce the volatility of emotional coupling and promote a transition toward the Background Superpower zone, where augmentation remains available yet unobtrusive, blending more naturally into social interaction.

Conversely, the framework allows for speculative transformation toward a Deceptive Superpower mode, where EmoPals selectively misrepresent emotional feedback to test social dependency on technological mediation. This could be explored as a critical design experiment on empathy manipulation to examine how users trust or contest affective technologies that read their inner states.

7.3.3 Case Study 3: Flytrap Hand

7.3.3.1 Explaining Flytrap Hand through the Framework

The Flytrap Hand illustrates two distinct trajectories within the Superpower Framework, corresponding to its two control settings: Randomised Time Control and Body Control. Both settings employ EMS to actuate the hand's grasp and release movements, yet their temporal and agency dynamics produce qualitatively different superpower experiences.

In the Randomised Time Control setting, the system initiates release actions at unpredictable intervals, making the experience unstable and system-dominant. Participants described feelings of surprise and frustration as their hands acted without volition, reflecting the characteristics of the Intrusive Superpower. Agency is almost system-led, awareness is explicit, and temporal volatility undermines the user's sense of bodily continuity. The experience evolves across multiple temporal phases: from initial curiosity and astonishment to adaptation and eventual cognitive fatigue. The randomness forced users into continuous negotiation with unpredictability, producing moments of bodily alienation but also heightened reflection on control and automation. This aligns with the idea that Intrusive Superpowers reveal the limits of trust and embodiment by exposing the vulnerability of human control to technological augmentation.

By contrast, the Body Control setting represents a more balanced distribution of agency. In this mode, releasing is triggered through the user's finger movement, which situates the experience closer to the Directive Superpower zone. The system remains perceptible and partially controlling, yet the user maintains a participatory role by consciously initiating release. Participants reported feeling that "the system followed my gesture", highlighting how the relationship became more guided. Over repeated use, temporal consistency enabled users to anticipate the EMS rhythm, and some began to internalise its feedback as a new mode of extended action, suggesting a trajectory toward the Empowering Superpower.

7.3.3.2 Extending Flytrap Hand through the Framework

Using the Superpower Framework, one can envision extending Flytrap Hand along multiple trajectories that explore the continuum between system dominance and embodied integration. The first trajectory would move the Randomised Time Control setting toward a more temporally stable and co-adaptive configuration, transforming the experience from an Intrusive to a Directive or Empowering Superpower. For instance, integrating EMG-based intention detection could allow the system to interpret early muscle activation signals, automatically halting EMS output when voluntary movement is detected. This would restore partial agency to the user, converting confrontation into collaboration. The resulting experience would retain the awareness of augmentation and reduce volatility.

Alternatively, an adaptation pathway could be pursued by employing machine learning to predict the user's grasping patterns across multiple sessions. As temporal consistency and predictive accuracy increase, the Flytrap Hand could fade into the periphery of awareness, evolving toward the Background Superpower that operates smoothly and reliably beneath conscious attention, offering seamless physical assistance. In such a case, the system's automation would no longer feel imposed but naturally embedded within the body schema.

Conversely, a speculative reconfiguration could push the system deliberately further into the Deceptive Superpower zone. A version of Flytrap Hand might intentionally alter the perceived timing or force of EMS actuation to explore users' trust boundaries, provoking reflection on agency, machine reliability, and bodily autonomy. Similar to dark pattern research, this design direction would not aim for comfort or efficiency but for critical engagement with how users negotiate technological authority over their own bodies.

7.4 Design Considerations

While the preceding sections describe distinct types of superpower experiences, in practice, users rarely inhabit a single type in isolation. Instead, these experiences unfold dynamically across time and context, shaped by evolving relations between agency, awareness, and temporal stability. The framework thus does not represent fixed categories, but rather a spectrum of experiential transitions, such as from empowerment to deception, through which users' perceptions of augmentation continuously shift. By understanding how the dimensions of awareness, agency, and temporal stability interact, we can derive high-level strategies for intentionally designing for or against each of the six experiential types. The following considerations are not rules, but guiding principles for human augmentation design.

7.4.1 Empowering Superpower: Predictive congruency and productive resistance

Empowering superpower experiences emerge when the system acts as an invisible amplifier of human ability. Users retain full agency and experience the augmentation as an extension of the self, operating through implicit awareness. In this state, the technology withdraws from the user's focal attention to mediate direct engagement with the world, functioning as "ready-to-hand" (Ihde, 1990). To achieve this embodied integration, the design needs to meet the brain's predictive coding mechanisms, which constantly generate forward models to anticipate the sensory outcome of an action (Friston, 2005; Wolpert & Flanagan, 2001). When the system's feedback matches these internal predictions, the system remains cognitively invisible and the brain attributes the action to the self (Blakemore et al., 2002). Therefore, designers should consider prioritising predictive congruency, ensuring that the system's outcome aligns temporally with the user's intention. Prior research findings suggest that artificial movements are perceived implicitly as voluntary and self-originated if they occur within a strict time frame relative to intention (Cornelio et al., 2022; Haggard, 2017a; Kasahara et al., 2019). As noted in the analysis of the Flytrap Hand study, the experience became empowering only when the system's actuation aligned perfectly with the user's intent, leading participants to feel the hand "just knew what to do" without conscious monitoring. To meet this predictive congruency requirement across different contexts, designers can consider using adaptive calibration, where the system learns and fine-tunes execution time to adapt to the user's specific biomechanical rhythm.

However, if a system completely removes all friction, it risks creating a "button-pushing" experience, causing users to lose their proprioceptive connection to the action, and potentially inadvertently diminishing their sense of achievement or skill (Bainbridge, 1983). Therefore, empowering superpowers should be designed with productive resistance, maintaining a minimum threshold of necessary physical effort to ensure the user remains actively engaged in the action and aware of their own contribution to it (Bjork & Bjork, 2011). By preserving the exertion-outcome link, the interaction ensures that the augmentation is felt as the body's capability rather than a service of the machine.

7.4.2 Reflexive Superpower: Interpretive ambiguity and defamiliarisation

Reflexive superpower experiences are characterised by explicit embodied awareness, where the system remains an object of conscious focus to foster a dialogue between human and machine. Reflexive designs intentionally bring the mediation into the foreground to provoke reflection on noticing, interpreting, and questioning how the system mediates perception and action (Sengers et al., 2005). Designers could foster this awareness by using ambiguity as a resource, providing feedback that is intelligible but ambiguous enough to prompt interpretation, guiding users to actively understand what the system is doing and why (Gaver et al., 2003). As noted in the EmoPals analysis, users entered a reflexive experience when they received an ambiguous emotion that required them to pause and interpret the reasons. They may reflect on how technological mediation influences their expression and empathy, thus understanding not only the system's operation but also their own embodied responses.

Furthermore, to prevent the user from sliding into habitual, mindless usage, designers need to consider the strategy of defamiliarisation, which is a principle of somaesthetic design (Höök, 2018). Our bodily actions often function on a pre-reflective “autopilot”, where even explicit feedback eventually fades into background noise over time. To trigger reflexivity, the design can disrupt these seamless expectations through delayed, distorted, or rhythmic feedback (Höök, 2018; Höök et al., 2016). For example, a biofeedback system can purposely misalign with the user’s actual physiological rhythm to force the user to “stop and listen” to their own body (Höök, 2018). By introducing intentional defamiliarisation or visible seams to disrupt habituation, users are encouraged to reflect on the system’s underlying mechanisms, limitations, and affordances (Chalmers & Galani, 2004). This helps deepen the user’s understanding of the technology, allowing them to explore and question the relationship between the system and themselves, as well as its integration into their everyday activities and social interactions.

7.4.3 Background Superpower: Peripheral interaction and granularity

Background superpower experiences occur when augmentation provides continuous support without demanding cognitive resources. Unlike the implicit integration of empowering experiences, the system operates alongside the user as a distinct but unobtrusive presence. Designers could achieve this presence by shifting the locus of interaction from the centre of attention to the periphery, allowing users to control augmentations through low-attention processing while maintaining focus on the real world (Bakker et al., 2016). As noted in the analysis of Wi-Fi Twinge, the superpower becomes a background experience when the body learns to ignore it. Therefore, designers should utilise perceptual channels that bypass visual attention, allowing the user’s primary focus to remain on the physical environment. For example, Pielot et al. (2012) work on tactile way-finding demonstrated that by mapping directional cues to a vibrotactile belt, the system creates a “sixth sense” that intuitively guides navigation, removing the need to interpret visual maps. In a superpower context, this implies that output should be mapped to haptic or ambient modalities that trigger instinctive responses rather than analytical responses.

Furthermore, to ensure the system maintains implicit awareness, designers need to consider the granularity of interaction. High-granularity interaction, such as high-precision tasks, fine motor control or complex decision-making, inevitably forces an unwanted attentional shift. Therefore, background superpowers should be designed for coarse microinteractions, defined by Wolf (2011) as brief interactions (under four seconds) that are simple to perform without breaking flow, such as broad gestures or binary toggles. Through procedural motor habituation, these actions become automatic, allowing interaction to operate seamlessly in the background without requiring the user's conscious focus.

7.4.4 Directive Superpower: Negotiable control and explainability

Directive superpower experiences occur when the system acts as a mentor or guide, influencing user behaviour through persuasion rather than coercion. Unlike the passive support of background experiences, directive systems demand attention to reshape decision-making. Designers can achieve this collaboration by establishing negotiable control, where the system provides scaffolding support that the user can choose to accept or override (Fogg, 2002). Users should have the right to question or modify the system's instructions to preserve their sense of agency. As observed in EmoPals, the system became directive when it subtly prompted users towards empathy via facial actuation. The actuation here is not a mechanical override, but a somatic cue, serving as a tangible representation of emotion that the user could choose to inhabit or resist. This somatic support is beneficial because it functions as a form of embodied priming, effectively lowering the cognitive threshold for action (Clark, 2010). By offering a bodily template, such as a predefined facial expression, this mechanism bridges the gap between perception and response, thereby reducing the effort required to formulate an empathetic reaction from scratch (Niedenthal, 2007). The cue thus creates a path of least resistance towards the target behaviour while ensuring the final locus of control remains with the user.

Furthermore, to prevent the guidance from feeling coercive, designers need to consider the explainability of intent. If a user does not understand why the system is directing them, the directions can create frustration. Therefore, directive superpowers should be designed with transparent, intuitive cues that function as suggestions rather than commands to communicate the system's logic, similar to "guidance-as-needed" paradigms in motor learning where the system only interferes when the user deviates significantly (Feygin et al., 2002). In a superpower context, this implies that the augmentation should exert influence proportional to the deviation, providing cues that have semantic meaning, such as increasing physical resistance to indicate a specific boundary or safety limit. Designers should contextualise the augmentation with clear intent, ensure that the guidance is perceived as a resource rather than a violation, transforming the interaction from a contest of wills into a co-authored negotiation.

7.4.5 Deceptive Superpower: Benevolent deception and revelation

Deceptive superpower experiences occur when the system manipulates perception without the user's conscious detection through ambiguity or illusion, creating a divergence between the system's objective behaviour and the user's subjective experience. Designers could use this divergence to enhance perceived capability by employing benevolent deception (Adar et al., 2013) to intentionally generate sensory cues that construct a coherent reality, regardless of the system's actual functional state. This approach leverages "automation bias" (Parasuraman & Riley, 1997), where users subconsciously trust and rationalise the system's output as truthful, allowing the fabrication to bypass critical scrutiny. As noted in the analysis of the Flytrap Hand, the experience became deceptive when users perceived patterns in purely random signals. The system successfully manipulated the users' reality, leading them to believe they were learning a skill when they were merely adapting to noise. By keeping the fabrication within the realm of implicit awareness, the system constructs a placebo effect (Dunne & Raby, 2021; Vaccaro et al., 2018; Villa et al., 2023), effectively enhancing user confidence through manipulated belief rather than functional instrumentality.

Furthermore, designers need to consider the mechanism of revelation to eliminate uncertainty and allow users to understand the manipulative behaviour, ensuring the design remains ethical. Permanent deception risks eroding trust (Adar et al., 2013). Therefore, deceptive superpowers should be designed as pedagogical loops that eventually reveal the truth, such as through a breakdown in the illusion or a post-experience debriefing. Through this revelation, deception serves as a tool of critical design, prompting users to reflect on their dependency on the system and the malleability of their own self-perception (Dunne & Raby, 2013).

7.4.6 Intrusive Superpower: Safe confrontation and temporal rhythm

Intrusive superpower experiences occur when the system momentarily overrides user control, creating a visceral sensation of being possessed by the technology. This experience can be designed to intentionally interfere with the user's agency to generate a high level of engagement. To implement intrusive superpowers responsibly, designers should consider adopting a strategy of safe confrontation, using the discomfort of lost control to challenge the user's bodily limits within ethical bounds (Benford et al., 2012). This strategy does not completely avoid discomfort, but it designs controlled disruptions that expose users to partial loss of control while ensuring their physical and mental safety, such as reversible augmentation, clear consent protocols, and immediate exit mechanisms. As observed in the Flytrap Hand study, users experienced an intrusive superpower when unexpected actuation conflicted with their residual control, compelling them to "fight" against the system. Consequently, designers should ensure that disruptions are framed by strict safety protocols, using involuntary actuation not as a violation, but as a mechanism for rapid pedagogical transfer or instinctual reaction, similar to systems that employ electrical stimulation to guide learning through direct muscle manipulation (Lopes et al., 2015; Tamaki et al., 2011). The safety boundaries also create a reflective space where users can safely interrogate who holds control, whether the body, the system, or the space in between.

Furthermore, to ensure the experience remains engaging, designers need to consider the duration of intrusion. Prolonged intrusive experiences may lead to physical fatigue and psychological rejection. Therefore, intrusive superpowers should be designed with a temporal rhythm that alternates between high-intensity system dominance and low-intensity user recovery (Mueller et al., 2011). Through this tension-release cycle, the user has time to cognitively process the influences of the augmentation, allowing the intrusive moment to be integrated as an exciting extension of capability rather than a loss of self (Benford et al., 2012). The design goal of intrusive superpower is to invite users to confront the discomfort of technological possession, encouraging them to reimagine what agency might mean in superpower forms.

7.5 Descriptive Validation

To evaluate the descriptive validity of the proposed framework, a five-day field study was conducted with an updated version of the Flytrap Hand system. This version retained only the body control setting, in which muscle stimulation for grasping and releasing was directly triggered by the system based on distance detection, removing the randomised time control condition. This validation aimed to explore whether the framework can capture and explain the lived trajectories of superpower experiences over extended real-world interaction. By moving beyond short-term laboratory observation, this study sought to examine whether the theoretical distinctions between experience types remain meaningful when users encounter superpower in their daily routines.

7.5.1 Method

Eight participants (4 female, 4 male, none non-binary or self-described; aged 21–34) were recruited to use the Flytrap Hand in their daily activities across five consecutive days. All participants had prior familiarity with interactive or wearable technologies but no previous experience with electrical muscle stimulation. Each participant wore the system for approximately half an hour per day, incorporating it into naturalistic activities such as picking up everyday objects, organising desks, or transporting lightweight items. Each participant kept a daily reflective diary describing their sensations, expectations, and perceived changes in control and familiarity. In addition, semi-structured interviews were conducted after the five-day study, allowing me to trace both the embodied and reflective evolution of superpower experiences.

7.5.2 Analytic Procedure

The data analysis proceeded in two stages, combining thematic interpretation with framework mapping. First, a reflexive thematic analysis (Braun & Clarke, 2019a, 2021) was conducted on transcribed interviews and diaries. Codes were generated inductively to capture experiential moments. These were

Figure 7.9: A participant shakes hands with another person while wearing the Flytrap Hand system.

then grouped into higher-level themes reflecting transitions between superpower types. Second, the qualitative data were recontextualised within the theoretical framework. Participants' self-mapped positions were aggregated to visualise collective trajectories across the three axes and to identify recurring transition pathways. These patterns were then interpreted to assess how well the framework captured participants' relationships with the system across time and contexts.

7.5.3 Findings

The analysis revealed that the participants' experiences evolved through four distinct phases: intrusive, directive, background, and empowering. Each phase corresponded to shifts in users' sense of control, awareness, and stability of the system. These transitions echo the trajectories outlined in the framework.

In the first two days, most participants described feelings consistent with the Intrusive Superpower. Although the system's stimulation patterns were predictable in logic, their bodily feelings were unpredictable. Users frequently reported “shock” and “strange” when their hand closed before they consciously intended to act. P3 stated: *“I knew what it was going to do, but I still feared every time. My body didn’t trust it yet”*. The explicit awareness of external actuation and involuntary muscle movement induced confusion and vigilance. Participants hesitated to bring their hands close to objects, describing the stimulation as “possessive” (P5). Four participants reported pausing in their early stage: *“[I] had to wait for the system to finish moving before resuming original action”* (P2). This phase was dominated by volatility, where bodily control was repeatedly interrupted by system interference. Despite it, three participants expressed curiosity and described the experience as *“magical”* (P1), *“superpower”*(P2), and *“kind of like my hand has its own brain”*(P7).

By the middle of the study (days three and four), participants began to adapt to the system’s behaviour. They no longer described it as purely intrusive but as something that could be “*anticipated and managed*” (P6). Their experience moved toward the Directive Superpower zone. Two participants reported that they learned to adjust the speed when their hand approached the object so that the EMS trigger would occur at a convenient moment. For example, P7 said: *“I’d slow down just before touching something, so the grab felt less surprising”*. This period reflected a shift from reactive to active engagement. The system remained in control, but participants began to internalise its timing, treating it as a partner with its own behavioural logic, as P1 explained: *“At first, it scared me because I didn’t know when it would act. Now I think of it like a partner. It’s still in charge, but I’ve learned how to move with it”*. Participants experienced the Flytrap Hand as a guiding force that could be negotiated with, and were aware of their own bodies and the system’s actions. However, adaptation brought new forms of cognitive load. Several participants mentioned the mental effort required to coordinate with the system’s augmented grasping, as P4 stated: *“It’s tiring to always think one step ahead of it”*.

Toward the final days, instances of Background Superpower and Empowering Superpower emerged. Participants described moments when stimulation was *“hard to notice”* (P2) or when the hand’s automated movement *“felt like my own action”* (P8). In these moments, the augmentation transitioned into an embodied action, operating below conscious attention. The stimulation faded into the background of their motor experience, allowing them to focus on the task rather than on the device. Four participants even described the system as helping or supporting their movements. For example, P1 said: *“I didn’t notice the stimulation anymore. It was just part of how I grabbed things”*. Participants also described reduced excitement and emotional flatness about the system in the final days, interpreting it as *“just a tool”* (P4), but felt their own abilities were enhanced, as P3 explained: *“Now, I feel like my hand movements are faster, and my grip strength is also stronger”*. However, this experience is not always stable and positive, and unexpected electrical stimulation could quickly revert the experience to an intrusive state.

The findings demonstrated that superpower experiences evolve as trajectories rather than discrete or static states. Participants’ transitions across intrusive, directive, background, and empowering phases aligned with the framework’s emphasis on the evolving interplay among agency, awareness, and temporal stability. The study also supported the claim that experiential shifts occur even when system parameters remain unchanged. As participants adapted to the consistent behaviour of the Flytrap Hand, their experiences changed substantially, highlighting that superpower experiences emerge through ongoing negotiation between bodily expectations and system actuation.

However, the deceptive and reflexive experience types were not fully observed within this validation setting, as the updated Flytrap Hand operated with a single, transparent actuation logic. Deceptive experiences rely on fluctuating system mappings or ambiguous feedback and require conditions in which users are uncertain about whether actions originate from themselves or the system. Similarly, reflexive experiences emerge when augmentation becomes a medium for self-monitoring or reflection, commonly arising in systems that modulate cognition or emotion rather than motor control. The configuration of this system cannot support the above conditions.

Chapter 8

Conclusion

In this thesis, I set out to answer the question: *How do we design superpower experiences while considering their fortunate and unfortunate negative effects?* To explore this question, I designed and studied three systems: Wi-Fi Twinge, EmoPals, and Flytrap Hand. Across these systems, I examined how users experience augmentation that feels beyond the ordinary ("empowering") but carries inherent unpredictability or discomfort. These explorations revealed that superpower experiences are not uniformly empowering, but are shaped by fluctuating relations between agency, awareness, and temporal stability. Through iterative analysis, I developed the Superpower Experiences Framework, which theorises how augmentation technologies generate diverse experiential patterns, ranging from empowering and reflective to intrusive and deceptive. The framework both descriptively explains the user experiences afforded by human augmentations and prescriptively suggests how designers can develop systems to produce an intended user experience.

8.1 Contributions to Knowledge

This thesis makes the following contributions to knowledge:

- This research contributes to design knowledge by documenting the design of three experiential prototypes: Wi-Fi Twinge, EmoPals, and Flytrap Hand. Each system explores a distinct mode of human augmentation: perception, cognition, and action. Through the development and evaluation of these systems, the thesis provides empirical and methodological insights into how augmentation can be designed and experienced as superpowers.

- This research contributes to design theory by introducing and elaborating the concept of the superpower experience as a lens for understanding human augmentation. It extends existing frameworks of human augmentation to encompass experiences that are simultaneously fortunate and unfortunate. This theoretical perspective shifts focus from performance and efficiency toward experiential aspects, enriching the theoretical understanding of how agency, trust, and embodiment evolve in HCI.
- This research presents the Superpower Experiences Framework, the theoretical conceptualisation of how to design and analyse augmentation through the dynamic interaction of agency, awareness, and temporal stability. The framework was derived from the synthesis of findings across the three case studies, each of which surfaced recurring experiential patterns and tensions. These insights revealed how users move between empowering, reflective, background, directive, intrusive, and deceptive superpower states over time. The framework provides a high-level understanding of the design space of human augmentation, offering descriptive value for researchers analysing how users interpret and position their superpower experiences, and prescriptive value for designers by guiding them toward an intended user experience.

8.2 Limitations and Future Work

This research has inherent limitations that should be acknowledged. Firstly, the primary contribution of this thesis lies in the development of the Superpower Experiences Framework, which was informed by three distinct case studies. These case studies provide a foundation for understanding how superpower experiences emerge across different modalities of augmentation. However, given their preliminary and exploratory nature, these case studies might not fully capture the range of possible superpower experiences, nor account for how such experiences might differ across longer timescales, larger populations, or alternative technological domains. Future research should expand upon these case studies to deepen our understanding of the complexities involved in superpower experience design, and I hope that my work could serve as a theoretical springboard for such broad-scale investigations.

Another limitation concerns the scope and duration of participant engagement. Each prototype was studied with relatively small participant numbers, typically in short-term deployments. While these studies provided rich qualitative depth, larger-scale and longer-term engagements are necessary to observe how users' perceptions and bodily responses evolve as augmented systems become integrated into everyday life. Future longitudinal studies that span several weeks or months could reveal deeper patterns of habituation, trust reconstruction, or ethical reflection. Future studies could also incorporate more demographically and culturally diverse participant populations to better understand how superpower experiences may vary across, for example, age groups, professional backgrounds, bodily abilities, and prior technological familiarity. I hope that the qualitative insights provided in this work will serve as a necessary baseline for structuring and interpreting the data from future longitudinal studies.

Additionally, the Superpower Experiences Framework has been articulated primarily from a qualitative phenomenological perspective. While some behavioural data (such as task completion time or adaptation patterns) were used to support analysis, these served mainly to contextualise participants' experiential accounts rather than to verify the higher-level theoretical constructs of the framework empirically. The synthesis of the framework drew heavily on thematic analyses of post-study interviews, reflective diaries, and designer observations across multiple prototype iterations. Given that the design of superpower experiences remains an emerging and underexplored area within HCI, a qualitative approach was the most appropriate foundation for theory building. Future research could empirically validate this framework to bridge qualitative design research with quantitative evidence, enabling comparative evaluation across augmentation systems. For example, the three axes of the framework (agency, awareness, and temporal stability) could be formalised into measurable constructs, such as physiological data measurement and longitudinal data tracking. Future validation work could also apply the framework to external case studies beyond the systems developed in this thesis, enabling an examination across independently developed augmentation technologies to strengthen the framework's generalisability.

Another limitation of this framework lies in its validation approach. The evaluation conducted in this thesis is primarily descriptive, focusing on interpreting and mapping existing user experiences within the proposed dimensions of superpower design. While this descriptive validation provides conceptual clarity and demonstrates the framework's interpretive power that can serve as a platform for the subsequent development of these actionable prescriptive design tools, it does not constitute prescriptive validation that evaluates the framework's applicability in guiding the design of new systems or predicting user responses in future implementations. Further research is therefore needed to examine how the framework can inform design practice, support iterative prototyping, and generate empirically grounded design principles that extend beyond interpretation to actionable prescription. In the end, such work could contribute toward the development of practical design guardrails and ethical evaluation methods for augmentation technologies.

Finally, future work should also evaluate the transferability of the Superpower Experiences Framework across other technological modalities, such as human-robot interaction, immersive XR systems, or AI-mediated systems. Validating on different technological modalities will reveal whether the three proposed dimensions apply to forms beyond EMS, or whether adjustments are needed for specific domains. Future work could also investigate practical, non-speculative and necessity-driven contexts in which augmentation serves functional or rehabilitative purposes rather than optional enhancement alone, such as assistive technologies for people with disabilities, rehabilitation systems, clinical interventions or geotechnology applications. Examining these contexts may reveal additional ethical, emotional, and social dimensions that differ from elective superpower experiences. Taken together, these directions position the Superpower Experiences Framework as a transferable analytical lens for future research in human augmentation and related fields, with potential to support a more unified understanding of the domain.

8.3 Final Remarks

Throughout this thesis, I have explored how the design of superpower experiences can reveal both the fortunate and unfortunate sides of human augmentation. What began as a series of design experiments ultimately developed into a deeper question about what it means to be human in an era of technological intimacy. As systems grow capable of extending our physical abilities while also guiding our emotions, shaping our cognition, and anticipating our intentions, the core question of HA switches from how to enhance the human body to how to coexist with technologies that think, feel, and act alongside us.

We live in a time when the figure of the superhero has become darker and more ethically complex, mirroring our evolving relationship with intelligent systems. The dark superhero symbolises our ambivalence: the thrill of augmentation intertwined with fear of domination, the desire to transcend human limits accompanied by anxiety of losing essential human qualities. This is the heart of superpower design. The frameworks and prototypes presented in this thesis are not intended to achieve seamless integration, but rather to focus on the conflicts that arise between technology and ourselves, moments when technology resists us, deceives us, or overwhelms us. It is through these experiences that we can see ourselves more clearly.

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