Exploring Superpower Design Through Wi-Fi Twinge

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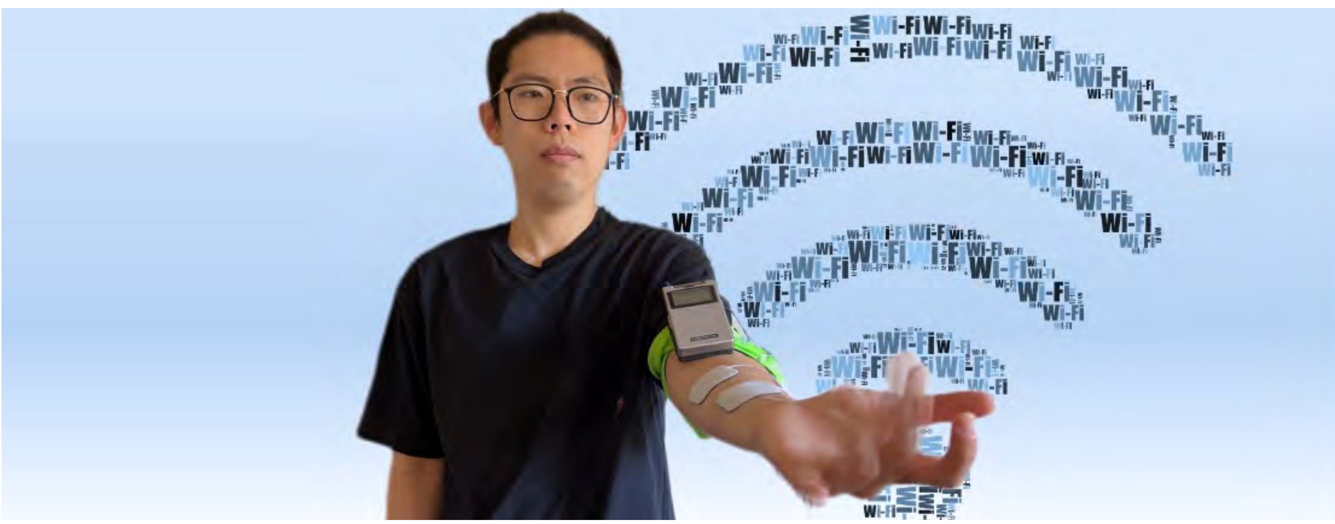

Figure 1: Wi-Fi Twinge, a system that aims to help understand superpower design by twinging the user's hand via electrical muscle stimulation in the presence of ambient Wi-Fi.

ABSTRACT

Technology-facilitated "superpowers" are a popular topic in human-computer interaction, providing people with the experience of having superhero-like fantastic abilities. However, science fiction literature tells us that superpowers can also be unfortunate. We designed Wi-Fi Twinge, a system that uses electrical muscle stimulation to extend human perception to sense unseen Wi-Fi signals, giving people an allergy-like twinge reaction to Wi-Fi: a superpower that can be seen as unfortunate while also having potential benefits. Through an in-the-wild study, interviews with 12 participants revealed that although the superpower from Wi-Fi Twinge induced negative feelings and impacted certain day-to-day activities, it improved awareness of self and the surrounding environment. We used these results to offer design tactics for creating future superpower systems that consider potential unfortunate side effects. Ultimately, we aim to advance our understanding of technology-facilitated superpowers.

TEI '24, February 11–14, 2024, Cork, Ireland

ACM ISBN 979-8-4007-0402-4/24/02…$15.00
https://doi.org/10.1145/3623509.3633352

CCS CONCEPTS

• **Human-centered computing** → **Interaction paradigms**.

KEYWORDS

superpower, augmented human, electrical muscle stimulation, wearables, human augmentation

ACM Reference Format:
Siyi Liu, Nathan Semertzidis, Gun A. Lee, Florian 'Floyd' Mueller, and Barrett Ens. 2024. Exploring Superpower Design Through Wi-Fi Twinge. In *Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24), February 11–14, 2024, Cork, Ireland*. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3623509.3633352

1 INTRODUCTION

Technology is getting closer to the body [64, 65], in particular, people are beginning to use their bodies to interact with computers in novel ways, giving rise to human augmentation technology [26, 84] that can extend human capabilities. This can enable people to experience what it might be like to have a "superpower", a capability beyond natural human ability that is experienced as intrinsic (originating from the individual) [14], realising the visions shown in science fiction. Examples of this include flying via virtual reality [85], X-ray vision via augmented reality [5], and telekinesis via brain-computer interfaces [21].

However, as we learn from the many cautionary tales that populate the literary corpus of science fiction, superpowers often come with unfortunate side effects. Examples include Rogue's ability to absorb power by touching people and leaving them in a weakened state (X-Men) [2], and Banner's ability to transform into the Hulk with an enhanced body and immense strength but also uncontrolled destructive tendencies (Marvel Comics) [1]. We call these "unfortunate" superpowers: superpowers with unpredictable negative consequences, even if they also have fantastic positive effects. Such "unfortunate" superpowers are characterised by a lack of or loss of control, resulting in the person experiencing a reduced sense of agency, i.e., the feeling of control over actions and their consequences. With this considered, it is arguable that in addition to the positive superpower-like experience enabled by human augmentation technologies, there also exists the potential for such technologies to produce an "unfortunate" superpower experience.

While previous research has examined the side effects of enhancing human capabilities with a focus on ethics [48, 73] and privacy issues [4, 99], the "unfortunate" experiential side effects of enhancing human abilities have received little attention. We are inspired by prior work that has explored "dark patterns" [16, 17, 24], which investigated the potential for deception and misuse in the design of new technologies, with the aim of shining light on these before they can be exploited by bad actors. Given the imminent uptake of emerging and future technologies [63], we believe that it is critical to carefully consider and mitigate the risks that users may face before they become widely adopted into the mainstream. We see the opportunity to investigate "unfortunate" superpowers as a mean to preemptively alleviate any negative side effects. As such, we believe that there is potential to investigate intentionally designing "unfortunate" superpowers that still have potential benefits to provide design knowledge to help avoid mistakes that may be difficult to rectify in hindsight.

We investigate these ideas through the design and study of "Wi-Fi Twinge" (Figure 1), 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 has become a fundamental part of people's everyday work and social life, yet we still have no innate Wi-Fi sense: it is still unseen and invisible. Considering this, we imagine a future where humans have evolved or augmented themselves to sense streams of technological processes such as Wi-Fi. To explore this, we designed Wi-Fi Twinge, which allows people to have an embodied sense of when Wi-Fi surrounds them by receiving different electrical stimulation wave patterns based on the surrounding Wi-Fi signal.

We consider sensing Wi-Fi a superpower because it provides an opportunity to expand the human senses and provides a superhuman experience of amplifying human perception via embodied channels inherent to human experience (i.e., the proprioception of flexion in reaction to Wi-Fi), in contrast to simply observing a reading provided by some external device [88]. The human body becomes an innate interface through which people experience their extra sensory abilities. Furthermore, the experience of sensing Wi-Fi holds similarities to science fiction superpowers, such as the ability to see into the spirit realm. With sensing Wi-Fi, people can optimise their wireless connectivity experience by maintaining a constant network connection while moving and facilitating communication. At the same time, it is also "unfortunate" in that it creates short-term bodily twinge reactions in the form of involuntary hand movements through the use of EMS. This could lead to negative impacts on daily activities, such as when the hands are involved in other tasks and the EMS actuation interrupts and hinders this activity.

In this paper, we detailed the design and evaluation of Wi-Fi Twinge through a 5-day in-the-wild study with 12 participants who were instructed to use the prototype in their everyday lives. We employed a statistical analysis of the Sense of Agency Scale (SoAS) and a thematic analysis of the interviews to induce insights gained from studying the user experience of Wi-Fi Twinge. The results suggested that Wi-Fi Twinge can elicit negative physical sensations that lead to discomfort and inconvenience in daily life (Figure 2), but also increases users' awareness of their bodies and the environment, indirectly changing their activities, facilitates reflection on themselves, and in some cases contributes to their overall well-being. We interpreted these results and provided design tactics to inform the discussion and design of superpower systems moving forward.

Figure 2: Wi-Fi Twinge usage scenarios: (a) Finger flexion affects operating a controller; (b) Finger flexion affects typing at work.

In summary, this paper makes three contributions:

- A system contribution in the form of an unfortunate superpower system that extends human perception to unseen Wi-Fi signals using EMS. This contribution could be useful

for system designers seeking inspiration on what types of superpower systems they could design, including unfortunate ones.
- An empirical contribution in the form of a thematic analysis of the interviews and a statistical analysis of the Sense of Agency Scale from an in-the-wild study with 12 participants using our system over 5 days. This contribution could be helpful for user experience researchers interested in understanding both the negative and positive experiences of superpowers.
- A design contribution in the form of a set of design tactics for the creation of future superpowers. These design tactics could be useful for human augmentation researchers when aiming to analyse existing superpowers, while also guiding the design of new systems toward the designer's intended user experience.

Ultimately, we aim to bring new opportunities for human augmentation through the lens of the underexplored perspective of unfortunate superpowers to advance our understanding of technology-facilitated superpower experiences especially considering not only their potential but also any possible unfortunate side effects and guide the future design of superpower systems.

2 RELATED WORK

In this section, we discuss related work, in particular, what we learned from prior research on superpower experiences, sensing invisible waves, actuating the body through EMS, and the sense of agency.

2.1 Superpower experiences

The concept of superpowers and characters with extraordinary abilities can be traced back to ancient mythology and folklore, which can be argued laid the groundwork for the development of superpower and superhero stories in modern literature and popular culture [40, 69, 81]. The contemporary use of the term "superpower" that refers to the possession of abilities beyond the ordinary appeared to start in the 1930s in American comic books and we find that it gradually found its way into other genres and media [18]. Transhumanism was then popularised, as a philosophical and intellectual movement advocating the use of technology and science to transcend the limitations of the human condition and achieve human augmentation and life extension [32, 61]. Likely inspired by the rising popularity of these concepts, researchers have explored various ways such as by using immersive technologies as used in human-computer interaction (HCI) research to give people the experience of having superpowers [100]. For example, Kenna et al. [39] 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" [62]. Similarly, Ishibashi et al. [34] presented the "Spider Hero" virtual reality system that allows the wearer to jump between buildings like Spider-Man via a web-shooting device. More recently, Kunze et al. [43] created superhuman sports, an application field that combines the athletic elements of sports with technology in order to overcome the physical limitations of the human body to achieve superhuman senses and abilities. For example, Lehtonen et al. [45] presented the "Super Stomp" mixed-reality trampoline game that grants players with superhuman abilities by exaggerating jump distance and providing aural and visual feedback in the game to augment their movement ability in the real world.

Research has shown that human augmentation provides novel opportunities for bodily experiences [84], which encompasses many genres: biomedical implants and prostheses that replace or restore human functions [6, 23, 104]; exoskeletons and wearable devices that extend physical abilities [90, 103]; and collaborative or assistive robots that monitor and motivate human work [59]. These systems show us that superpowers can be seen as an experience achieved by human augmentation technologies to empower the individual. Therefore, in this paper, we consider human augmentation to be the use of technology to realise the extension of human capabilities, which can at times produce the experience of having a superpower. Superpower experiences are a specific subset of experiences generated by human augmentation that involve the user perceiving the ability bestowed on them by the augmentation as intrinsically emerging from their own innate abilities (e.g. their own physiology). However, the prior work overlooked the potential tendency for such technologies to also produce negative effects. For example, what if users hear something with their augmented hearing superpower that they do not want to or should not hear?

Although prior research found superpowers worth investigating and various approaches have been explored in terms of technological contributions [85, 100], our knowledge of how to design superpowers while considering their negative side effects is limited. We believe that this is, at least in part, due to a limited understanding of the experience of having a superpower, not only including all its benefits but also unfortunate side effects. Hence, with our work, we aim to address this knowledge gap. In particular, we aim to contribute to our understanding of the design of superpowers by beginning with an "unfortunate" superpower that triggers an allergy-like twinge reaction to Wi-Fi signals.

2.2 Sensing invisible waves

Sensing invisible waves like Wi-Fi signals through visual assistance systems has been the subject of previous HCI research. For example, Mann et al. [56] designed an augmented reality (AR) system that enables users to see, understand and photograph the otherwise invisible electromagnetic waves. Grönvall et al. [25] presented a system to turn radio signals into visual and tactile stimuli to give users new bodily experiences. Other examples include depth and thermal cameras for exploring environments that are invisible to the naked eye [3], and a field-of-view visualisation system to make vision itself visible [55]. We draw from such work that investigated systems of sensing invisible waves to explore the angle for sensing Wi-Fi signals via amplifying an existing perception and augmenting the current bodily response. We argue such user experiences may be improved through using the user's own physiology as the medium of information communication, lowering the user's awareness of the presence of their technology, as it is integrated into daily life and cannot be distinguished from their native senses. When technologies disappear in this way, users might be able to freely use them without thinking and might appear to begin to trust that the superpower is a permanent force from users themselves [79, 86].

2.3 Actuating the body through electrical muscle stimulation

Over the past decades in the field of HCI, researchers have built several systems based on electrical muscle stimulation (EMS) as output paradigms to actuate the user's body [53, 95]. EMS delivers electrical signals to muscles, typically via non-invasive surface electrodes placed on the skin [80]. The electrical signals elicit action potentials on motor nerves, which leads to muscle fibres contracting [58]. EMS electrodes allow the user to operate their hands relatively unencumbered due to their small form factor and portability [95]. Prior research has highlighted the growing popularity of using EMS in interactive systems, including in applications such as instructing intricate movements [94], providing force feedback [52] and playing games with one's own body [74, 75]. For example, Pfeiffer et al. [80] proposed a pedestrian navigation system that changes walking direction by stimulating the sartorius muscle. The associated systems were inspiring for us as they suggested that EMS technology could be beneficial for superpower-like experiences as it uses the body's own muscles.

The use of EMS rather than other haptic feedback modalities (e.g. a vibrotactile motor) requires users to sense Wi-Fi through interoceptive processes (specifically proprioception) [78], which might heighten the experience of the sensation emerging from their own innate physiological processes, speaking to the thought that users might regard the ability to sense Wi-Fi to be part of their own abilities. Another technology we could have used would have been an exoskeleton [15, 22]. However, we did not choose an exoskeleton because we thought it might be difficult to wear, hindering the user through its physical form factor in everyday life even when it is not triggered, affecting the user's feeling of having a superpower by replacing it with a feeling of wearing a machine that has a superpower [13, 27]. Furthermore, we found most exoskeletons to be heavy, hindering our participants from wearing them for longer periods [87].

However, even though EMS has now reached unprecedented levels of dexterity, such as allowing individual fingers to flex independently [93], EMS-based interactions suffer from limitations on actuation: it is an involuntary muscle contraction that can cause discomfort or even distract the user [41]. As a result, we argue it might be an "unfortunate" side effect if people perceive that such muscle movements are initiated and controlled by the EMS rather than by themselves. When electrical muscle stimulation actuates movement, people may not be able to recognise who is in control of their body and experience their body as something else [75]. This may affect their sense of control over their bodies and thus their sense of agency, which is an important determinant of whether the augmentation experience will be perceived as a superpower.

2.4 Sense of agency

The sense of agency (SoA) is the "experience of initiating and controlling an action" [10]. Agency involves the feeling of voluntary control of bodily movement and the judgement of the cognitive experience of ownership [92]. It distinguishes self-generated and self-controlled actions from actions generated and controlled by others [60]. For example, we have mostly accurate and voluntary control when we move our body, hence we know it is obedient to our own will rather than a machine or someone else compelling us to move. 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 [28].

Research has found that physically actuating the human body (such as through EMS) can lead to a loss of feeling of agency because users have less control over their bodies [76]. However, the sense of agency is not entirely objective, and current work in EMS showed that the user's sense of agency can be partially preserved by delivering EMS impulses that enable the user and the system to move congruently, but complete retention cannot be achieved [38]. These previous works inform us that the sense of agency should be considered when designing interactive systems. However, the associated studies did not investigate how a sense of agency is affected by introducing a superpower. This could be important to know, as superpower design often involves introducing a system component that may have an impact on the control of the human body, which can significantly shape the overall experience [67, 68].

The Sense of Agency Scale (SoAS) was developed to directly assess the general sense of agency [96]. It was derived from a factor analysis based on a review of the psychological literature and validated in different populations with good psychometric properties [31]. According to the factor structure, 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. With this considered, we decided to ask our participants about their sense of agency using this scale. We hoped that this might enhance our knowledge of the design of superpowers by understanding how participants' sense of agency is affected.

Taken together, although prior work explored superpower design and used EMS to augment bodily experiences, there seems to be still only limited knowledge about how to design superpowers, especially considering not only their potential but also any possible unfortunate side effects. To begin closing this gap, our work aims to answer the following research question: How do we design superpowers, especially considering both their potential and any possible unfortunate side effects, beginning with an understanding of "unfortunate" superpowers?

3 WI-FI TWINGE DESIGN

To begin answering the question above, we designed "Wi-Fi Twinge". We ideated the design concept through discussions and explorations amongst ourselves, the authors, one of whom with 25 years and one of whom with 15 years of experience in interactive system design. Together, we have designed over 40 interactive systems over the years. We acknowledge that we could have engaged, for example, potential users in the design process, following a traditional user-centred design process [72]. However, we did not do this because we see our design as being more of a provocative artifact that serves as a research vehicle to explore a particular research question rather than a specific solution to an existing problem, speaking to the research-through-design tradition that values the creative craft of the designer [105].

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, we anticipate that the low sense of agency people experience over their fingers and wrists when actuated could result in an unfortunate superpower experience that users might prefer not to possess.

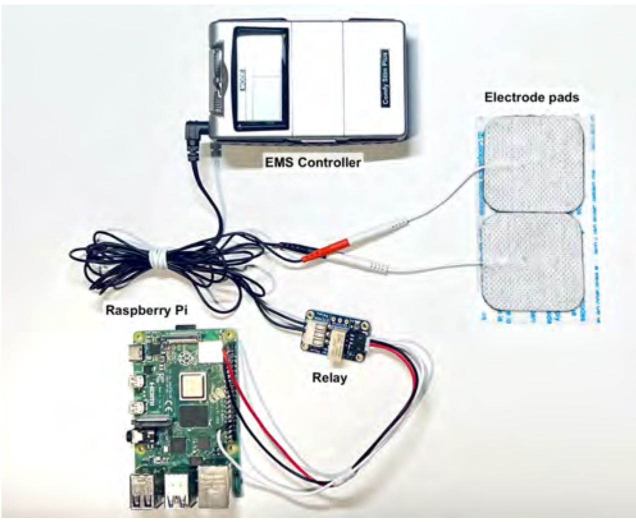

Figure 3: Wi-Fi Twinge's components.

3.1 System architecture

Wi-Fi Twinge comprises two main components: a "Raspberry Pi" and an EMS device ("Comfy EMS") with 2 self-adhesive electrode pads (Figure 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.

3.2 Wi-Fi sensing

We chose to sense Wi-Fi signals because Wi-Fi is easily sensed with mobile devices and does not need much power, allowing our device to feature a small form factor that enabled our 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 we anticipated that our participants might want to engage with our 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 [35, 57, 102], hence speaking nicely to our unfortunate side effects of superpowers. Therefore, we believed that focusing on Wi-Fi could be a worthwhile topic to investigate as part of an unfortunate superpower. We also considered other technologies, such as Bluetooth, however, 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 us to collect more data. However, we encourage future work to investigate other phenomena that can be sensed but are usually invisible to users, to further enhance our 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, we 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.

3.3 Mapping Wi-Fi signals to hand movements

To offer people the superpower of "feeling" Wi-Fi signals, we decided to consider sensory information in the form of muscle actuation that we 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 we also support the experience of perceiving Wi-Fi signals while the user might be busy otherwise (for example, when having a conversation) all while supporting ambient awareness (i.e., without the explicit need to click on a Wi-Fi signal strength button) [46]. Furthermore, we believe that our embodiment approach suits a wider range of users, as our 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 required to have knowledge that Wi-Fi signal strength is measured in dB. As such, the embodiment approach could be seen as more culture- and expertise-agnostic than the common screen-based apps for Wi-Fi strength.

We 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 [36]. Therefore, we believe that involuntary hand movements caused by muscle actuation, as a result of an unfortunate superpower, might lead to various negative side effects impacting daily life. However, at the same time, we believed 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).

To induce hand movements, we employed EMS as its use has been described previously in the literature as a successful way to promote body movement [20, 54, 77]. In addition, we were inspired by prior work that found that EMS use can facilitate novel bodily experiences, providing both positive and negative sensations [41, 74]. This aligned well with our intention to investigate superpower design including its positive and negative effects. The EMS device contains two electrodes (Figure 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.

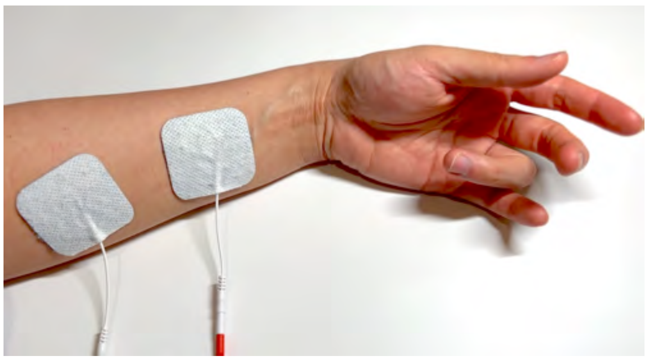

Figure 4: EMS's electrode placement and finger flexion.

3.4 Wave patterns for muscle stimulation

The EMS device we used ("Comfy EMS") 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). We could have designed our own EMS device to have more control, however, prior HCI research has suggested using commercial EMS devices for actual and perceived safety reasons [41, 53]. Therefore, we chose other attributes of EMS as variables: duty cycle and frequency to form 4 different monophonic wave patterns for muscle stimulation (Figure 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, we set the duty cycle to 0.8, 0.5, 0.29, 0.13 and 0 to reduce actuation time by 0.2 s in turns. Frequency is the count of the total work cycles (on and off phase in total) per second. Higher frequency means we turn the EMS on and off more frequently. We 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 0.2 s to match Wi-Fi signal strength levels.

We chose to adjust the duty cycle and frequency because we 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 [20]. Furthermore, we 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. We 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 [42, 44].

4 STUDY

The following section discusses the methods employed to conduct the in-the-wild study and evaluate our system, Wi-Fi Twinge. The 5-day study was designed to understand the user experience over a longer period. We wanted to see how users experienced the superpower the first time around, but also when they became more familiar with it. While we could have chosen a shorter study time, we wanted to ensure capturing a broad and comprehensive variety of experiences resulting from the EMS stimulation to ensure rigorous analysis. Another reason was that we wanted to ensure that participants were able to experience a variety of situations and activities where the superpower could have been perceived as either positive or negative. We could have also extended the study time, however, found the duration long enough for our participants to experience a wide range of everyday scenarios. Nevertheless, we acknowledge that future work could investigate longer study duration, such as 1 month.

4.1 Participants

We recruited 12 participants (6 men, 6 women, none non-binary and none self-described), aged between 27 to 33 years (mean = 29.08, SD = 2.02). Participants were recruited through advertisements by means of our 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. All participants volunteered for the study. The study was approved by the ethics committee of our institution and all participants provided written informed consent prior to their participation.

4.2 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 instruction 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, for showering, bathing or swimming. We also provided them with a video containing these instructions for reference at home.

To calibrate the system, participants were 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 the researcher. Next, the researcher checked the placement and calibrated the amplitude of the EMS current. Based on repeated tests on the researchers' bodies, we applied a constant EMS pulse-width of 200 µs and a pulse-rate of 100 Hz. Starting from 0 mA, participants were guided by the researcher to slowly increase the intensity by turning a dial on the EMS device until the desired intensity of movement was reached, where the participants' fingers and wrists flexed. Participants were 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

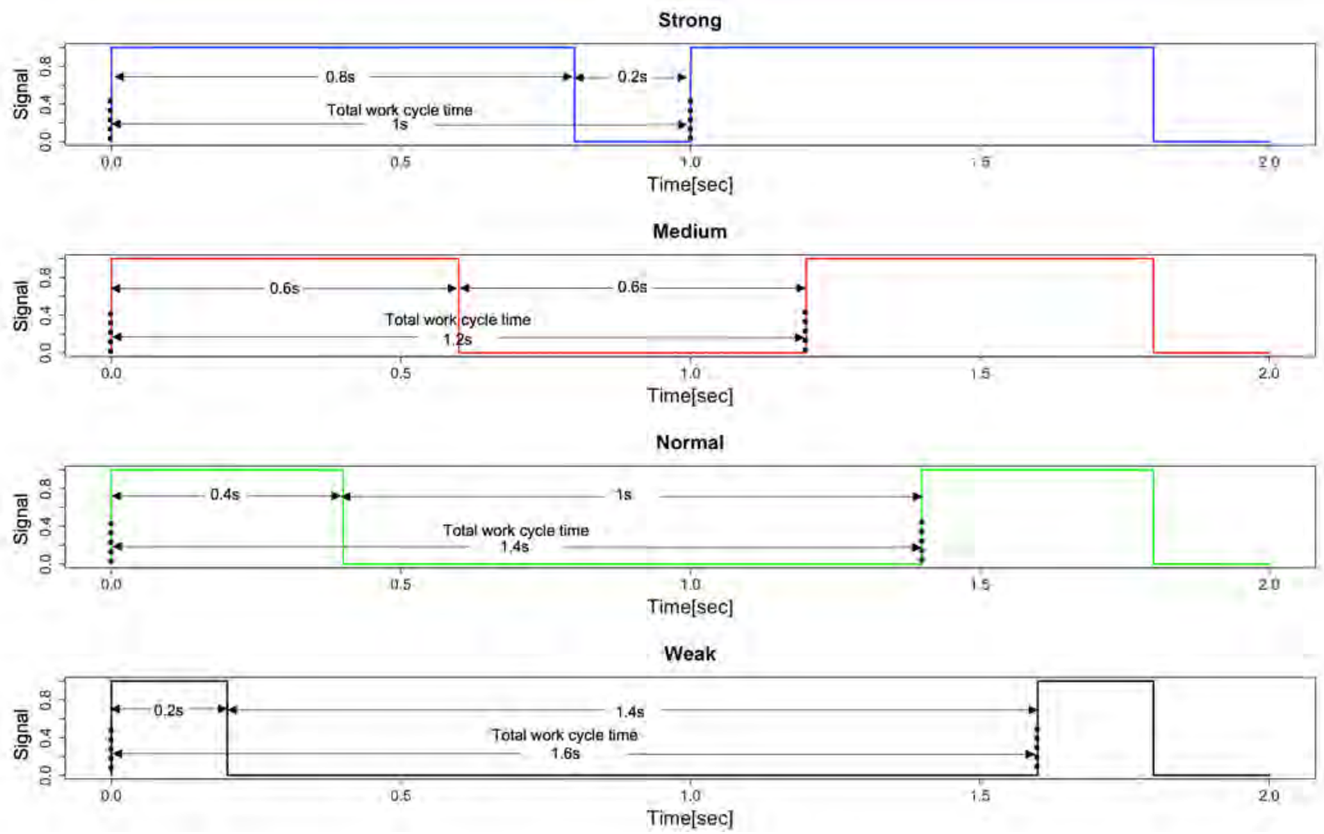

Figure 5: The EMS's signal for four levels of Wi-Fi strength from "strong" to "weak". Note that when the Wi-Fi strength is below "weak", no EMS simulation is presented (i.e., 0Hz). In the diagram, 0 and 1 represent the ON and OFF states; frequency is the count of total work cycles per second, i.e., frequency equals the inverse of the total work cycle time.

was given to the participants for later reference. During the study, we informed participants 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 participants 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 we aimed to understand the user experience in real-life situations. Participants were instructed that they could use the Wi-Fi Twinge system at any time of the day and anywhere, whether working, studying, entertaining, etc. We also instructed participants to "simply go about their daily activities as usual" (Figure 6).

After each use, participants were asked to complete a digital diary to record the activities they did, the time at which they wore the system, and how they felt while wearing the system. At the end of the 5 days, participants were asked to complete the Sense of Agency Scale (SoAS) [96]. We chose to ask participants to fill out the SoAS survey because we 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. We used this scale because it has been validated with good psychometric properties [31]. 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 our participants in the study [30, 91]. However, we did not investigate any specific tasks and our participants engaged in different activities during the study. Therefore, we believed that it would be difficult to gain meaningful insights from this data. Taken together, we believe that our use of the survey represents a valid and practical approach to answering our research question. However, we acknowledge that other surveys, including yet-to-be-developed ones around superpowers, used in future studies might complement our work.

Along with completing the SOAS, participants were required to take part in a semi-structured interview that lasted approximately 30 minutes. The interviews included 16 questions about participants' interactions with the system and any potential physical and emotional effects. Questions that we 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, we considered calibration differences in our interviews by always asking what the EMS experience was like, including how it felt and how the resulting movements looked. Furthermore, we asked participants to demonstrate how they used the system, including what intensity setting they used.

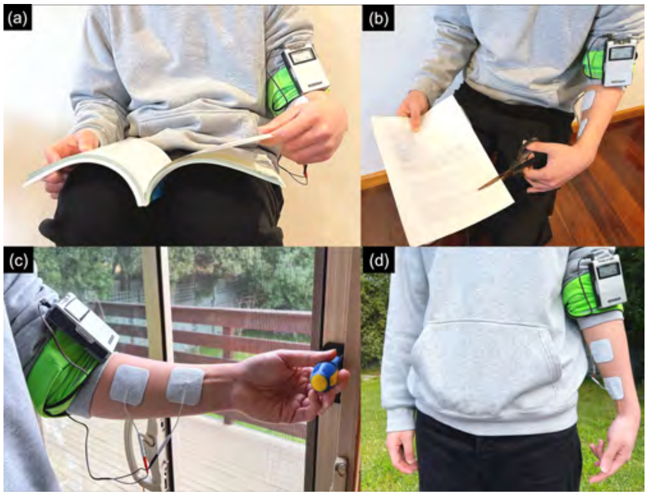

Figure 6: Some of the daily activities of the participants wearing the Wi-Fi Twinge system. (A) Turning the pages of a book. (B) Using a scissor. (C) Using a screwdriver. (D) Walking in the park.

4.3 Data analysis

As the Sense of Agency Scale is ordinal in a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree), we 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. We asked participants 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. We initially used the results of Hurault et al.'s study [31] as a baseline. However, in considering feedback from colleagues, we 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 of Hurault et al.'s study. 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, we decided to conduct a second round as a new baseline to allow for a multiple comparisons analysis which we could use to understand participants' sense of agency without the use of our 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 more pure report of their everyday sense of agency, leaving comparison purely to statistical analysis. We acknowledge that the 6-month follow-up survey might have included other unknown confounding effects.

To analyse the interview data, we employed thematic analysis [11, 12]. The inductive thematic analysis approach was used to identify themes by distilling and articulating meaning from the data. Interviews were audio recorded and transcribed for qualitative analysis in Nvivo. A question and a response from a participant were combined and considered as one unit of data. In total, 255 units of data were included in the analysis. Two researchers then read the transcripts three times to get familiar with the data and coded the data via the "Delphi method" [51] in which codes were iterated over four meetings in three weeks until codes were agreed upon across five researchers. Then, the codes were used to generate three high-level themes.

5 RESULTS

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

5.1 Quantitative analysis of sense of agency

Figure 7 shows the participants' responses to the Sense of Agency Scale. We found a significant difference in the SoNA score, in which the SoNA of Wi-Fi Twinge (mean = 11.25, SD = 4.90) was higher than the baseline (mean = 7.25, SD = 3.65), V = 66, p = 0.037 (Figure 8). The comparison of SoPA (mean = 17.58, SD = 6.57) and SoA (mean = 30.33, SD = 10.09) with the baseline (SoPA: mean = 20.25, SD = 4.41; SoA: mean = 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 our study compared to the baseline.

5.2 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 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.

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

This theme describes 92 units about how participants interacted with and how they felt unfortunate and fortunate from Wi-Fi Twinge. We first describe sub-themes that indicate that our system was indeed an unfortunate superpower. Then we 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

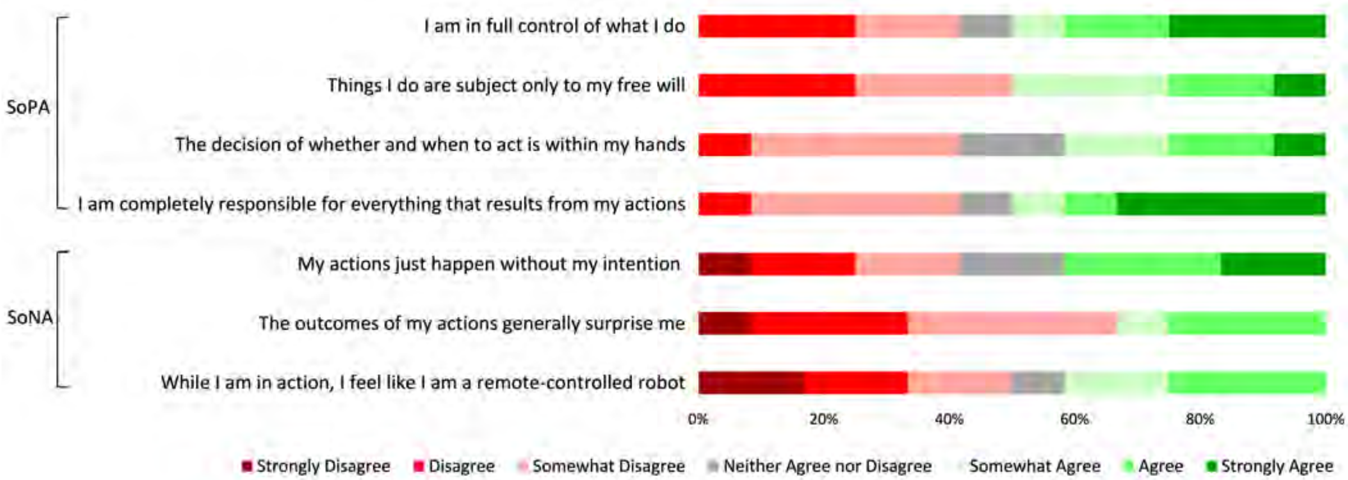

Figure 7: Participant responses to the Sense of Agency Scale.

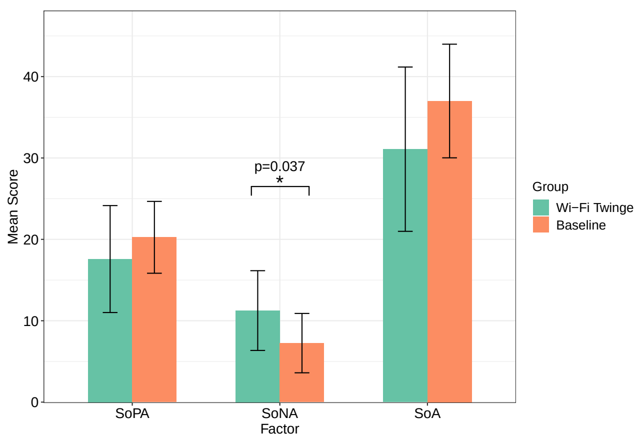

Figure 8: The average score of the Sense of Agency Scale (SOA) and its subscales (SoPA and SoNA) compared with the baseline. Error bars represent one standard error of the mean.

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 feel hard to do what I have to do, [so] I couldn't catch the train*". Participants spoke about how their hand 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 our 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, we 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 our 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. We postulate that the bodily nature of our system could have fuelled that physiological reaction, i.e., fear, especially if we 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 our 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 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*".

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

This theme describes 116 units about 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 forearms, 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 [3]. 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 we are 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. Our system also changed how participants perceived their environment. Interestingly, P12 added: "*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. 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 further 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 participants not only gained 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 [43]. Furthermore, one participant reported that the system made them reflect on their free will, that is, how much in control their lives are in general [55]. For example, P1 said: "*[I became] more conscious about how in control I am*".

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

This theme describes 43 units about how participants perceive 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 created 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*".

6 DISCUSSION

In the following, we discuss our findings, derive design tactics for future superpower systems, and discuss limitations and future research work.

6.1 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 unfortunate side effects by the system. This result aligned with the goal of our study design, as our 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 participant's Sense of Positive Agency and overall Sense of Agency scores.

Our 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. Our 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 postphenomenology [9, 33, 98]. Wi-Fi Twinge is considered a mediator that influences the way we perceive and engage with our surrounding environment, and as an extension of the human body, enabling people 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 [66–68]. Our findings suggest that bodily ownership is a critical determinant in deciding whether or not a technology enables a person to experience superpowers, and as we mentioned earlier, using a person's own physiology can be a part of what makes it a superpower. Therefore, our 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 in order 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 [7, 10]. For example, Mueller et al. [66] 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 machinery 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 our 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 we 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" type systems, which is slightly different from Mueller et al. [66]. Our 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.

Furthermore, we discovered that more dark patterns existed during the study after the exploration mentioned above, and they did not align with our original intentions. This implies that design elements might be misused due to an oversight of their impact on the human experience [17]. One participant felt embarrassed to use Wi-Fi Twinge on public transport, where the human experience extended to socialising, including interactions and engagements with other people. It might be used as an intentional dark pattern to embarrass them in social situations. Some participants had bad feelings about Wi-Fi signals and interpreted the Wi-Fi signal to be hazardous to their health due to the unfortunate effects of the system and EMS. This suggests that EMS has the potential to be more severe than simple vibrotactile output, and thus EMS could be used as a dark mode to reinforce the severity of certain information.

6.2 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 [70].

However, as per our 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. Our 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 have 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 [29, 37, 89]. 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 [47, 83]. This confirms the prior theory that through interacting with sensory-enhancing systems, the ability to understand and empathise with the feelings of others may be strengthened [19, 29, 101]. This embodied experience, rather than an abstract understanding enabled by text or speech, could make people more engaged and immersed in the environment, thereby heightening sensorial experiences and 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 can facilitate bodily awareness [76], 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 [97].

Taken together, our 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.

6.3 Design tactics

Building on our craft knowledge of having gone through the design process of Wi-Fi Twinge and the findings of the study, we now propose a set of tactics for designers aiming to create future fortunate and unfortunate superpower systems.

6.3.1 *Consider the mapping between input and output.*

The mapping between the input and output of a superpower is complex and users can find understanding this relationship difficult the first time they use it. Users may feel confused and therefore require time to explore the mapping relationship. Norman [71] suggests that mapping relationships should be "natural", using physical and biological analogies as well as cultural standards. We agree that "natural" mapping could offer a most "intuitive" feeling, leading to immediate understanding and a more efficient system. But it might also reduce creativity and playfulness because it encourages people to follow familiar and conventional interaction patterns. The "natural" mapping for Wi-Fi signals could be visual output because Wi-Fi is a radio wave that can be seen as an invisible light. However, since we aimed to design an unfortunate superpower, we chose an unusual mapping: from Wi-Fi signals to hand movements to provide users with a novel and unique system. Meanwhile, we used a rather obvious mapping for hand movements and EMS, where stronger Wi-Fi signals result in longer EMS activation times and shorter rest times. Accordingly, we suggest that designers should consider carefully when choosing to use the "natural" or "unnatural" mapping between input and output for fortunate and unfortunate superpowers, especially if the enhanced ability is uncommon and invisible. For example, if designers want to develop a hearing superpower, they could consider "natural" mapping such as mapping sound content to text to enhance usability and efficiency, or unnatural mapping such as mapping sound volume to body temperature to increase creativity and playfulness.

6.3.2 *Consider the extent of allowing users to alter the control over superpowers.*

Sense of agency is a complex phenomenon because each person's feeling is different and subjective. From the interviews, we found that control over superpowers was a key determinant in assessing the sense of agency and distinguishing unfortunate superpowers. Some participants perceived Wi-Fi Twinge as an unfortunate superpower because they could not control the superpower directly; instead, they had to change their location to control the superpower indirectly. Low control over superpowers appeared to limit physical and mental demands, allowing users to focus on their own changes and thus increase self-awareness, but users may feel uncomfortable with feelings of helplessness and loss of control. Therefore, we recommend that designers consider the extent of allowing users to alter their control over superpowers when designing superpowers, especially for intentionally unfortunate systems, where a lower degree of control and sense of agency may be more likely to lead to unfortunate superpowers. For example, it may be easier to lose control by having the body navigate automatically throughout the day compared to regaining control of the body when you stop.

6.3.3 *Consider reducing the physical presence of the device to increase the sense of bodily ownership.*

We recommend that designers consider reducing the physical presence of the superpower device to increase the sense of "bodily ownership" to facilitate superhuman-like experiences. With Wi-Fi Twinge, the cables of the device were described as annoying and distracting, drawing the attention of participants toward the device and reminding them it was a machine controlling their movements. Therefore, we suggest that superpower systems should be out of sight and mind for participants to feel integrated with their bodies. To achieve this, designers could consider alternative technologies that reduce participants' attention to the device and reduce the presence of the technology, such as microdevices, ingestible and implantable devices [49, 50].

6.3.4 *Consider indirectly facilitating intended behaviours.*

Participants reported that they tried to escape places with a large amount of Wi-Fi signals to avoid negative bodily sensations, hence walking outside into nearby parks: this could be regarded as a desirable behaviour as being outdoors is associated with positive well-being [8]. This finding suggests that rather than creating a system that encourages people to go outside or a robot that moves people outside, a designer who aims to facilitate such behaviour change (like spending more time outdoors) could turn an action they do not want to promote (being indoors, with too much Wi-Fi) into an unfortunate experience where participants feel that it is their free will that makes them go outside. If designers want to facilitate behaviour change, they may consider indirectly allowing users to discover the negative impacts of the unintended behaviour to keep participants' sense of agency. As such, the superpower design would leave participants' overall sense of agency unaltered when aiming to promote intended behaviour but engage with a little loss of control (like our EMS twinge) instead.

6.4 Limitation and future work

Our work has several limitations. Firstly, the use of EMS requires a calibration procedure and hence can lead to calibration differences. Previous studies have noted that such calibration is recommended when using EMS as each body is different [82]. We note that we could have considered the differences by logging the use of our system through, for example, a camera. However, we found this to be outside the scope of this work and noted that prior work also refrained from such data collection to consider EMS calibration differences [41]. Future work could complement our approach with other methodologies to enrich our results. Secondly, we only did the quantity analysis for the SoAS. In future work, we can imagine evaluating the translation of Wi-Fi signals into electrical signals with measurements based on Wi-Fi heat maps to assess the accuracy of the signal strength classification. Thirdly, we have only investigated one particular unfortunate superpower. Future work might want to design more prototypes around different concepts of unfortunate superpowers to complete our understanding of designing superpowers and design tactics. Finally, we have yet to prove that our design tactics based on the exploration of unfortunate superpower systems lead to better systems. In the future, workshops with designers who use these tactics could verify that our tactics are effective.

7 CONCLUSION

In this paper, we explored human augmentation design through the lens of unfortunate superpowers. We designed a system called Wi-Fi Twinge that extends human perception to Wi-Fi signals. The system allows users to sense unseen Wi-Fi signals through electrical muscle stimulation, causing involuntary flexion of the fingers and wrist to create an embodied experience. Through interviews from an in-the-wild study where 12 participants engaged with the system over 5 days, we found that even though the unfortunate superpower caused some hindrance to participants' daily lives, it heightened participants' awareness of their bodies and surrounding environment, indirectly changing their activities, facilitates reflection on themselves, and in some cases contributed to their overall well-being. Taking these results together, we provided a set of design tactics to guide future superpower system designs. Ultimately, we aim to advance our understanding of technology-facilitated superpower experiences especially considering not only their potential but also any possible unfortunate side effects and guide the future design of superpower systems.

ACKNOWLEDGMENTS

Florian 'Floyd' Mueller acknowledges the support from the Australian Research Council, especially DP190102068, DP200102612 and LP210200656. We thank Rakesh Patibanda for his guidance on interviews and hardware. We also thank our participants greatly for their time and insights. Lastly, we thank those participants who agreed to be featured in the photographic material included in this publication.

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