Title
Understanding Embodiment: Connecting Ownership, Agency, and Peripersonal Space

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Author
Trieu, Patrick Hau Don

Publication Date
2022

Peer reviewed|Thesis/dissertation

Understanding Embodiment:
Connecting Ownership, Agency, and Peripersonal Space

By

PATRICK HAU DON TRIEU
THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Mechanical and Aerospace Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Jonathon Schofield, Chair

Wilsaan Joiner

Shima Nazari

Committee in Charge

2023

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ABSTRACT

Understanding Embodiment: Connecting Ownership, Agency, and Peripersonal Space

Recent advances have allowed robotic prostheses to become increasingly sophisticated in the movements they perform and the functions they offer. However, these devices are still perceived by users as separate machines, rather than true limb replacements. Therefore, an important next step in the evolution of robotic prosthesis is to promote the sense that they are a part of the body. Here, the concept of embodiment represents a cognitive connection between the patient and their prosthesis. Embodiment is the experience of owning and controlling your body. It emerges when our intentions, body's actions, and their sensory outcomes align with what our brains predict we will see and feel. ***The objective of this study is to develop a research platform (robotic experimental setup) and protocol that allows us to explore embodiment***, by studying the relationships between its three constituent components: ownership (the feeling our bodies belong to ourselves), agency (the sense of authoring our actions), and peripersonal space (the perceived space surrounding one's body in which one can interact with their environment). Although well investigated individually, there is still little research in how these components interact to form a cohesive sense embodiment. This information is vital to designing and tuning control and sensory systems for prosthesis so that they are more closely perceived as body parts.

I have designed a research platform that strategically manipulates the sensory and motor information provided to participants during an experimental task that requires participants to operate a robotic hand. The hand is controlled by EMG signals from an armband that monitors muscle activity, as a measure of motor intentions. The participant will see the robotic hand moving and we manipulated sensory outcomes of the hand's actions through three possible outcomes: an LED light will illuminate when the robotic hand contacts objects, a beeping tone that may play, and/or vibration motors in a haptic glove worn by participants may activate. We positioned the hand at different locations in front of the user to manipulate peripersonal space. Together this allowed us to measure user intentions, control motor actions, and manipulate sensory feedback; all the sensory motor channels involved in forming a sense of embodiment. We used multiple validated measures such as ownership and agency questionnaires, intentional binding, and proprioceptive drift to capture the formation of the senses of agency, ownership, and changes in peripersonal space. Finally, I performed preliminary testing with a small cohort of N=7 able-bodied participants. This allowed us to assess the effectiveness of the experimental design, capture the variability of the embodiment measure, identify future refinements, and prepare planned data collection activities with larger cohorts of participants. Early testing established that providing constant vibration in the haptic glove to indicate when the robotic fingertips touch an object offers stronger ownership and agency values compared to using pulsing vibration for feedback. These tests also revealed that roughly 18 grasps (repeated experimental trials) is the optimal number for the participants to perform the task, as ownership and agency values increases when the participants approaches 18 grasps and then plateau after this point.

Chapter 1

Introduction and Background

Recent technological advances have allowed robotic prostheses to become increasingly sophisticated in the movements they perform and the functions that can be offered. However, these devices are still perceived by their users as separate machines that must be operated to achieve tasks, rather than truly integrated limb replacements. Therefore, an important next step in the evolution of robotic prosthesis is to understand how to promote the sense that a prosthesis is a part of the body, termed embodiment. This will allow for greater user acceptance, use, and effective control of robotic prostheses.

1.1 Motivation and Importance

With the increasing availability of robotic prosthesis for patients afflicted with upper limb amputations, there has been a significant thrust in the field to understand how these devices may be integrated seamlessly with users [1]. As robotic technologies grow increasingly dexterous and autonomous, there are increased possibilities for user frustration, impacting their perceptions of trust and cooperation [2], [3]. These negative emotions may be warranted by the poor performance of the prosthesis, but we often misjudge technology and place unfair expectations on them [2], [4]. We as humans are quick to distinguish ourselves as separate from cooperating machines and prone to blame them for errors [2], [5]. It is critical for users to be more accepting of their capabilities to overcome any doubts that would hinder the performance of the prosthesis. Promoting a sense of prosthesis embodiment is a crucial step toward overcoming any concerns and is the cognitive connection necessary to be the driving force behind its use and acceptance. This connection will lead to the cooperation of machines and meaningful collaborative actions to promote more forgiving interactions. The human-machine relationship between the patient and the prosthesis showcases the importance of how the patient views the prosthesis since its performances heavily relies upon their cognition of how it resembles their missing limb.

1.2 Embodiment

Our brains constantly distinguish ourselves as separate from our environment, the tools we use, and other people. These distinctions between "self" and "other" shapes how we perceive every action performed [2]. Our locus of control is defined as the extent to which we believe that we control the events that occur around us, as opposed to external forces [2], [6]. There is inherent bias in this perceived control, specifically self-serving bias in which we are inclined to disproportionately credit ourselves for positive outcomes of actions while blaming negative outcomes as things beyond our control [2], [7].

This self-serving bias is a major barrier to the effective use and acceptance of modern robotic prostheses, spurring on negative emotions, potentiating frustration, and promoting problematic interactions between the user and machine. As the user becomes more negatively predisposed to technology, a "blame cycle" is created where the system receive increasing blame for errors while these errors promote negative emotional states that reinforces the displacement of blame [2], [3]. To break this blame cycle and negative biases, it is vital to create more forgiving relationships between humans and their cooperating robotic prostheses. If technology can be perceived as embodied by the user, many of the existing biases can be flipped for the benefit of forging more effective and forgiving cooperation.

Embodiment is defined as the combination of experiences in owning and controlling a body and its parts, and it emerges from the integration of intentions, seeing the body and its motor actions, and sensory outcomes [2], [8]–[11]. Embodiment is a desirable outcome for prostheses. If a user were to perceive a device as part of their body, they would also perceive the additional function it offers as their own body's function leading to perceptions of being more capable and independent.

The perception that our bodies belong to ourselves is a multisensory experience that is surprisingly malleable. Stimuli from interactions with the external environment are integrated to allow us to perceive ourselves [2], [12]. By simply manipulating multiple sensory cues from interacting in our environment, we can temporarily and harmlessly manipulate the brain's representation of our bodies [2], [8], [13]. This sense of embodiment is comprised of three constituent components: a sense of ownership, a sense of agency, and peripersonal space [8], [12]–[14].

1.3 Sense of Ownership

The sense of ownership is the feeling of "mineness" toward one's own body parts [2], [11]. This is usually described through statements such as "This is *my* hand," or "*I* am feeling that stimulus." Thus, it is mostly experienced at the fringe of consciousness [2], [11], [14]. It is believed that this sense is largely a product of visual and cutaneous touch-based information; that is, this experience is built on seeing and experiencing touch sensations on the body [10], [11], [13], [15], [16]. The experience of ownership is found to not just be constrained to one's own biological body parts but can be induced in other objects, owing to its dynamic and adaptable nature [10], [11], [16]. Based on the available multisensory and sensorimotor information, the brain can compute which are our own body parts, such as arms and legs, and updates this body representation at conscious and non-conscious levels [2], [13].

Much of the current knowledge surrounding ownership stems from experimentation with body ownership illusions, such as the rubber hand illusion [8], [13], [16], [17]. In these illusions, researchers manipulate the sensory signals from the different modalities that are involved in the multisensory integration that allow for the sense of ownership. When the spatial, temporal, visual, and somatic signals from a limb align, ownership for that limb is induced for the person. Through these illusions, other non-conscious temporary physiological changes have been observed: temperature changes, touch and pain sensitivity, skin conductance, and cortical excitability [2], [18]–[22]. Further research has also seen temperature decrease and slowed processing of tactile input in the actual limb, and selective activation of brain areas related to anxiety and interoceptive awareness when the fake limb is under threat of pain and injury [13].

The sense of ownership can be measured explicitly through questionnaires about the current body representation and implicitly through psychophysical temporal order judgements and residual limb measurements such as temperature changes [23], [24]. Achieving a sense of ownership will aid a user to view a robotic prosthesis as a part of their “bodily self.”

1.4 Sense of Agency

The sense of agency is the experience of initiating and controlling an action [8], [11], [23]. This is usually described through statements such as “I am moving my leg,” “I am the one who is in control of this car,” “or “I pressed the button to make that happen.” Thus, this experiences allows one to differentiate self-generated actions from actions generated by others [2], [8], [25], [26]. When we intend to perform a motor action with our bodies, our brains naturally predict the sensory outcomes. The sense of agency arises when our motor intentions, brain’s predictions, and sensory outcomes align [11], [15]. Furthermore, this property is what the ethical and juridical concepts of free will and moral responsibility are based on [11], [26], [27]. We, as humans, innately trust our own body to carry out the actions we intend. Thus, an intrinsic sense of agency is formed when this is fulfilled [23].

Agency can be measured explicitly through psychophysical questionnaires that ask participants to whom or what they attribute an event or action, requiring inferential judgments of self-attribution [17], [23], [28], [29]. Agency can also be measured implicitly through intentional binding tasks [23]. This is accomplished by having participants recognize a perceived difference in self- and externally-generated actions. As the participants performs an action, agency implicitly manifests as a non-conscious perceptual compression of time between actions and their sensory consequences, otherwise known as intentional binding [29], [30]. In this task, the participants would report the time perceived between the action and its outcome. Thus, a shorter perceived duration of time correlates with a more strongly sense of agency [31], [32]. In the context of operating robotic prostheses, achieving a sense of agency will aid the user to view that they are truly responsible for the actions that they perform in collaboration with their artificial limb.

1.5 Peripersonal Space

Peripersonal space is the final constituent component of embodiment and defined as the perceived region of space surrounding one’s body in which one can reach and interact with external objects [2], [11]. This large, flexible geometric representation of space mainly functions to guide our movements [13], [33], [34]. If one were to be consistently using a tool such as a rake, the brain would adjust and expand this peripersonal space to adapt to the user’s new acute awareness of the tool’s physicality and reach [2], [35]. In the case of a robotic prosthesis, the user’s peripersonal space should adapt to the reach of the prosthesis, akin to an intact biological limb. Establishing an appropriate peripersonal space aids in the perception of one’s own body and accelerates tool use proficiency [2], [36]. A visuoproprioceptive mismatch can disturb a person’s peripersonal space, inhibiting any experience of embodiment [13]. This also extends to body illusions, such as those involving real and fake hands. In the case of body illusions, the presence of a fake limb placed in an irregular position warps the individual’s peripersonal space due to their misaligned sense of vision and touch.

Body ownership illusions have been extensively studied by researchers in order to understand how the temporal, spatial, and semantic relationship of different sensory modality interactions in the elicitation of these illusions [13]. Research with these body and rubber hand illusions have employed different levels of mismatch in terms of alignment, orientation, and posture that can affect peripersonal space to varying extent, while the intensity of the illusion is also affected [13], [37]. Illusory hand ownership experiments on monkeys have demonstrated that observation or visuotactile stimulation of the fake hand and individual’s real hand causes enlargement of the visual receptive fields of the intraparietal sulcus (IPS) and ventral and dorsal premotor cortex (PMC) neurons in order to encode the false hand’s position [8], [11], [12], [17], [38], [39]. Damage to pathways connecting these areas have shown inhibition of illusory limb ownership [12], [40], [41]. This demonstrates that there are some overlapping brain mechanisms for ownership illusions and proprioceptive drift [16].

Peripersonal space can be measured through proprioceptive drift. In a scenario where the user is visibly presented an artificial hand and hides their real hand, the user is induced with an illusory sense of ownership by manipulated sensory cues. When asked to blindly localize the position where they experience their real hand to be, the user tends to mislocalize their real hand's position towards a false hand. This observation is known as proprioceptive drift, and occurs within the unaware participant (non-consciously) [11], [16], [17], [42], [43]. In the context of prostheses, achieving peripersonal space will aid the user's perception of their robotic prosthesis as part of their own body, as well accelerate their own proficiency in using it as their own limb.

1.6 Current Research

There is little research in how these three aspects; sense of ownership, sense of agency, and peripersonal space influence each other and interact to form a cohesive sense of embodiment. Most of our current understanding of ownership, agency, and peripersonal space comes from research involving body illusions, which are psychological phenomena in which the perception of one's own body significantly differs from the configuration of their own physical body, in terms of ownership, size, location, etc [13]. This perception is altered through manipulating the multisensory and sensorimotor stimulation that is received by the brain [2], [13]. Most of these body illusion experimental paradigms consists of rubber hand illusions, that are made artificially and are fake (usually rubber), and its variations. The illusory hand is placed in a visible, anatomically plausible position in front of the participant, while their own real hand is hidden from view. Then, the experimenter repeatedly strokes both the false and real hand synchronously. As the participant see this action and feels the sensory stimulation, an involuntary embodiment is induced over the fake hand [2], [8], [11]–[13], [16], [17].

Many of these body illusion experimental paradigms proved fundamental in studying the underlying mechanisms and measures that affect embodiment, ownership, agency, and peripersonal space individually. Many of these studies acknowledge some connections between these aspects. Many rubber hand experiments have proposed interplay between the sense of ownership and the sense of agency, suggesting that these two concepts may promote each other [2], [8], [11]. There is also conflicting research on the sense of ownership, peripersonal space, and proprioceptive drift: Some state that proprioceptive drift is a major measure and influence on ownership [8], [11], [12], [15], [17], while others argue that proprioceptive drift is a measure of peripersonal space [2], [13]. For the purposes of this study, we will recognize proprioceptive drift as a measure for peripersonal space.

Although much of the current research do recognize some connections between these concepts, there is still little understanding in how the sense of ownership, sense of agency, and peripersonal space interact with each other to form embodiment. To fill this knowledge gap, we suggest it is necessary to view these relationships occurring simultaneously in an experiment paradigm. This would allow one to observe how these 3 aspects directly influence each other and how they would promote embodiment, and how the current embodiment and its parts are reinforced by the prior experience.

1.7 Objectives

Understanding these relationships will allow us to better learn the nature of how our brain identifies our own bodies and actions. This information can prove vital to designing and tuning control and sensory systems for prothesis so that they are more closely perceived as a part of one’s body. Therefore, ***the long term applications of this work is to*** develop a better understanding of how the sense of ownership, sense of agency, and peripersonal space can influence the larger concept of embodiment, which is the combination of experiences in owning and controlling a body and its parts; which stems from the integration of our intentions, motor actions, and sensory outcomes [2], [8]. ***The objective of this work*** was to perform preliminary investigations of the relationships between ownership, agency, and peripersonal space, by developing a research platform and protocol that allows us to strategically manipulate the sense of embodiment and studying the relationships between its 3 parts. This platform had to allow us to measure user intentions, control motor actions, and manipulate sensory feedback; all the sensory motor channels involved in forming embodiment.

Chapter 2

Measurement System Design

2.1 Goal

To investigate how the relationships between ownership, agency, and peripersonal space, it was necessary to develop an experimental paradigm and the accompanying research platform that could simultaneously manipulate these principles with able-bodied humans. It is established that the brain's representation of our bodies can temporarily and harmlessly be manipulated by controlling sensory cues in the interactions with our environment [2], [8], [12], [13]. Thus, this platform must allow us to measure user intentions, control motor actions, and manipulate sensory feedback; all the sensory motor channels involved in forming embodiment.

2.2 System Description

All experiments and system development were conducted in the system in the Bionic Engineering and Assistive Robotics Laboratory (BEAR). The system is a research platform that strategically manipulates the sensory and motor information provided to participants during an experimental task that requires participants to operate a robotic right hand. It closely resembles the typical setup for rubber hand illusion experiments but altered to manipulate sensory cues and allow the user to actively control the rubber hand opening and closing all while providing haptic (vibration) stimulation to the operator's fingertips [2], [8], [11]–[13], [16], [17].

The robotic hand built for this platform was the Powerhand from the Myosim device utilized by the BLINC lab at the University of Alberta, Canada [44]. It was composed of 3D printed PLA material, driven by a Dynamixel MX-64AT servo motor to move in the single-degree-of-freedom of open-close, and equipped with three inexpensive capacitive force SingleTact sensors on the index, middle, and thumb digits, as shown in Fig. 2.1. This robotic hand was controlled by the BrachI/Oplexus software, an open-source graphical user interface (GUI) designed for myoelectric prosthesis control and enables the EMG signal interpretation and end effector motion, also created by the team at the University of Alberta [44], [45].

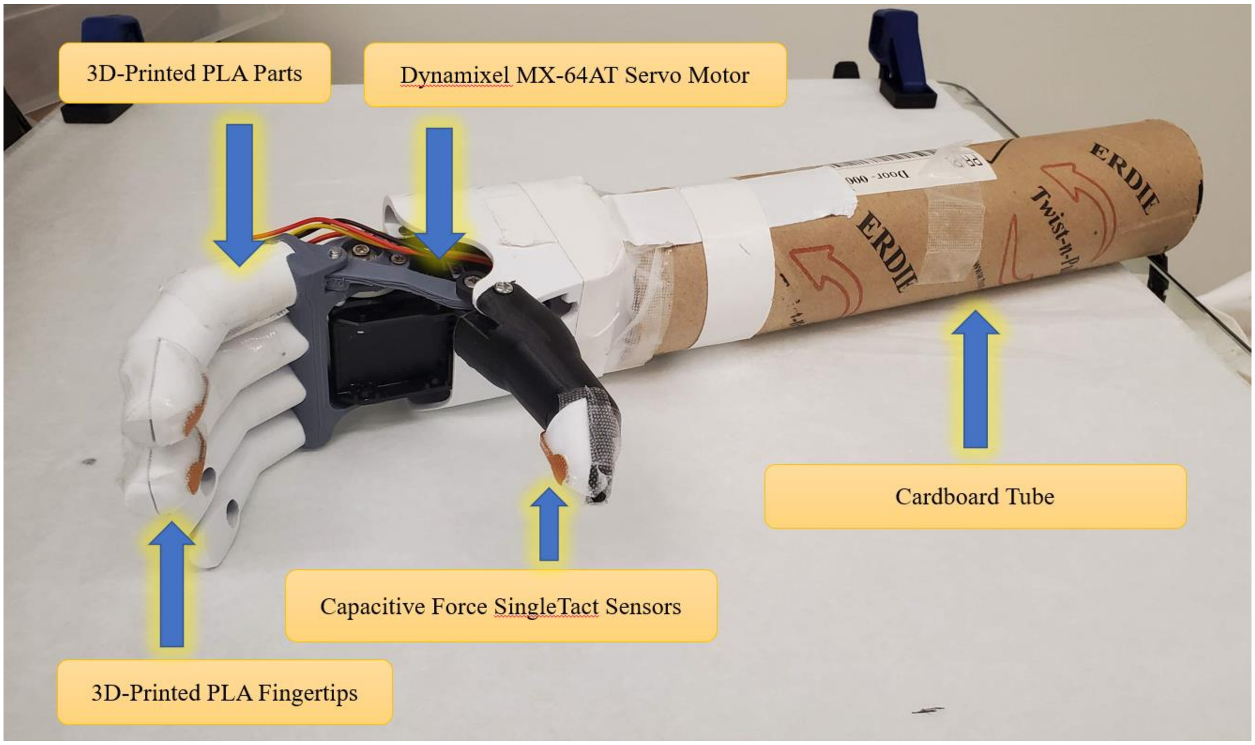

Figure 2.1: The Myosim Powerhand

In the experiment, participants donned a wearable Thalmic Labs Myo armband for prosthetic robotics control [46]. This was a non-invasive, consumer device that was designed for video game control and measured muscle activity (EMG) from the surface of the skin. The robotic hand was controlled by these EMG signals, which act as a measure of motor intentions. Participants also donned a fabric glove with vibrators install in the fingertips to provide haptic feedback (much like a smart phone). Subjects were seated at a double layered table in which the robotic prosthetic hand is placed on the top layer along with a box with a LED light. The subject placed their real right hand on the lower layer and were able to use the Myo armband to trigger the robotic hand to perform open-close motions. A monitor display depicting green or red colors was placed in their peripheral vision to allow them to know when they were in control of the open/close function of the robotic hand. The participant saw the robotic hand moving and upon closing and griping the light box, the sensory outcomes of the hand’s actions were manipulated through three possible feedback actions: an LED light that illuminates, a beeping sound tone might play, and/or vibration motors in a haptic glove might activate. The subject was given 10 minutes to acclimate and interact with the experimental setup. The setup can be seen in Fig. 2.2, Fig. 2.3, and Fig. 2.4.

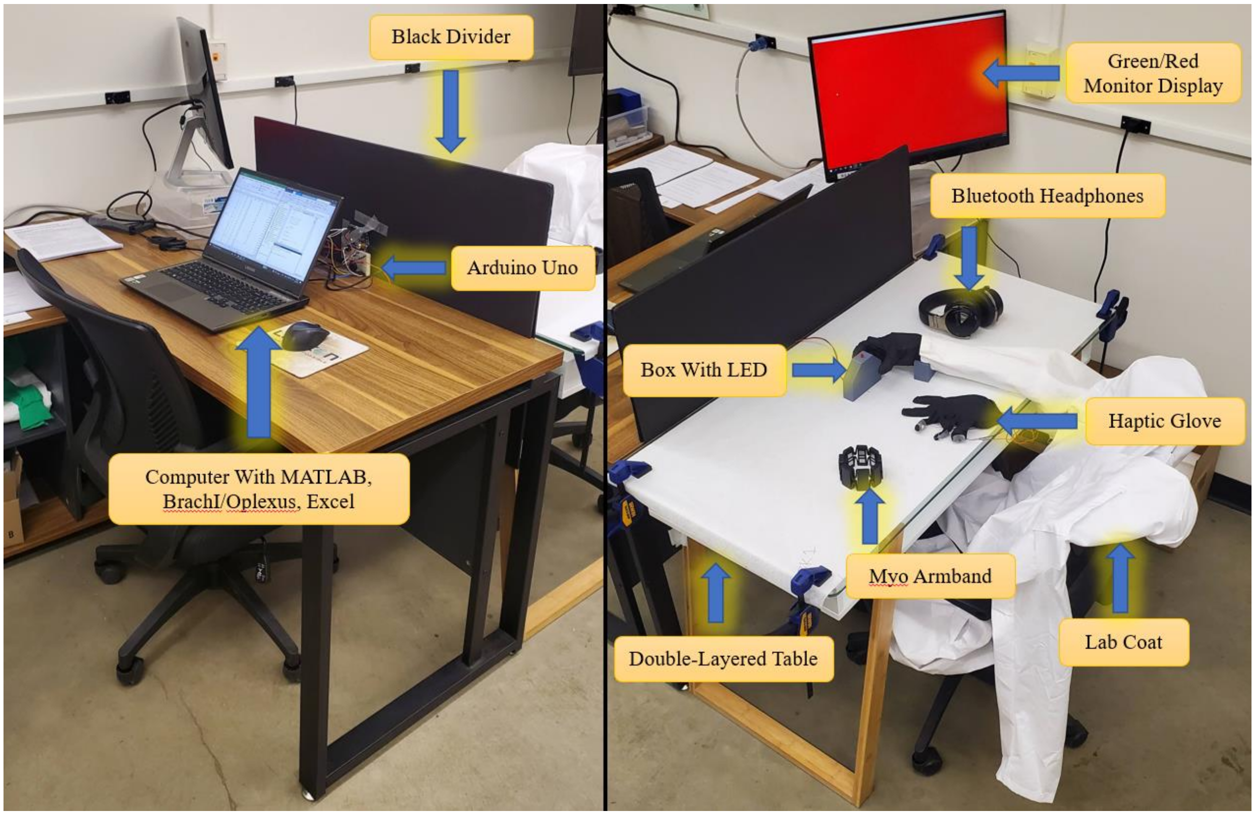

Figure 2.2: The setup for embodiment evaluation. Experimenter side on left. Participant side on right with top layer in view.

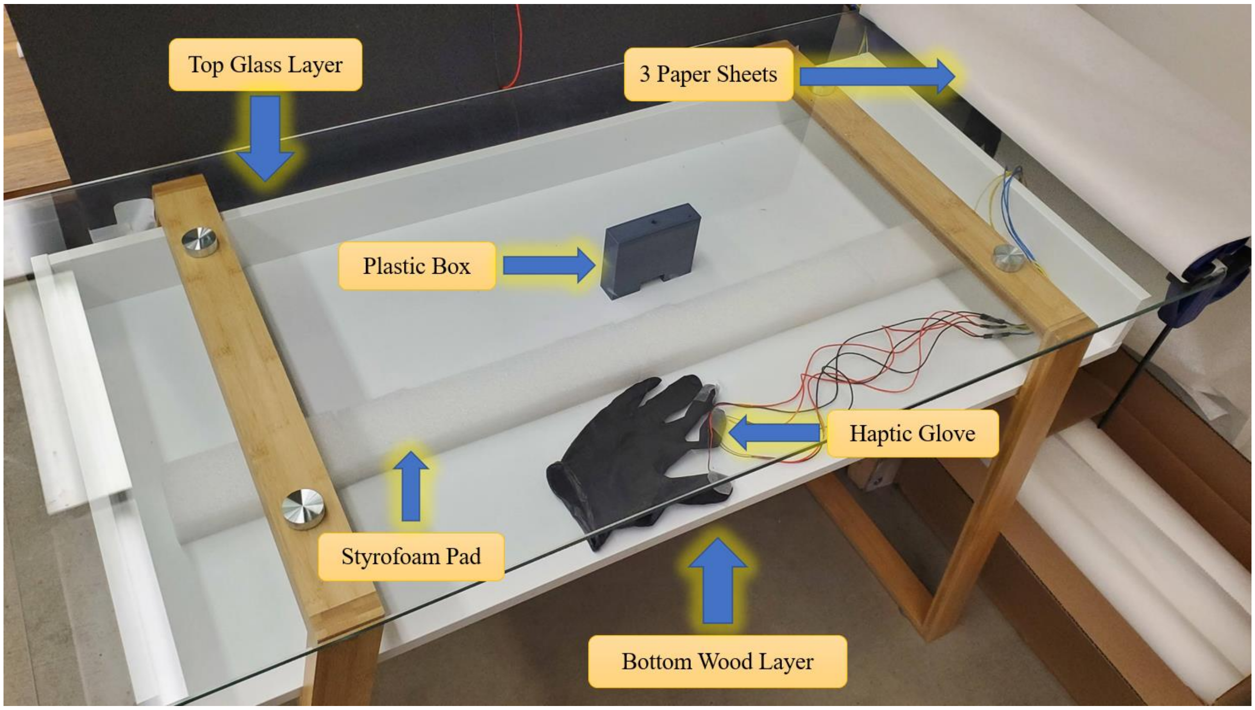

Figure 2.3: Bottom layer of setup on participant side.

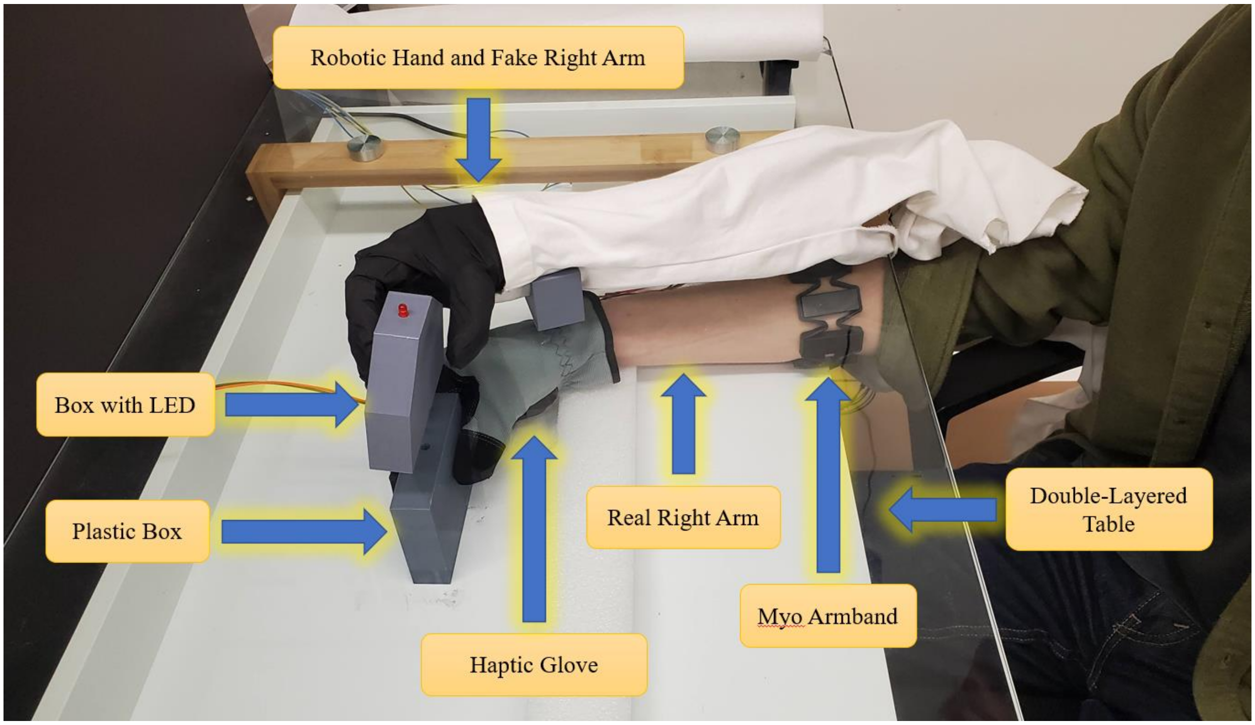

Figure 2.4: Exposed view of table setup in use by participant.

The double layered table had 3 paper sheets laid over to obscure the glass top layer. On the second paper layer, there were 3 black short vertical marker lines drawn in the middle of the table with the following spacing as displayed in Fig. 2.5: the leftmost line would align to the participant's body center (C), the middle line was 8 inches to the right (M), and the rightmost line was another 8 inches to the right (F). These spacings were chosen in consideration of the space allowed by the table. An Arduino Uno microcontroller was used to read force values from the SingleTact sensors on the robotic hand, play the sound tone on the piezoelectric speaker module, and light the LED on the 3D printed PLA light box. This microcontroller was controlled by a MATLAB program that ran the experimental setup and log data. This can be seen with the computer stationed on the experimenter's side as seen in Fig. 2.2.

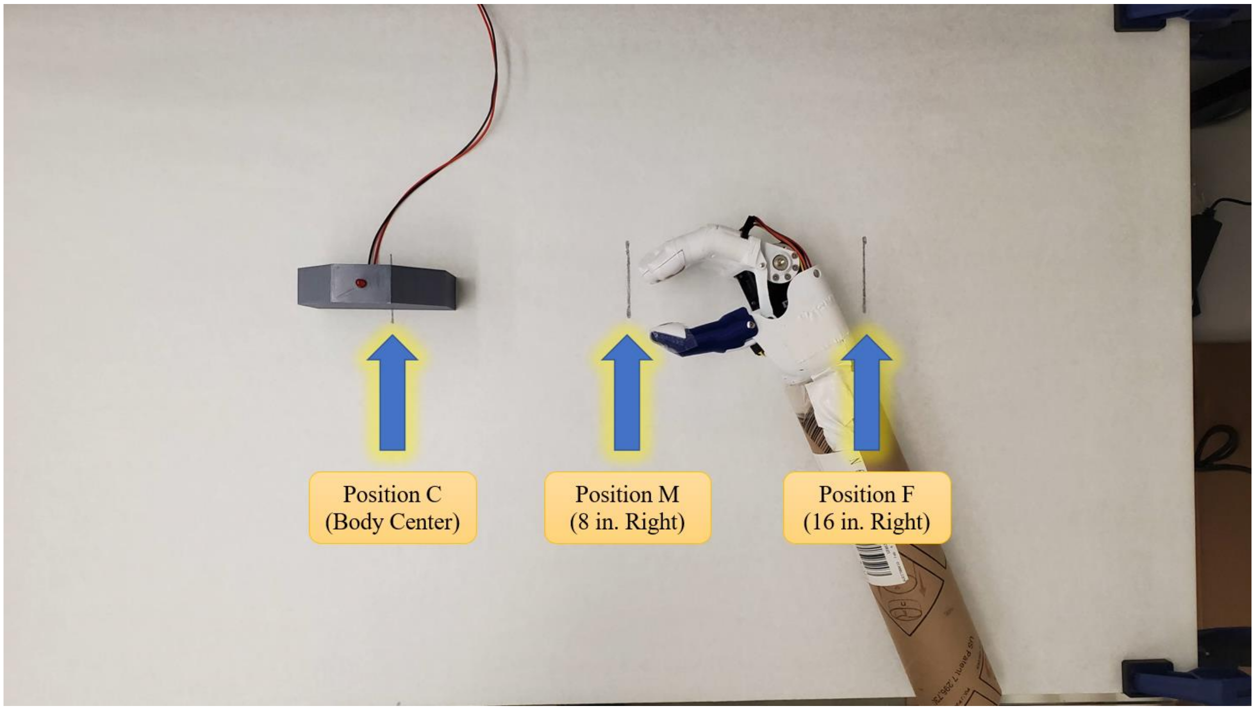

Figure 2.5: Position lines drawn on top of the setup

In order to facilitate the illusion of the robotic hand being the participant's real hand, both the robotic hand and their real left hand (which was placed on the top layer of the table) wore black gloves. They donned a lab coat that connects to the robotic right hand. Wireless headphones playing white noise was used to drown out the noise of motors moving within the robotic hand but adjusted enough to allow the user to hear the sound tone. Fig. 2.6 shows how the participant is outfitted in the aforementioned equipment.

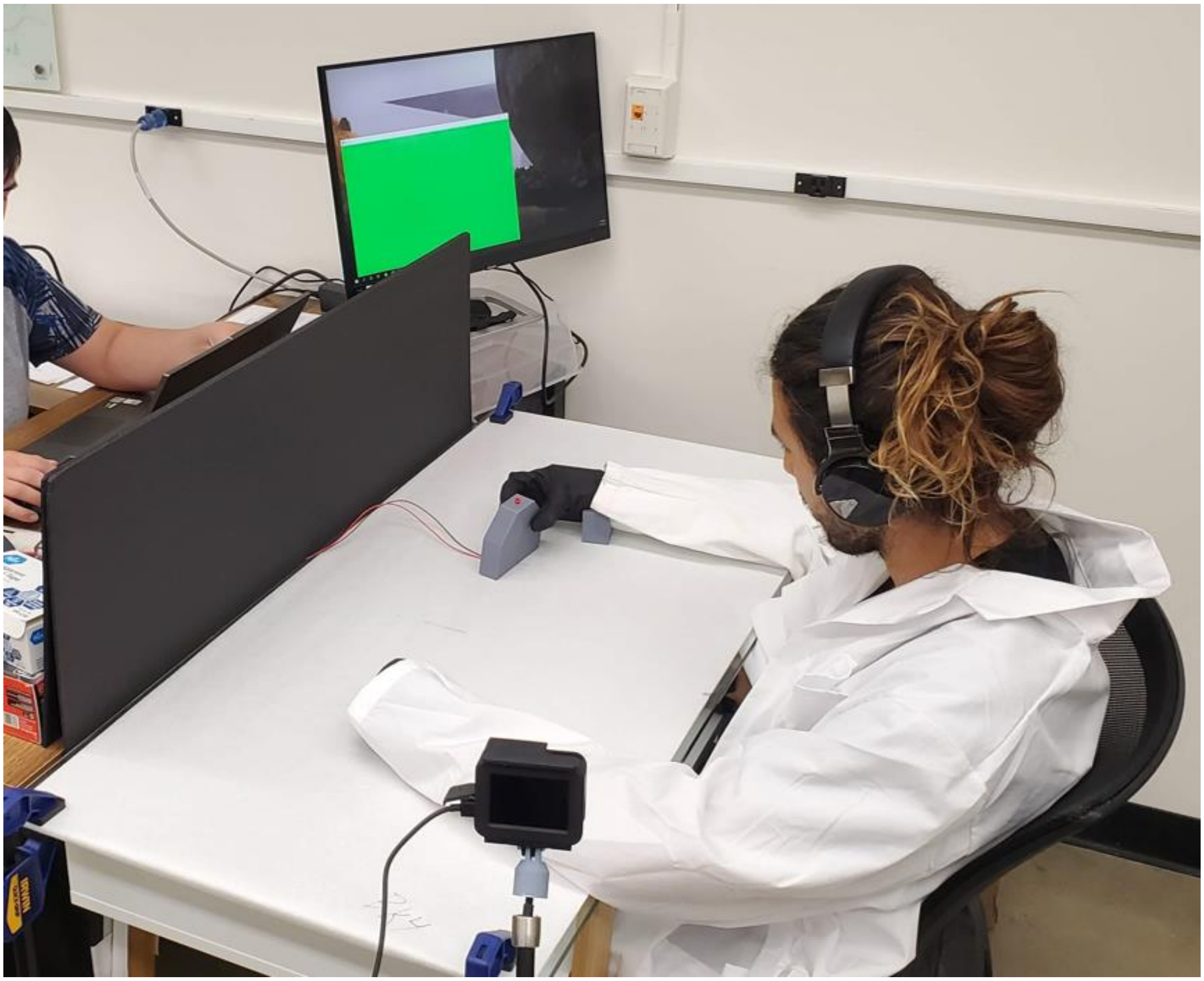

Figure 2.6: Experiment setup in use.

In each trial, the subject was tasked to control the robotic hand, disguised like their own hand, with the Myo armband to grip the light box for 1 second. They saw the LED illuminate, then heard an audible beep, and reported their estimation of the time delay between these events [23]. This was repeated 18 times, creating one block of trials.

We manipulated the following variables during this task, as highlighted in Table 2.1: touch feedback conditions (fingertip vibration, no vibration, or watch the robotic hand move), the physical position of the robotic hand on the table in front of the participant (close, medium, far), the time delay between when the LED is illuminated and the audio tone is presented (300 ms, 500 ms, 700 ms) [23]. We employed a full factorial design in which each combination was used (27 combinations repeated 6 times for a total of 162 trials). Trials were strategically separated into blocks to allow the subjects the opportunity to take breaks. This experiment ran for approximately two hours in total. Table 2.2 showcases an example of a set of trial blocks used in one experiment.

Manipulated Variables & Conditions			
Touch Feedback	Control with Vibration On (BUZ)	Control with Vibration Off (NB)	Watch Robot Hand Move (WATCH)
Position of Robot Hand	Close (C), directly in front	Medium (M), 8 in. right	Far (F), 16 in. right
Tone Delay	300 ms	500 ms	700 ms

Table 2.1: The three manipulated variables and their three corresponding conditions used in the experiment. The setup tests with every combination of variable conditions.

Block Number	Position	Feedback
Block 1	C	BUZ
Block 2	C	NB
Block 3	C	WATCH
Block 4	M	BUZ
Block 5	M	NB
Block 6	M	WATCH
Block 7	F	BUZ
Block 8	F	NB
Block 9	F	WATCH

Table 2.2: Randomized sample of a full set of trial blocks. Each block tests for a combination of position and feedback condition. In each block, there are 18 trials: 6 trials for each of the tone delay condition, which are randomly distributed within the block.

Multiple independent measures were used to capture the formation of the sense of ownership, agency, and changes in peripersonal space. These included ownership and agency questionnaires, intentional binding (task in which subjects estimate time interval between LED and audio tone), and proprioceptive drift (distance between subject's perceived hand location and their real hand location) administered during and at the end of each experimental block [2], [11], [17], [23]. Testing sessions were video recorded, and questionnaire results, proprioceptive drift, and time interval estimations were tabulated.

2.2.1 Sense of Ownership Measurements

The participant's sense of ownership was manipulated in the varied touch feedback conditions. We anticipate user control with haptic fingertip vibration response should allow for the highest level of ownership. Removing haptic vibration feedback should reduce this sense of ownership. Finally, taking control from the user to have them simply watch the robotic hand move should have the least level of ownership.

The formation of the sense of ownership was captured through the 16-statement ownership and agency questionnaire, based on prior questionnaires used in rubber hand illusion experiments and adjusted for this research platform [17], [23], [47]. Four statements refer to the feeling of ownership, while four statements relate to the feeling of agency. The remaining statements are control statements, four for ownership and four for agency. The participant reported their subjective experience on the 7-point Likert scale ranging from “-3” (totally disagree) to “+3” (totally agree), and “0” indicating neither agreement nor disagreement (“uncertain”). The statement order was randomized between three different forms to ensure that the participant’s accidental biases were minimized. For data analysis, the scores for ownership, agency, ownership control, and agency control were obtained by taking the average of the scores for the four statements related to ownership, agency, etc.

2.2.2 Sense of Agency Measurements

The participant’s sense of agency was manipulated by some of the user control conditions. When the user was given control of the robotic hand, there should be a strong sense of agency. Removing this control to have the user watch the robotic hand move should strongly reduce this sense of agency (the experimental condition termed ‘watch’).

The formation of the sense of agency was captured through two methods: explicit agency in the agency questionnaires, and implicit agency in intentional binding. Explicit agency was measured through the 16-statement ownership and agency questionnaire described earlier [17], [23], [47].

Intentional binding used the time interval task to measure the implicit sense of agency [23]. This time interval task specifically referred to when the participant reports their estimation of the time delay between the LED on the light box illuminating and the following beeping audio tone. This implicit measure allowed us to view the background cognitive processes that occur between a motor action and sensory event, which would not be explicitly perceived by the individual. This measure was achieved through the participants' characterizing a perceived difference in self-generated vs externally-generated actions [23], [29], [30]. When a self-generated action was performed, agency implicitly manifests as a perceptual compression in time between the action and the sensory consequences. Thus, as the participants reported their estimation of time delay, a shorter perceived duration of time corresponds to a more strongly formed sense of agency [23], [30]–[32].

2.2.3 Peripersonal Space Measurements

The participant's peripersonal space was manipulated by placing the robotic hand at different locations in front of the user, specifically the close position directly in front of the subject (C), the medium position 8 inches to the right of the center of their body (M), and the far position 16 inches far right of the center of their body (F). These locations were chosen based on the available space provided by the table used in the setup. Peripersonal space was captured through proprioceptive drift, specifically the distance between subject's perceived hand location and their real hand location [2], [11], [12], [17]. At the end of each experimental block, the participant closed their eyes and used their free left index finger to indicate the perceived location of the real right hand on the top layer of the table. This location was marked on the top paper layer with a marker, and the distance between this location and the leftmost line (indicating the participant's body center) was measured.

Chapter 3

System Refinements

In the prototyping of the experimental setup and paradigm, preliminary testing was conducted to ensure that the setup fulfills the necessary conditions for the user to achieve embodiment with the artificial robotic hand. This included: 3.1) altering the visual appearance of the hand so that it is realistic enough for the participant to perceive it as a part of their body [2], [8], [11], [13], [16], [17], 3.2) improving specific instrumentation to allow the feedback to become refined in a timely manner, 3.3) establishing a haptic feedback strategy, which utilizes a constant vibration feedback through the vibration pulse parameters, that allows for strong embodiment, and 3.4) ascertaining the number of hand grasps (experimental trials) needed for subjects to establish embodiment.

3.1 Visual Refinements

It is known that life-like rubber hands are more readily embodied that non-realistic ones and thus we refined our robotic hands visual appearance to be as visually congruent to participants. Thus, the user would be more likely to believe that the false hand to be a part of their own body if it had a realistic appearance [2], [8], [11], [13], [16], [17].

First, the light box that the participant interacts with was changed in design over the course of the prototyping, as shown in Fig. 3.1. Initially in the form of a large rectangular block, the interactive box was made thinner and had its corners cut. This was intended for the participant to be able to observe more of the robotic hand without it being occlude by the box, as well as make the box easier to grasp.

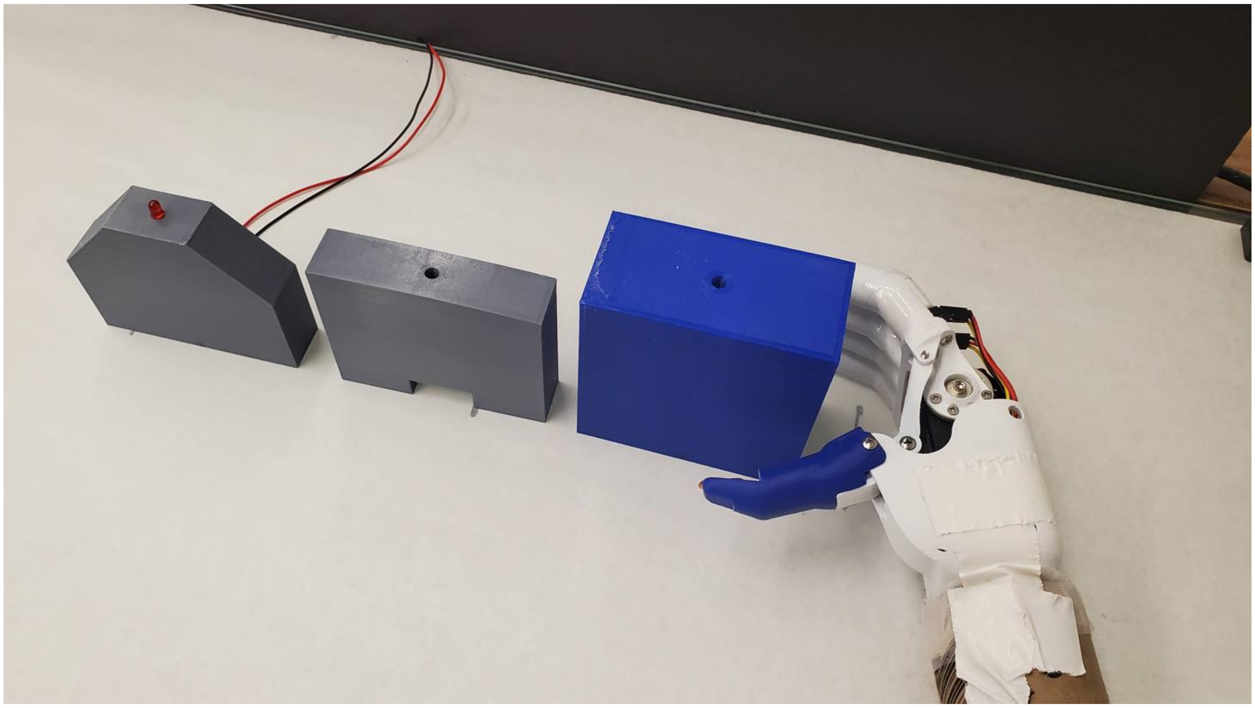

Figure 3.1: Different interactive light box prototypes. Prototype 1 on the right, prototype 2 in the middle, and final version on the left

Next, a black nitrile glove was worn by the artificial hand to cover its 3D printed and electronic parts and make it look less robotic. Depicted in Fig. 3.2 below, a cardboard tube and coat sleeve was attached to the robotic hand to add an arm to the illusion. Furthermore, a pair of matching black nitrile gloves was given to the patient to adorn on both hands to immerse them deeper into the illusion. Although their real right hand was hidden from view, minor tactile cues from feeling and seeing the nitrile glove allowed for deeper immersion.

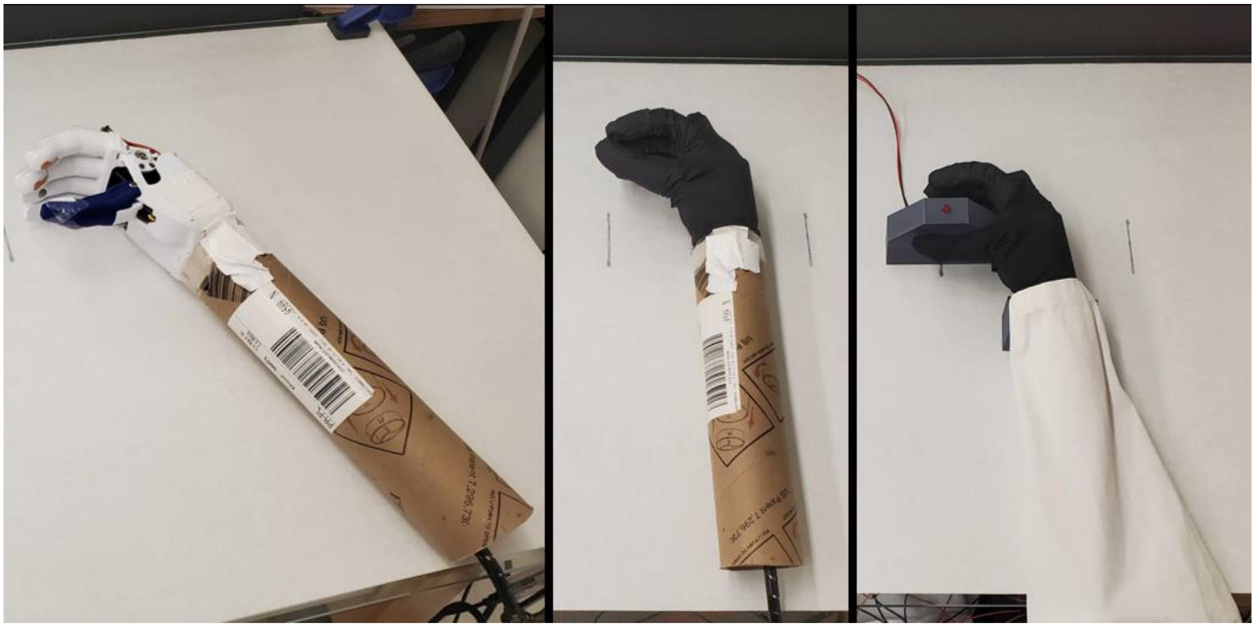

Figure 3.2: Breakdown of robotic hand immersive illusion. From left to right, a cardboard tube is connected to the robotic hand, then a black nitrile glove is worn, and a coat sleeve is attached.

As shown in Fig. 3.3, the robotic hand and fake arm was attached to a lab coat (which included styrofoam stuffing in the upper arm of the sleeve) that was to be worn by the user. When the subject donned a glove in their left hand, the coat allowed for a symmetric appearance in which it appears that the subject has placed both hands on the table, illustrated in Fig. 3.4 below. A pair of headphones were added to the setup, which would play white noise. This would reduce the amount of the motor's noise heard from the robotic hand, but also let the user hear the audible tone from the task.

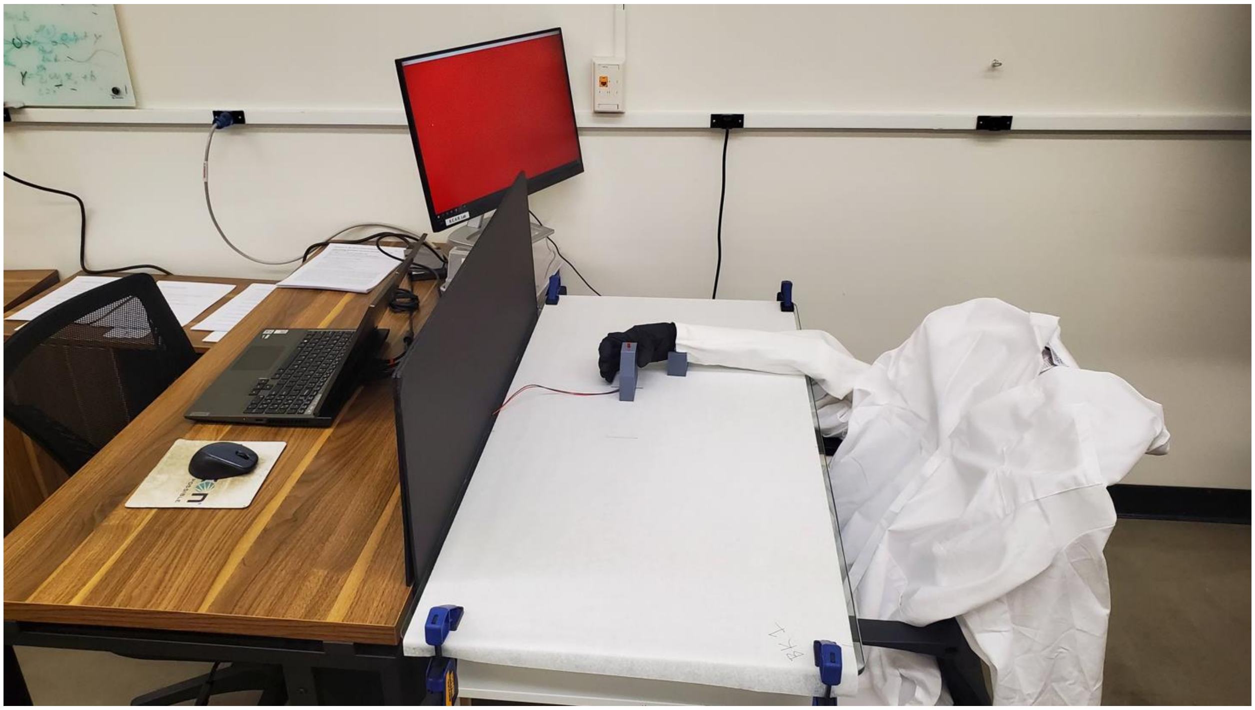

Figure 3.3: Full equipment used for visual illusion in the setup.

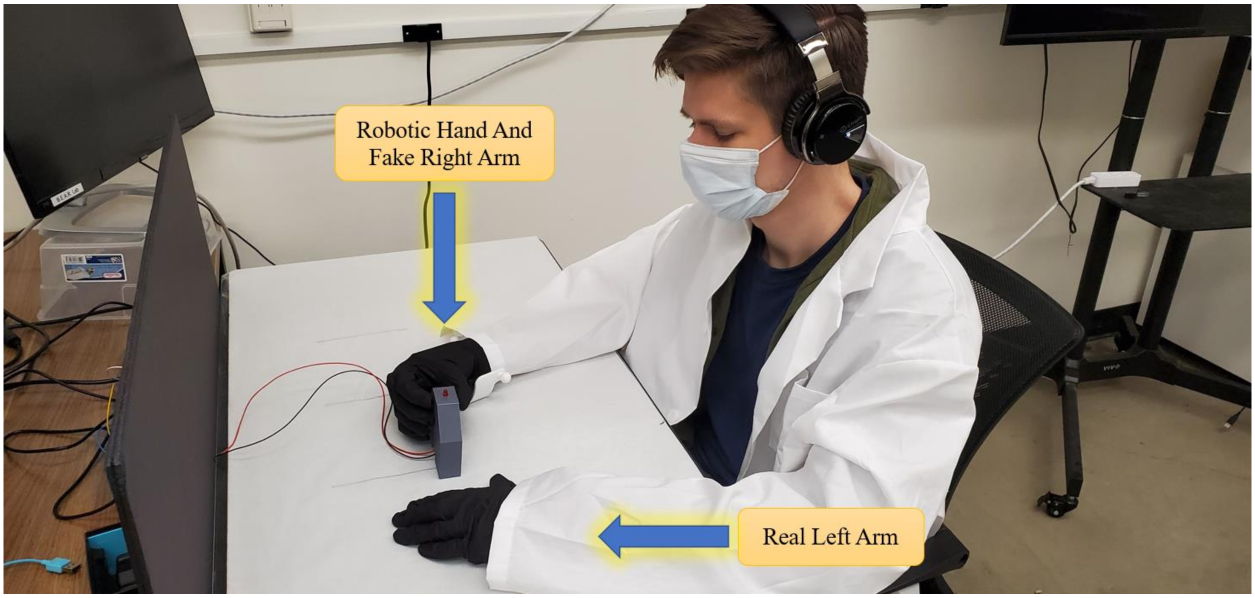

Figure 3.4: Equipment worn by participant for visual illusion in the setup during use. Note that their real-right arm is hidden under the table at the bottom layer.

3.2 Instrumentation Refinements

In the initial version of the prototype, the fingertips of the robotic hand were made of silicone rubber, specifically Dragon Skin™ 10 NV as shown on the right in Fig. 3.5 [44]. This was to simulate the soft feel of human skin and add a better grip. Three Singletact force sensors were placed on the index, middle, and thumb fingers over these silicone rubber fingertips [44]. These sensors would trigger the haptic, visual, and audio feedback to the user in the setup. However, use of the rubber silicone fingertips created an inherent deadband in the force sensors. This meant that the robotic hand was required to grasp the interactive box with a high amount of force to enable detection by the force sensors, instead of the sensors instantly reacting when the hand interacts with box. As shown in Fig. 3.6, different orientations of the sensors (above and below fingertips) and fingertip types were tested to mitigate this deadband. The final configuration of force sensors placed over 3D printed PLA fingertips was found to work the best, being the most sensitive with detecting initial contact of the fingertips on to the light box. The PLA fingertips used are displayed on the left in Fig. 3.5.

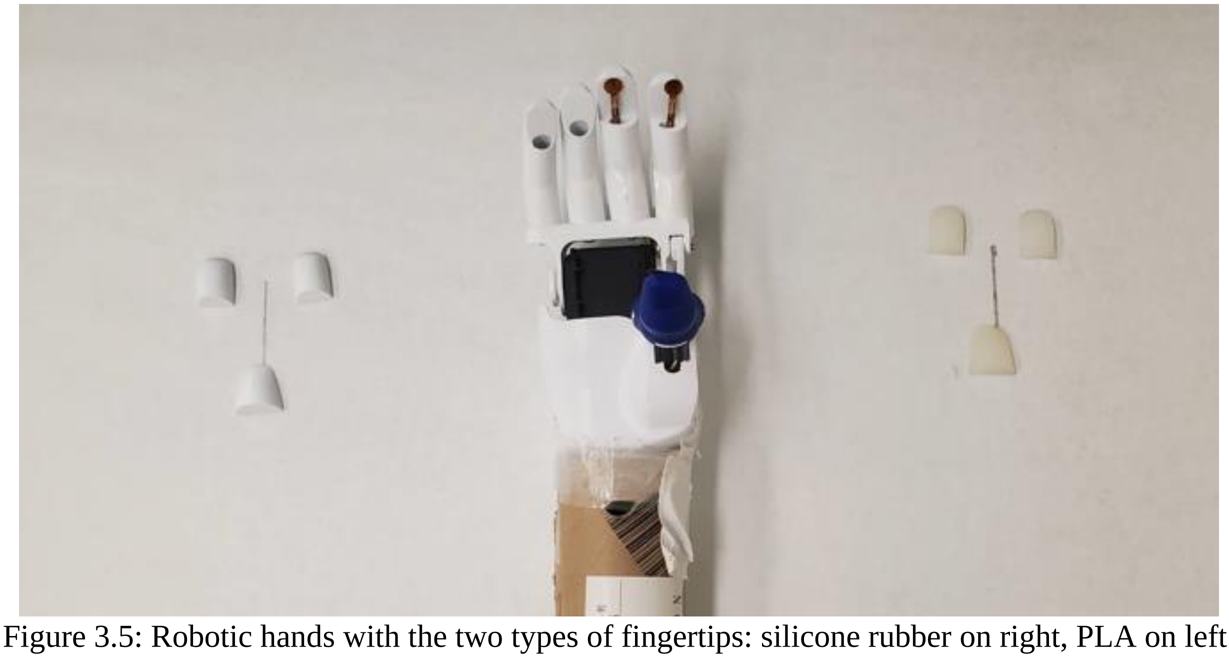

Figure 3.5: Robotic hands with the two types of fingertips: silicone rubber on right, PLA on left.

Figure 3.6: The different orientation of the sensors tested during prototype testing. From left to right: sensor above silicone rubber fingertips; sensor below silicone rubber fingertips; sensor above PLA fingertips.

3.3 Haptic Refinements

The question of which haptic feedback strategy was to be used arose during prototype development. Since there is not much research in regard to whether pulsing vibration or constant vibration is better for embodiment, early testing was conducted to discover which option would be the best for our experimental paradigm. This was done with three participants in which they were subjected to 6 trials of 8 robotic hand grasps, alternating between pulsing and constant haptic feedback. Ownership and agency questionnaires were given after each trial. The average ratings for ownership and agency were then taken from these questionnaires [17], [23]. As shown in Table 3.1, this testing established that providing constant, consistent vibration in the haptic glove for feedback offers stronger ownership and agency values compared to using pulsing vibration for feedback. It can be assumed that the user associates the feedback of vibration with the act of grasping the box, replacing the modality of touch.

	Ownership			**Agency**		
Participant	**1**	**2**	**3**	**1**	**2**	**3**
Mean Rating (Pulse)	1.0833	0	-1.1	1.8333	1.75	2.15
Mean Rating (Constant)	1.5833	0.0833	0.5	2.25	1.6667	3

Table 3.1: Mean ratings for ownership and agency under pulsing and constant haptic feedback with three participants. Here, scores above 0 indicate the formation of ownership or agency.

3.4 Task Refinements

In the development of our experimental trials, it was imperative for us to know how many grasp tasks were needed to achieve embodiment in each trial. Early testing was conducted with three participants, in which they were subjected to 5 randomly assorted trials consisting of either 9, 18, 27, 36, 45 grasps. As with the early haptic testing, ownership and agency questionnaires were given after each trial, and of which average ratings were taken and calculated. According to the results as depicted in Fig. 3.7, roughly 18 grasps is the optimal number for the participants to perform the task, as ownership and agency values increased when the participants approach 18 grasps and then plateaued after this point.

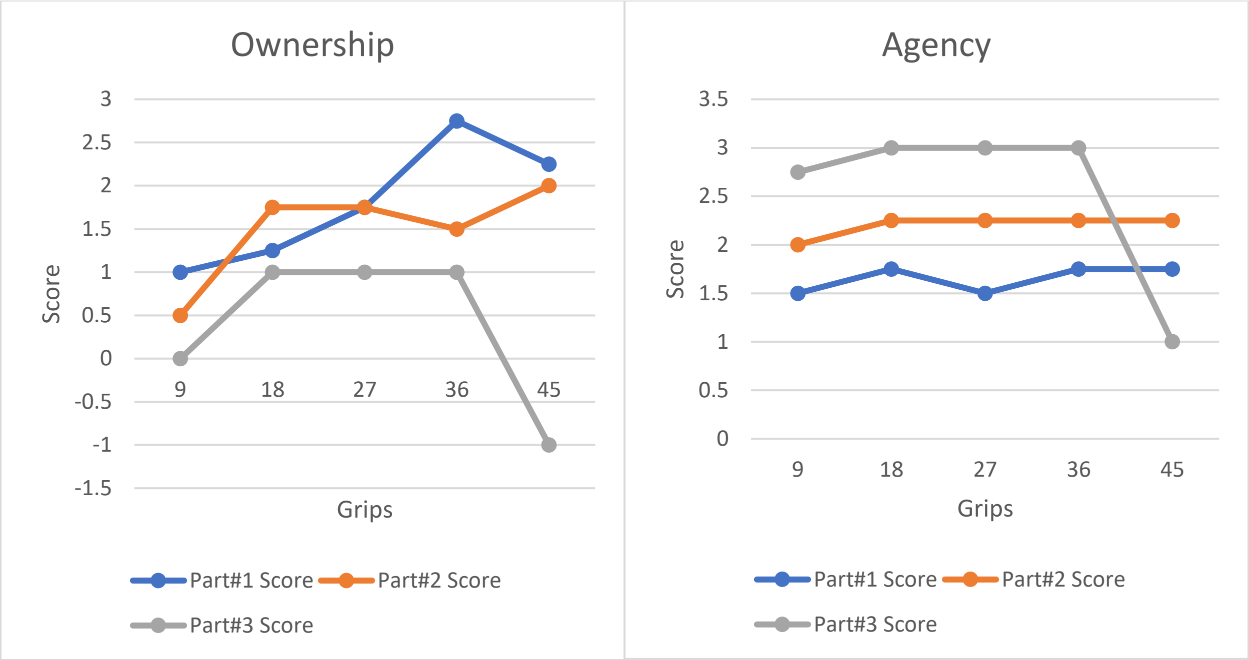

Figure 3.7: Ownership and agency scores plotted against number of grips for three participants.

Chapter 4

Feasibility Testing

With our embodiment evaluation systems fully established, the design and refinement of which was highlighted in the prior chapters, we were able to completely run the experimental protocol. Throughout the preliminary testing, we investigated the feasibility and efficacy of the experimental design in being capable of manipulating ownership, agency and peripersonal space; capturing the variability of embodiment measures; identifying future refinements; and preparing planned data collection activities with larger cohorts of participants in future studies.

4.1 Conditions

Our experimental protocol was conducted in the Schofield (BEAR) laboratory on the UC Davis main campus. We recruited participants according to our criteria of healthy adults between the ages of 18-70 years old, English speakers able to understand verbal and written instructions, and no impairments that may affect their sensory or motor systems. Since the participants were required to communicate with the experimenter throughout testing and control the experimental system with their right arm, we excluded those with cognitive deficits, limited hand movement due to injury or disease, neurological or other musculoskeletal condition impacting biological motor control and/or sensory perception and are unable to understand English. Our protocol was approved through UC Davis' Institutional review board (study #: 1835978-1), and subjects provide informed consent prior to participating.

As mentioned before, the participant’s sense of ownership, agency, and peripersonal space was manipulated through controlling specific variables during the experiment task. In order to influence their sense of ownership, the touch feedback condition of the robotic hand was varied between control with vibration (BUZ), control with no vibration (NB), and watching the robotic hand move by itself (WATCH). To facilitate the measure of intentional binding effects (a measure of the sense of agency), the time delay between the LED illumination and an audio tone was randomly set to the values of 300 milliseconds (ms), 500 ms, and 700 ms [23]. Finally, peripersonal space was manipulated by positioning the robotic hand at different locations in front of the user: directly close in front (C), 8 inches right of the center of their body (M), and 16 inches far right of the center of their body (F).

4.2 Data Collection

Preliminary testing was performed with a small cohort of N=7 able-bodied participants. Data was manually tabulated in Microsoft Excel and Power BI software to capture time interval estimations (intentional binding effects), questionnaire scores, and distance measurements (all described in chapter 2). Descriptive statistics on the collected data was performed to identify and characterize relationships between intentional binding, ratings of ownership and agency questionnaires, and distance measurements (proprioceptive drift); these included correlation matrices, Pearson correlation coefficients, and linear mixed models.

4.3 Analysis Results

We began analyzing the data collected from our participants by inspecting the individual measures of ownership (questionnaire scores), agency (questionnaire scores and time interval estimates), and peripersonal space (proprioceptive drift distance measurements). The mean and standard deviations were also calculated for each of the measures. This data was compiled into the box-and-whisker plots with individual data points, as well as line and bar graphs for comparison.

For our explicit measure of ownership, score ratings were taken and calculated from the ownership and agency questionnaires given at the end of each block of trials (N=18 of individual trials in a block, each block presented a different set of feedback conditions). Positive ratings indicate agreement, 0 indicate neutrality, and negative ratings indicated disagreement [17], [23]. Although there is a degree of variability in this data shown in Fig. 4.1, we were able to ascertain some trends and results. Vibrational feedback applied to the participants’ fingertips (BUZ) was generally associated with the highest ownership values, no vibration (NB) was associated with reduced ownership, and not controlling the robotic hand (WATCH) resulted in the least sense of ownership. Universally, as the hand moved further from the participant, ownership questionnaire scores also decreased correspondingly.

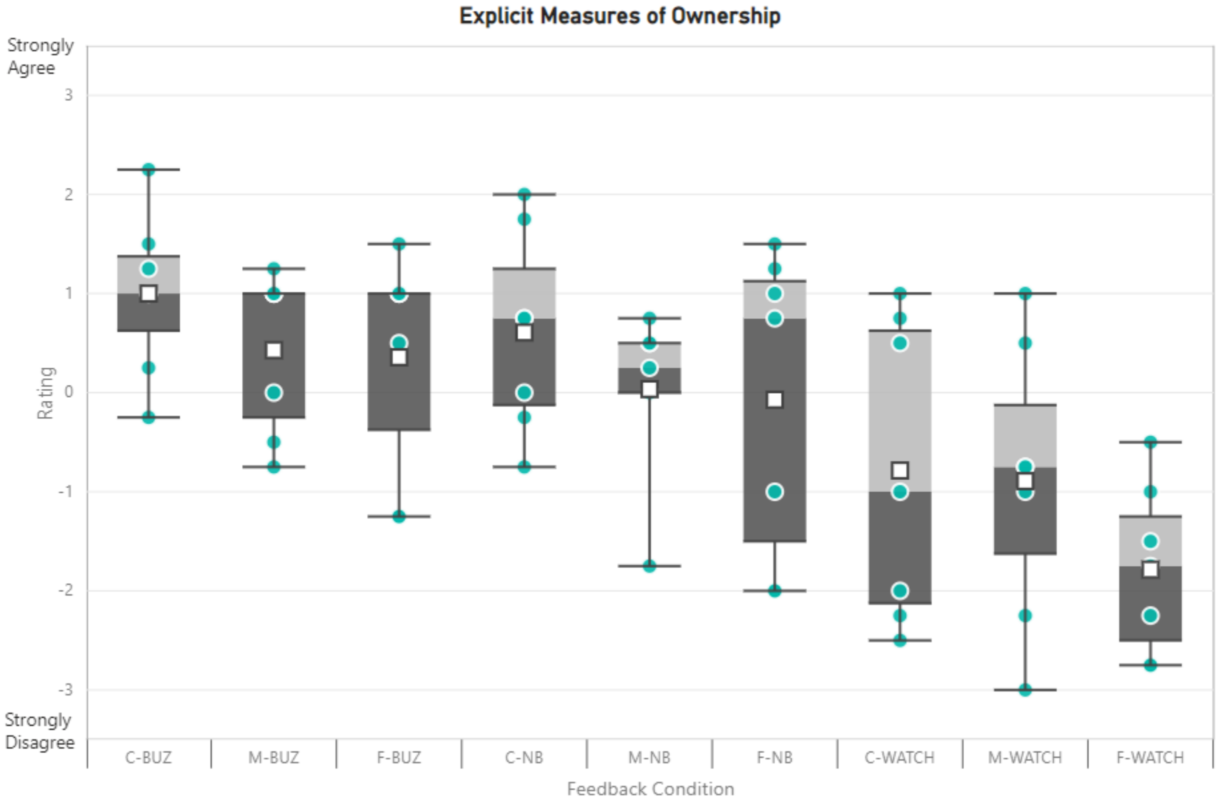

Figure 4.1: Explicit measures of ownership under each feedback condition. The blue data points are values calculated and taken from each participant. The white square indicates the mean value, the light gray box represents the upper/third quartile, the dark gray box represents the lower/first quartile, and the top and bottom whiskers denote the maximum and minimum values respectively.

For our explicit measures of agency, score ratings were calculated from the ownership and agency questionnaires in a similar manner as with the measures of ownership [17], [23]. These responses show a clear pattern as highlighted in Fig. 4.2. That is, when the participants were allowed to control the robotic hand, they were explicitly able to obtain high positive values of agency as indicated in their questionnaire scores. When control of the hand is removed (WATCH), the participants reported low negative values of agency.

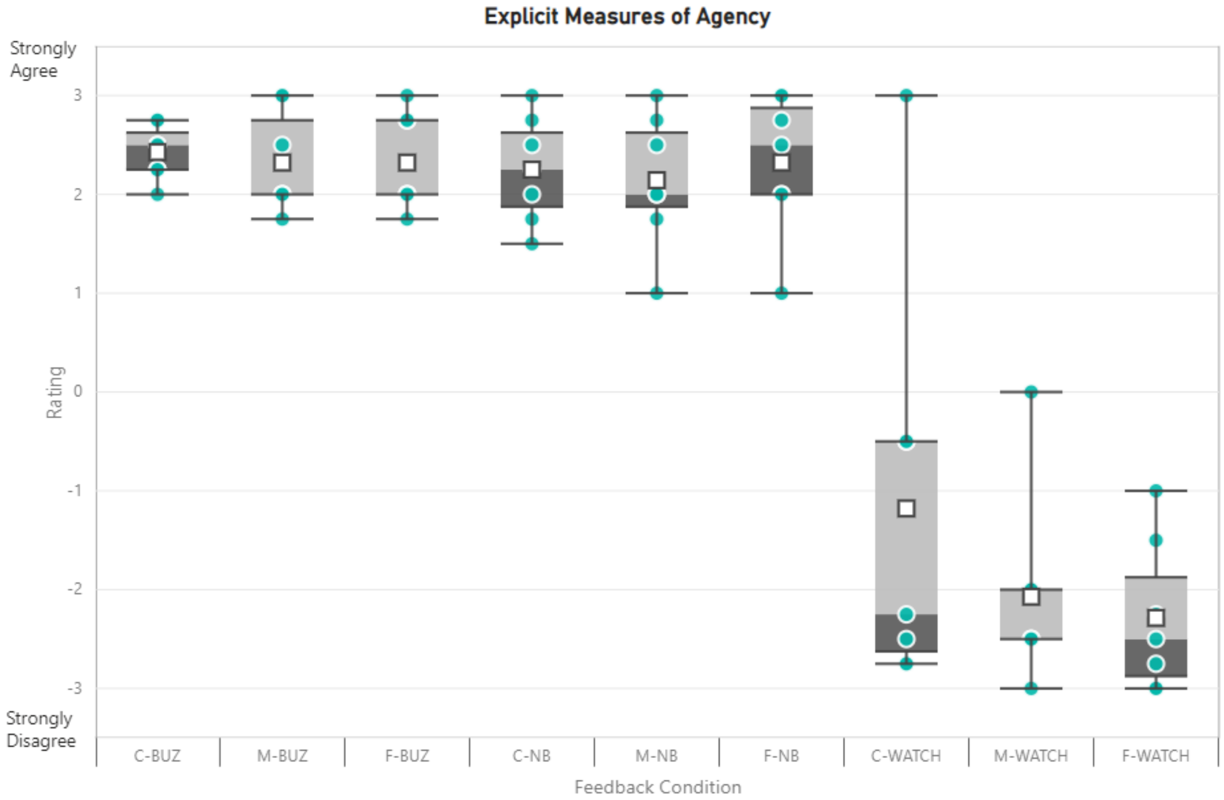

Figure 4.2: Explicit measures of agency under each feedback condition.

For the implicit measures of agency captured through intentional binding (time interval estimate task), the participant's estimated time intervals were subtracted from the actual time delay presented between the completion of a trial (fingertips grasp the block and LED illuminates) to the auditory tone being played. Reported values were averaged over experimental blocks of trials and thus for each feedback condition. With these average difference values, a more negative value indicates a stronger average sense of agency (temporal attraction), since lower time estimates correspond with strong sense of agency [23]. Based on the data in Fig. 4.3, the strongest implicit agency values were obtained when there was vibrational feedback with control of the robotic hand. Interestingly, this testing also showed that there were strong agency values when there was no vibrational feedback while hand control was disabled. In our setup, using haptic vibration applied to the participants' fingertips acts as a sensory proxy for the artificial robotic hand contacting the light block. Although agency needs an internal model, this result suggest that further examination is warranted to investigate the effectiveness of vibration feedback as a sensory feedback modality to promote the sense of agency.

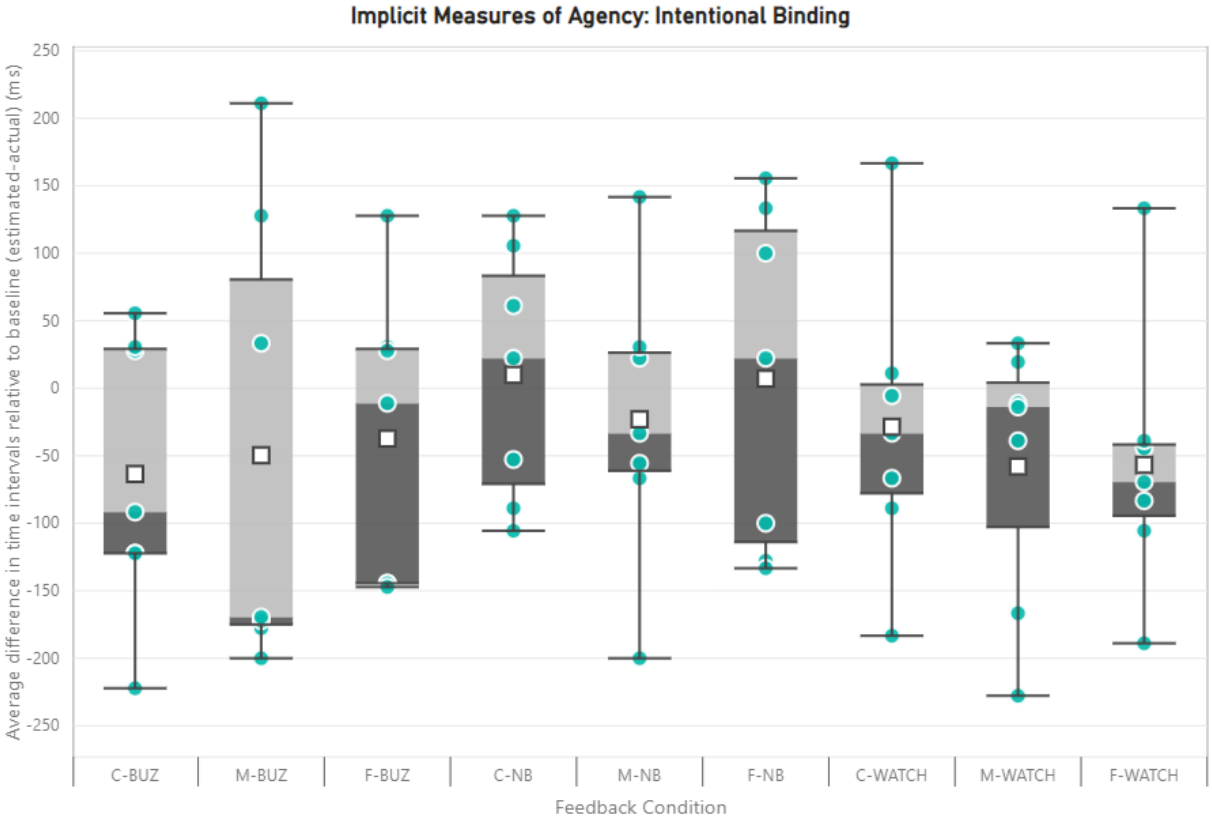

Figure 4.3: Implicit measures of agency via time interval estimates under each feedback condition.

Both implicit and explicit measures of agency were correlated with each other as depicted in Fig. 4.4. This was produced by calculating the average time interval estimates and the average agency questionnaire scores for each feedback condition, and then plotting these values as shown in Figure [23], [47]. Examination of this plot reveals certain details. Giving the participants vibrational feedback (BUZ) when controlling the robotic hand allows them to obtain greater explicit agency and strong intentional binding values. Removal of the vibrational feedback saw a decline in binding values, while retaining high explicit agency scores. However, disabling both robotic hand control and vibration feedback was associated with stronger binding and lower explicit agency values.

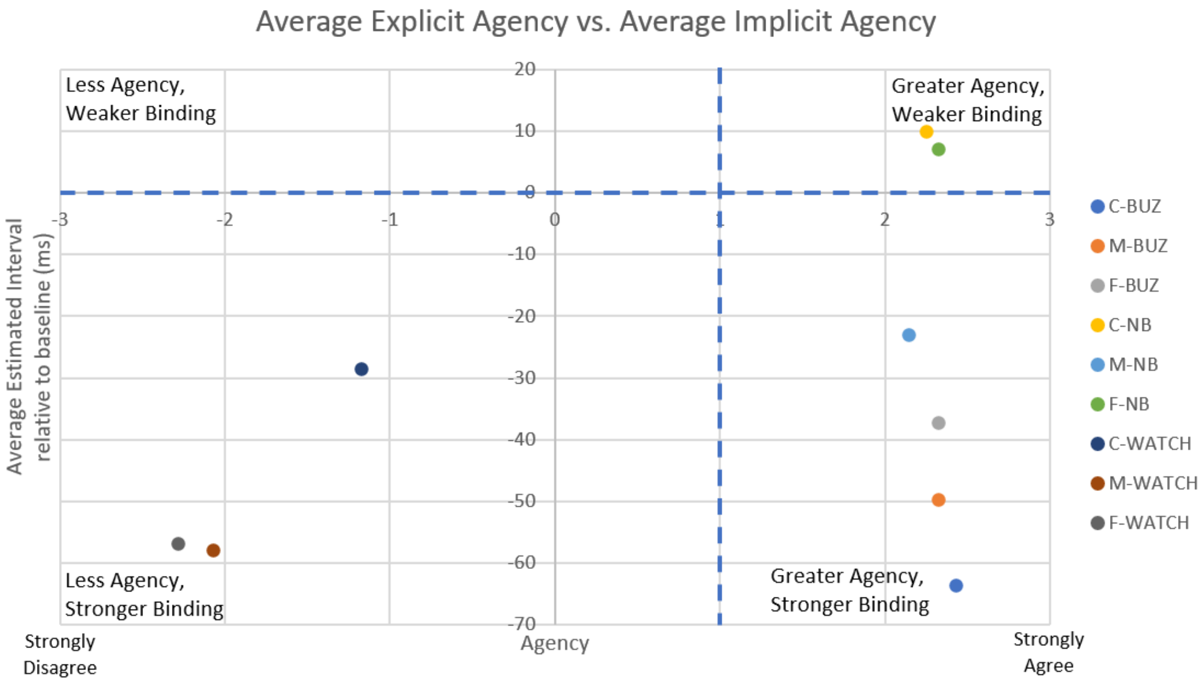

Figure 4.4: Average explicit and implicit measures of agency for each feedback condition. Average explicit agency results are plotted on the x-axis, and average delay interval estimates are plotted on the y-axis. Moving right along the x-axis denotes an increase in the explicit experience of agency, while moving up along the y-axis denote a decrease in the implicit sense of agency.

It must be noted that in the measures of ownership and agency, there was large amount of variability in the responses of the participants, indicating that they are affected by the embodiment illusion induced through our experimental setup to varying degrees (Fig. 4.5, Fig. 4.6, Fig. 4.7). There were cases like Participant 4 shown in Fig. 4.5 that did not readily experience embodiment effects over the artificial robotic hand, as reflected in the low measures of explicit ownership and agency. Meanwhile, there existed cases such as Participant 5 in Fig. 4.6 in which they were very susceptible to embodiment illusions, regardless of feedback conditions. These occurrences in addition to participants with more moderate responses akin to Participant 7 in Fig. 4.7, introduced wide variability in the preliminary data reported here.

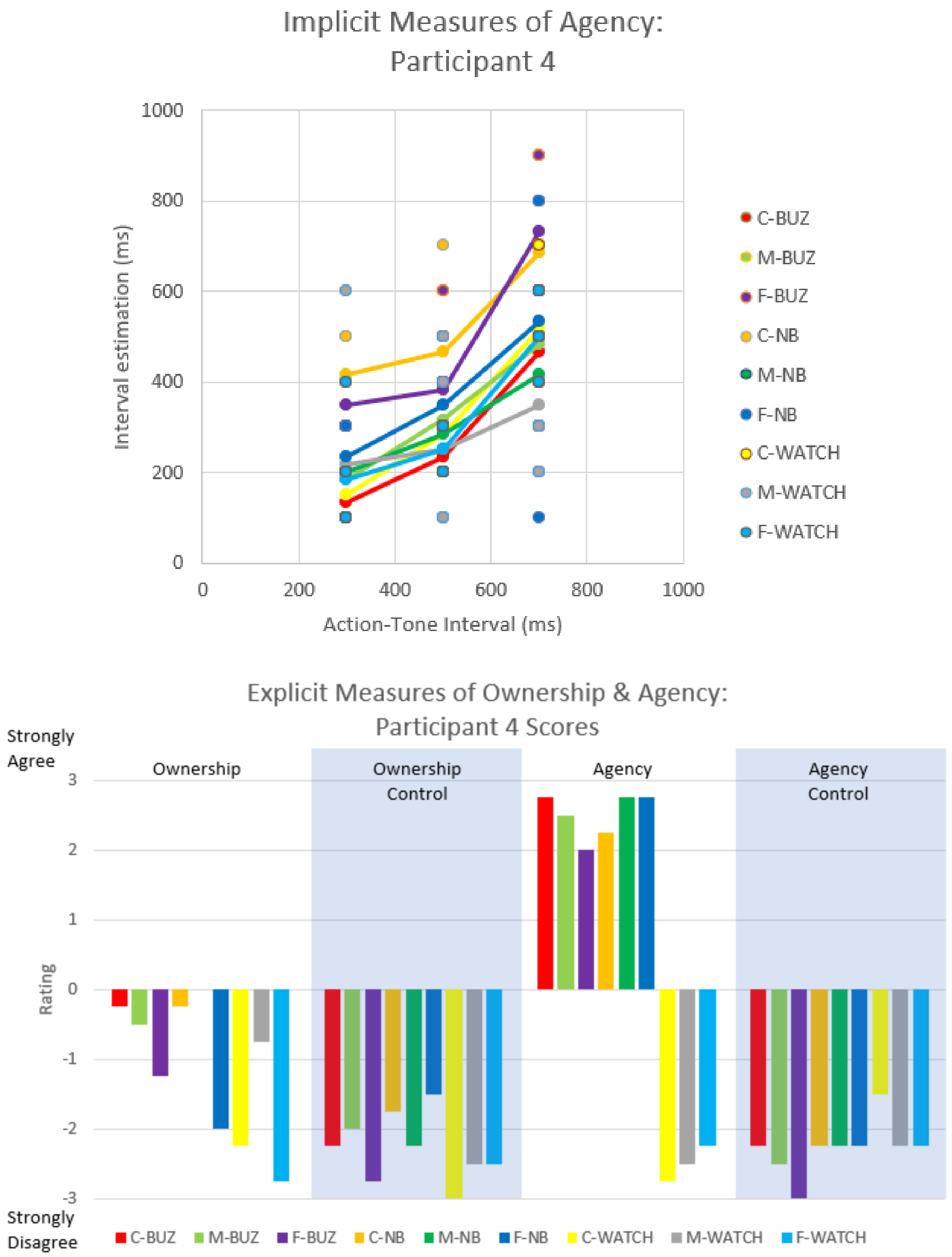

Figure 4.5: Individual data for participant 4.

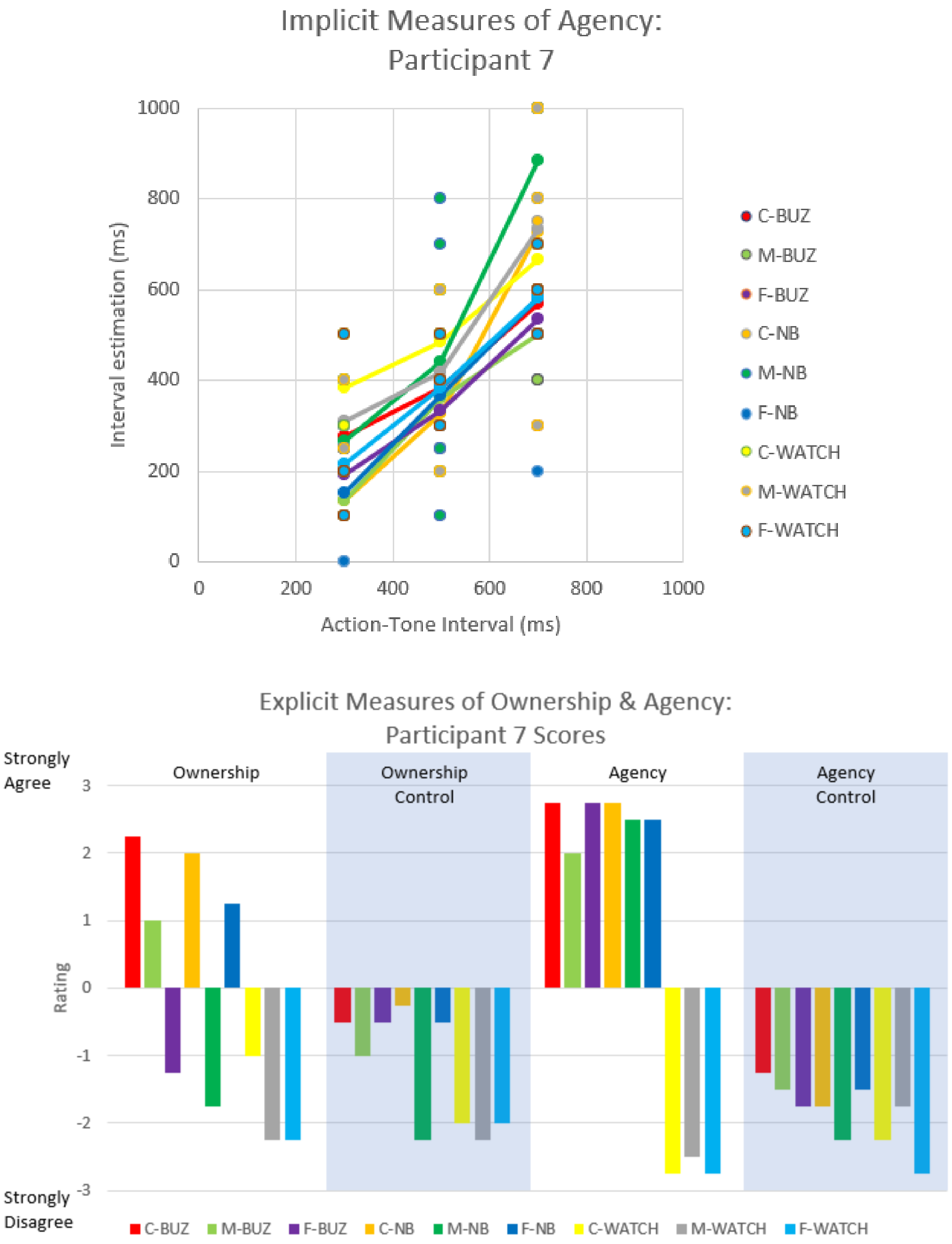

Figure 4.6: Individual data for participant 7.

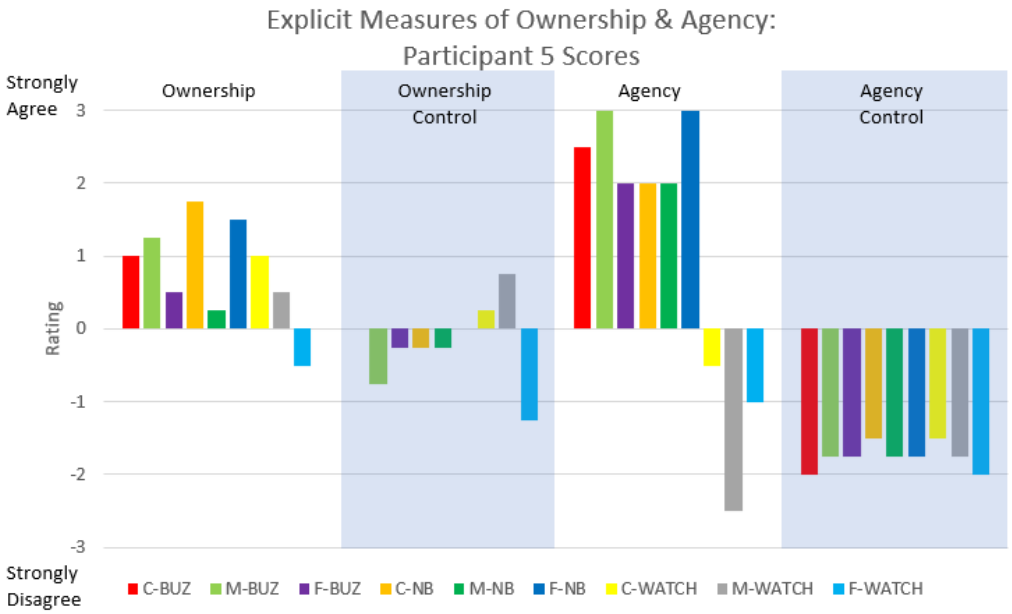

Figure 4.7: Individual data for participant 5.

Note for Fig. 4.5, 4.6, 4.7, explicit measures of ownership and agency under each feedback condition are displayed on top. These calculated scores are based on the ownership and agency questionnaires [17], [23], [47].

Implicit measures of agency under each feedback condition are exhibited above. This data is based on the participant's interval estimates for the delay time between the LED light illumination and the audio tone plotted across each actual time delay interval [23], [47]. The average is also plotted for each feedback condition. The angle of response in the tone guess can represent the level of intentional binding. 45° indicates that the estimate is equal to the actual delay. Less than 45° indicates that there is better sense binding as the interval estimate is lower than the actual delay time.

The measure of peripersonal space was evaluated through the distance of proprioceptive drift, which was taken at the end of each block of trials testing a feedback condition [2], [11], [12], [17]. A general increase in proprioceptive drift was observed as the artificial hand moves from the close position in front of the subject (C), to the medium position 8 inches to the right (M), to the far position 16 inches to the right (F). This trend can be seen in Fig. 4.8.

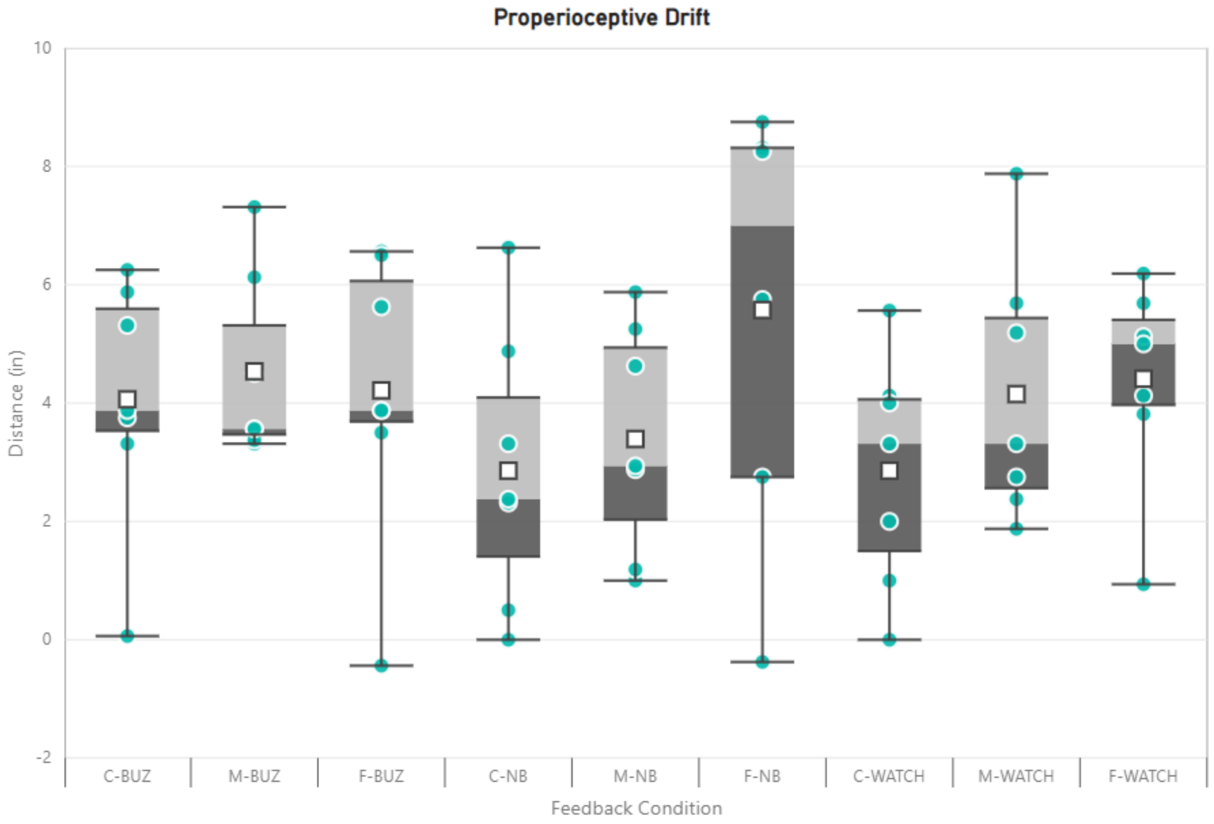

Figure 4.8: Measure of peripersonal space via proprioceptive drift (inches).

4.4 Relationships between measures

A Pearson correlation coefficient matrix was created between the four measures of explicit ownership and agency, implicit agency (intentional binding), and proprioceptive drift to examine relationships between ownership, agency, and peripsersonal space in the formation of embodiment. Each of the measures were plotted against each other using values across all the feedback conditions together to find the corresponding R-squared value. The correlation plots and matrix are presented in Fig. 4.9 and Fig. 4.10, respectively.

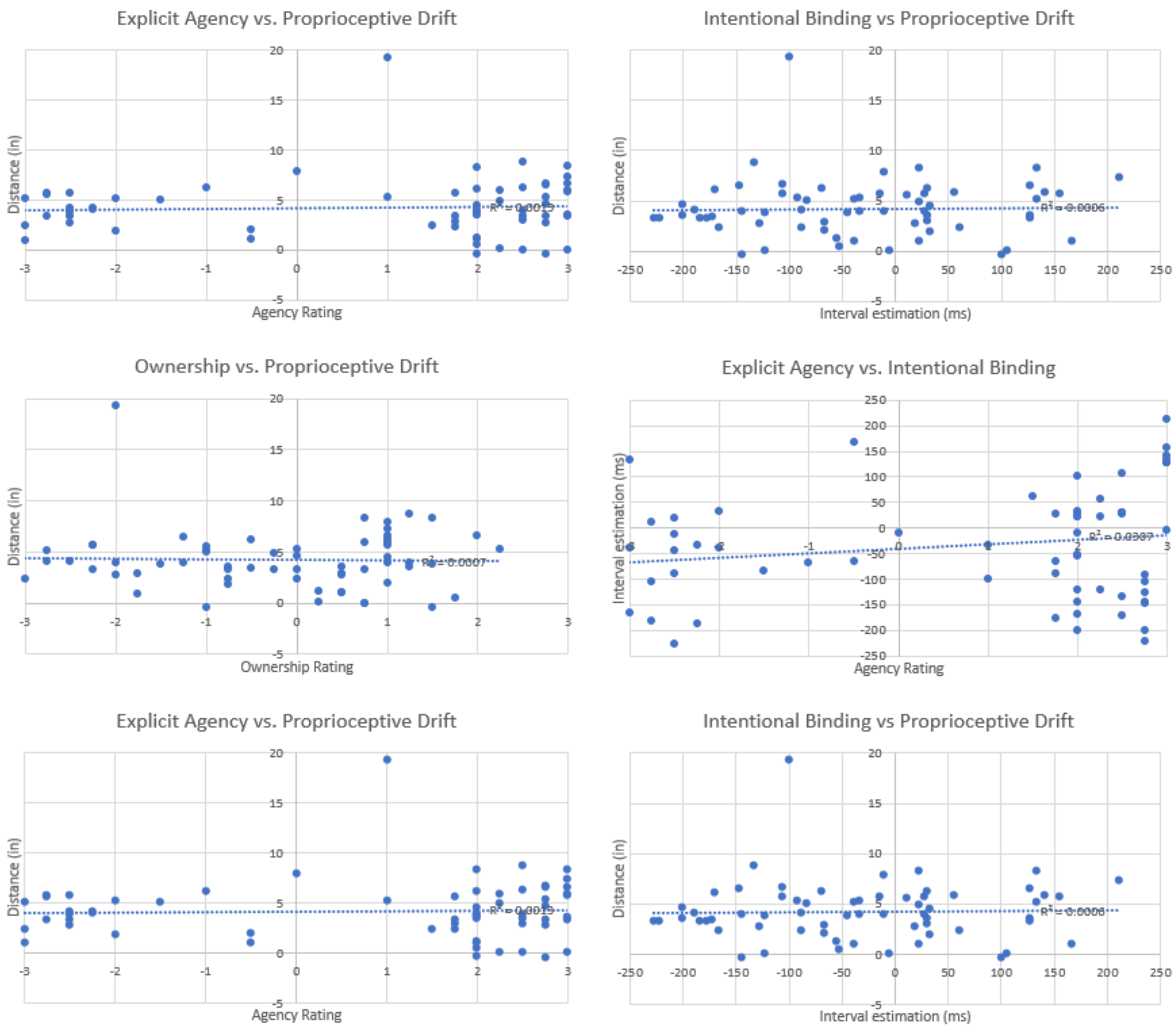

Figure 4.9: Correlation plots (with R-squared lines) between the four measures of explicit ownership and agency, implicit agency/intentional binding, and proprioceptive drift.

Correlation Matrix

	IB	PD	OWN	AGN
IB	1	0.00061936	0.075656	0.030699
PD	0.000619	1	0.000736	0.001334
OWN	0.075656	0.00073591	1	0.460502
AGN	0.030699	0.00133372	0.460502	1

Figure 4.10: Pearson correlation coefficient matrix between the four measures of explicit ownership and agency, implicit agency/intentional binding, and proprioceptive drift.

Although there were some visible patterns in the plots, there was wide variability and likely not enough data to draw meaningful conclusions from the correlation plots and matrix.

The current small sample size was not enough to allow us to determine any clear statistical relationship between the four measures of explicit ownership and agency, implicit agency/intentional binding, and proprioceptive drift. We require many participants to build a larger sample size in order to discern any relationships between ownership, agency, and peripsersonal space as they form embodiment. This pursuit in increased sample size is an ongoing development in future studies involving our embodiment evaluation system in our lab, extending past my thesis research.

Although the relationship among the four measures were not able to be determined, the system is clearly capable of manipulating individual experiences of embodiment. Thus, this thesis was able to establish the fundamental experimental test-bed to enable us to pursue the question of relationships among measures using larger sample sizes.

Chapter 5

Conclusions and Future Directions

This thesis aimed to establish a research platform and the tools necessary to experiment with interactions of ownership, agency, and peripersonal space to form embodiment, in order to uncover how these three parts interact and influence the sense of embodiment. Understanding these relationships will allow us to elucidate the nature of how our brain identifies our own bodies and actions. This information can prove vital to designing and tuning control and sensory systems for prothesis and other assistive mechatronic devices so that they are more closely perceived as a part of one's body.

Despite the presence of significant variability in response of certain measurements, the experimental protocol and our developed system demonstrated the feasibility in acquiring relevant measures to quantify and manipulate the three constituent components of embodiment: ownership, agency, and peripersonal space. Some of this preliminary data has unveiled patterns relating certain feedback conditions, motor control, and sensory outcomes to ownership, agency, and peripersonal space. This includes vibrational feedback association with high ownership values as shown in Fig. 4.1, and the presence of high agency values when participants were allowed to control the robotic hand as showcased in Fig. 4.2. However, this study is limited by its small sample size to ascertain strong conclusions. Despite the limitations, we were able to create the foundations of this embodiment evaluation system in the hope of its expansion and helping those it can truly benefit.

It is necessary for this protocol to be applied to a large-scale population to confirm our findings from the preliminary experiment. A large study group would allow us to further determine the correlations between ownership, agency, and peripersonal space during embodiment. Currently our lab is implementing larger sample sizes and performing tests involving our embodiment evaluation system. This experimental setup could also be expanded for future embodiment testing with disabled participants and other unique groups.

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