A Sense of Urgency on the Sense of Agency: Challenges in Evaluating Agency and Embodiment in Virtual Reality

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Figure 1: A depiction of all control conditions in the experiment as seen in the user's point-of-view in the virtual mirror. Control conditions from left to right: Low - control over head only, Medium - control over head and torso, and High - control over head, torso, and arms.

Abstract—Control over an avatar in virtual reality can improve one's perceived sense of agency and embodiment towards their avatar. Yet, the relationship between control on agency and embodiment remains unclear. This work aims to investigate two main ideas: (1) the effectiveness of currently used metrics in measuring agency and embodiment and (2) the relationship between different levels of control on agency, embodiment, and cognitive performance. To do this, we conducted a between-participants user study with three conditions on agency (n = 57). Participants embodied an avatar with one of three types of control (i.e., Low - control over head only, Medium - control over head and torso, or High - control over head, torso, and arms) and completed a Stroop test. Our results indicate that the degree of control afforded to participants impacted their embodiment and cognitive performance but, as expected, could not be detected in the self-reported agency scores. Furthermore, our results elucidated further insights into the relationship between control and embodiment, suggesting potential *uncanny valley*-like effects. Future work should aim to refine agency measures to better capture the effect of differing levels of control and consider other methodologies to measure agency.

1 Introduction

Virtual reality (VR) enables users to explore and interact with seemingly endless virtual worlds by proxy of a virtual avatar. Virtual avatars serve as the user's graphical representation in their virtual environment and allow interaction with the virtual environment [19,63]. Avatars also impact how one perceives and interacts with their virtual environment. As users create an identity with their avatar, their behaviors and perceptions may deviate from what would be their norm [28,67]. For instance, users with an attractive avatar will self-disclose more information and position themselves closer to a confederate in their virtual environment [67]. Users have demonstrated deviant behavior with avatars of varying weight [50,51], height [67], age [40], and even race [2] [62]. Indeed, perceptions of affordances within the virtual environment, such as object size perception [3,45], depth perception [15,43], and passability perception [8,9,66] are altered by both the inclusion of a avatar and the avatar's characteristics.

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1.1 Avatar Embodiment

This section investigates avatar embodiment and how embodiment can be achieved. In light of embodiment, we discuss the properties of embodiment and how these properties manifest within the user based on conditions of the virtual simulation or avatar.

The sensation that the self and the virtual avatar are one and the same is called virtual embodiment. Kilteni et al. describe this sense of embodiment as the feeling of "being inside, having, and controlling a body" with regard to VR [32]. When users are afforded a sense of embodiment, it is possible to imbue psychological change within the user beyond the behavioral and perceptual changes described previously. For instance, users embodying an avatar of another race may experience racial bias changes [4,48,68], or users embodying an avatar of another age may experience age bias reduction [5,38].

As VR experiences can range from many contexts, full avatar embodiment may not always be applicable. Kilteni et al. describe avatar embodiment as the combination of the senses of agency, self-location, and ownership [32]. The three senses briefly refer to the sense of being in control (agency), the sense of being co-located with your avatar (self-location), and the sense that the avatar's body is your own (ownership) (see Section 2.1). Kilteni et al. describe that embodiment is a continuous scale, with our physical bodies assumed as the default of maximal embodiment (i.e., full sense of agency, self-control, and ownership) [32]. The individual senses of embodiment are also experienced continuously and can be measured as such, with our physical bodies' senses referring to the maximum capacity on the scale. However, embodiment may still be experienced in minimal intensities if senses are absent or inhibited [68].

Depending on the use case, users may not be afforded all senses of embodiment. For instance, the user may not have complete self-location with their avatar [27,68] or even control over the entire avatar body [66]. Control of humanoid avatars in VR is often afforded through visual-tactile stimulation and motion tracking of the physical and virtual bodies [35,64]. However, such tactics to provide a sense of agency to the user are not always feasible, especially when affording users control is atypical (e.g., non-humanoid avatars) [29]. Other times, control over only certain humanoid limbs is necessary or possible. As a result, the representation of the avatar and the capabilities granted to the user for their avatar will often vary.

1.2 Defining Control vs. Agency

In this section, we provide a distinction between the terms "control" and "agency" as they are used throughout this article. We refer to **control** as the total scope of capabilities that a user is afforded in their avatar and is an objective component/characteristic of a virtual experience. When researchers study one's sense of embodiment, we attempt to measure how much control a user *feels* they have. This is measured as a term called **agency**. Specifically, agency refers to the component of embodiment called "sense of agency" which is the *subjective* sense of global motor control over the avatar such that the avatar behaves as the user expects. Control and agency are ultimately related, and one would generally expect that as control improves, so too should the sense of agency [32].

Note that the control actually afforded to users is objective. The amount of control afforded to a user is objectively defined by what the system allows the user to do. Despite this, agency is generally measured through self-reports of how much control the user feels they have [1,6,32].

1.3 Motivation

Accurately measuring virtual embodiment and its components is critical to understanding it. Kilteni et al. described the need to formally measure embodiment, its components, and their relationship in their seminal work [32]. As a result, numerous articles have worked towards measuring embodiment and elucidating the impact that the senses of embodiment have on each other [11,13,21,27]. Particularly, Gonzalez-Franco & Peck created the Avatar Embodiment Questionnaire [25], which later re-defined embodiment with the components of Appearance, Response, Ownership, and Multi-Sensory [46]. The re-defined embodiment components encapsulate Kilteni et al.'s original three senses; however, certain senses, such as agency, were altogether removed as a core sense and instead embedded within other components.

Metrics for the sense of agency have provided conflicting results. In Peck & Gonzalez-Franco's work, the primary reason for removing agency as a component was its unreliability as a metric. Other prior works have echoed mixed findings regarding agency's importance to embodiment [1,11,16,49]. In some cases, higher control over the avatar improved embodiment [16] and agency [37]. In other cases, higher control led to no significant differences [16,37,49] or even a decrease in agency [33]. Literature has even found that simply manipulating the representation of avatars can completely alter perceptions of agency [1]. Despite the conflict in results, it has been established that the sense of agency is critical to the sense of embodiment.

We suggest that agency's removal as a core sense in works such as Peck & Gonzalez-Franco's is due to the method of measuring agency over the avatar [46]. Since the sense of embodiment is a subjective sense of how embodied a user feels, it is not necessarily unreasonable that the individual senses of embodiment are subjectively measured. However, An effective, proper measure of agency ought to be able to reflect the literal degree of control afforded with respect to our physical bodies. Thus, we reason that the previous conflicting results on agency are due to how we are currently measuring the sense of agency in standard questionnaires.

1.4 Scope and Contribution

This work aims to demonstrate how control relates to the sense of agency and impacts the sense of embodiment while establishing if measures for the sense of agency properly capture its impact. It is challenging to quantify the impact of agency without being able to measure agency properly. Therefore, a primary objective of this work is to determine if current agency metrics are effective and can even differentiate between different degrees of agency afforded to a user. To determine this, we measure embodiment and the sense of agency in three conditions with increasing degrees of control over the virtual avatar. Participants are assigned an avatar that is afforded control of only their head (Low condition), control of their head and torso (Medium condition), and control of their head, torso, and arms (High condition).

Our findings in this work demonstrate that increased control impacts embodiment. However, current agency metrics do not reflect this degree of control, which may indicate that these measures are sub-optimal. Furthermore, our results highlight the complex relationship between agency and embodiment and shed light on how varying levels of agency can improve and even inhibit embodiment. Lastly, this research contributes to the growing body of work on embodiment and its effects on cognitive performance.

2 Related Works

2.1 Sense of Embodiment

The sense of embodiment over an avatar refers to the feeling that the avatar and the self are one and the same. The understanding of embodiment and its senses continues to evolve, and as such describing the components can be challenging. The senses of embodiment originally included ownership, self-location, and agency [32].

Ownership refers to the sensation that the avatar's body belongs to the user [32]. When one possesses an avatar in a virtual environment (unembodied), the experiences that occur in the virtual environment may often be attributed as experiences occurring for the avatar. A sense of ownership over the avatar indicates that the user is attributing those virtual experiences to the self rather than as experiences occurring for a separate, independent avatar [48, 57]. *Self-location* refers to the sensation that the avatar's body is physically co-located with the user. One can think of self-location as analogous to presence: self-location is the relationship of one's self and the avatar, and presence is the relationship of one's self and the environment [32,39]. In real life, one's body and sense of self are co-located by default. In virtual environments, one can have control over an avatar that is not co-located; thus, a sense of self-location may be absent. When the space that a user feels to be located aligns with the space provided by the avatar, the user is said to feel self-located within the avatar.

Agency encompasses the aspects of global motor control that one possesses over the avatar. This global motor control may manifest in psychological forms such as intent or the conscious experience of one's desire to perform an action. Global motor control also entails the literal actions or movements selected by the user [32]. It is important to distinguish the sense of agency from the degree of control afforded to a user. The sense of agency refers to the perception of authority in intention, behavior, and portrayal of action [10]. We expect that the degree of control afforded to the user should align with the sense of agency experienced by the user. However, as the sense of agency is subjective, this may not be adequately reflected. For instance, if the visual experience of the user's action does not align with the user's expectation, the sense of agency can be negatively impacted [20,55].

Further definitions of embodiment encompass and expand upon the senses of ownership, self-location, and agency. De Vignemont describes the sense of embodiment in terms of three dimensions (Spatial, Motor, and Affective) that directly correspond to the subjective senses of self-location, agency, and ownership, respectively [12]. Other aspects such as tactile sensations [56], the external appearance of the avatar [57], and response to external stimuli [26] are known to impact the sense of embodiment as well [25]. More recently, Peck & Gonzalez-Franco's work re-defined the sense of embodiment as four primary components:

the external appearance of the avatar (*Appearance*), the response to external stimuli (*Response*), ownership over the avatar (*Ownership*), and sensory aspects such as touch (*Multi-Sensory*) [46]. While senses such as ownership remain their own individual component, senses such as self-location and agency are redefined within the scope of Multi-Sensory, Response, and Appearance. The relationship between the senses of embodiment and how they individually impact embodiment is complex [54, 64, 69]. For instance, improving the sense of ownership can indirectly improve self-location or agency, and vice versa [52, 64]. Embodiment is maximized when each sense is maximized. Still, embodiment can occur to a lesser degree when at least one sense is minimally present [68]. Even in situations where the avatar is non-humanoid or one of the senses of embodiment is altered, users can still feel embodied in their virtual representation [29, 36, 42].

2.2 Agency

Providing users with control over their avatars enhances their sense of embodiment [32, 35, 64]. Agency is described as the sense of global motor control over the avatar such that the avatar behaves as the user expects. [10, 32]. It is a subjective sense of how much control one feels they have over the body's intention, actions, and "conscious experience of will [10]."

Achieving a sense of agency in VR has been explored in a number of ways. Modern VR systems can afford 6-degrees of freedom, which allows for translation and rotation in 3D spaces. Using head-tracked displays and controllers, one can calculate movements in VR to mimic the movement of the real-world user through inverse kinematics [16]. More robust systems even allow for fully tracked body suits that can more definitively map user movements to their avatar [58]. We assume that agency is maximized when a user's avatar mimics their real-life behavior, though this is not necessarily the case [22, 29]. Agency hinges upon a user's prediction for their action and the resulting action that actually takes place [22, 23]. In other words, a sense of agency can be achieved if the user controls their actions in a manner sensible to their perception of their actions.

The sense of agency plays a critical role in embodiment. The understanding of embodiment today would dictate that improving the objective control afforded to the user should improve the sense of agency and embodiment as a whole. In this work, we investigate the relationship between objective control, sense of agency, and sense of embodiment to determine if current agency metrics properly capture the relationship expected.

2.3 Cognition in VR

Cognitive tests such as the Stroop test are utilized to assess one's short-term memory and cognitive function [30, 34]. Such tests have been utilized in varying capacities within the psychology field. One must employ strategies to offset the cognitive load provided by these tests to succeed. Humans naturally tend to rely on gestures for such recall, and studies have shown that the inability to gesture directly inhibits recall [24, 60]. In the realm of VR, the natural view of the body is occluded by the HMD; however, such occlusions can be rectified with the involvement of an avatar. Peck & Tutar found that performance on Stroop tests was positively correlated to embodiment of an avatar (e.g., self-location) [49], suggesting that avatars may affect working memory. Steed et al. also investigated the effect of embodiment on cognitive tests and working memory [60]. Participants who had an avatar and had agency over their avatar performed better on their respective cognitive test. When a user experiences a higher degree of embodiment, the ability to perform recall for the cognitive test is less inhibited. Thus, one could expect that if a user scores higher on embodiment and agency, the performance on the cognitive test would correlate positively. The present work utilizes cognitive tests to better understand how agency and embodiment relate.

3 System Description

3.1 Apparatus

The immersive virtual environment utilized for this study was developed using the Unity 2017.4.0 LTS game engine software and was rendered on an HTC Vive HMD using a Lenovo Legion 5 laptop equipped with an Intel i7-10750H 2.6GHz processor, 16GB of RAM, 512GB SSD, and an NVIDIA GeForce RTX 2060 graphics card. The HMD has a 110○ field of view with a frame refresh rate of 90 Hz. The HTC Vive controllers were used to facilitate user input (responses) for the Stroop test investigated in this study as described in Section 4.3. During pilot testing, the simulation's frame rate was measured, ensuring that it was stable and approximately equal to the maximum possible refresh rate of the device (90Hz).

3.2 Virtual Environment and Avatar Control Conditions

A virtual environment was created to study the effects of agency on embodiment (see Sections 4.3 & 4.2 for Task and Study Design). The virtual environment and study design were based on prior work by Peck & Tutar [49]. The virtual environment was arranged to be similar in size and design to the physical co-located space. The room was rectangular and furnished with a desk and a chair, where the user was seated for the duration of the experiment. On the desk was a black monitor which contained the text, UI elements, and instructions as needed. At the end of the desk, directly in front of the user was the virtual mirror where the user could see themselves during the avatar embodiment phase and Stroop test. The room was staged as an office and thus included other desks and chairs in the corner, wall art hanging on the virtual walls, a cabinet with a lamp fixed on top with books placed adjacently, and another floor lamp placed in the opposite corner visible to the user. The intention was to use familiar objects in creating a realistic perception of space, size, and scale within the experimental setting.

The user was situated at the physical lab space's desk and chair, which were co-located with the virtual lab space and desk. Before each experiment began, the user's selected avatar was scaled such that the avatar's height matched the user's height. In each condition, the user had control over part of the virtual self-avatar. Since the virtual experiment took place seated, the avatar legs were stationary. We describe the level of control and its implementation below.

Low. In the Low condition, the user could only control their head via rotation. Translational movements of the head were not afforded for two primary reasons: (1) translation of the head is not a typical motion as humans tend to move their upper bodies or neck to move their head rather than the head individually, and (2) head position data from the HMD would be applied as neck and spine movement rather than head movement to avoid unnatural animation. Control over torso, arms, and hands was also not afforded. Orientation data from the HMD was applied to the avatar's head to generate the rotation in VR.

Medium. In the Medium condition, the user could control both their head and torso. Control over arms and hands was not afforded. The head movement was consistent with the Low condition, where only rotation was possible. However, with the addition of torso movements, the user could move the whole of their upper body. Users largely restricted their movements to lateral movements, altogether ignoring upward movements, as they were seated. The inclusion of motion in the torso also technically allowed for movement of the head as the head moved along with the torso. In sum, control in the Medium condition included everything possible in the Low condition combined with control of the torso.

Inverse kinematics was utilized to calculate motion for the torso since no additional motion-tracking data was captured outside of the HMD and hand-tracked controllers. Inverse kinematic position and rotation weights are calculated and set dynamically as users move their HMD. The avatar's spine is also rotated using quaternions based on the avatar's spine's position and the user's head position (offset with a constant).

High. In the High condition, the user could control their head, torso, and arms. The head movement was consistent with the Low and Medium conditions, where only rotation was possible. The torso movement was consistent with the Medium condition, allowing for movement of the whole of their upper body. In sum, control in the High condition included everything possible in the Medium and Low condition combined with control of the arms.

Inverse kinematics was utilized to calculate motion for the arms

Figure 2: The avatar in the virtual environment with a congruent Stroop trial ("XXXXX" written in green) and incongruent Stroop trial ("Red" written in blue).

	Agency A Survey Item
A1	I felt that the movements of the virtual body were caused by my own movements [6]
A2	The movements of the virtual body responded to the movements of my real body [18]
A3	The movements I saw the body in the mirror make seemed to be my movements [26]
A4	I felt like I was able to interact with the environment the way I wanted to [1]
A5	I liked being able to control the movements of the avatar [48]
A6	I had the feeling that I had control over the virtual body [53]

Table 1: Agency A survey items with references to the articles that used these survey items. Items **A1**, **A2**, **A3**, and **A5** completely capture the measure of agency or relevant concepts in their respective surveys. **A4** and **A6** are sub-scale items from their respective surveys.

and hands. The inverse kinematics for the torso were consistent with the Medium condition. Arm orientations and positions are also calculated and set dynamically as users move their HMD and hand-tracked controllers. These calculations follow typical (inverse) kinematics equations using the position, displacement, and velocity of the individual hand-tracked controllers.

4 Experiment

4.1 Research Question and Hypotheses

The overarching aim of this study is to answer the following research question: **"How does the degree of control over an avatar affect users' perceived levels of agency and embodiment towards the avatar?"** Downstream of this, we are interested in determining if measures for agency accurately capture the intended data. Evidence shows that current methods measuring users' subjective perceptions of agency may not accurately measure this construct [1, 17, 33, 46, 49]. Based on prior work, we expect that there will be no significant differences between the three conditions in terms of measured subjective agency. Yet, previous research has determined that agency is conducive to embodiment [32, 60, 64]. Assuming that subjectively perceived agency and embodiment are related measures of body-ownership illusions, the relationship between agency and embodiment should be positively correlated. We operationalize embodiment and agency using measures described in Section 4.4.

To study our research question, we designed a between-subjects study, manipulating the degree of control afforded to participants in the three conditions. The effect of the increasing levels of control should be evident in several ways if the measure for self-reported agency is accurate. One would expect self-reported agency scores to increase as more control is afforded. In turn, self-reported embodiment scores should increase as well. To validate this, the effect of increased embodiment may be evident in the VR experience, as in a cognitive test seen in prior work [5, 49, 60]. It is hence expected that users assigned to the High condition will perform significantly better on the Stroop test than those assigned to conditions affording lower levels of control over the self-avatar.

If the sense of agency can be properly measured, the following hypotheses should be supported:

H1. Users in conditions with higher control will self-report significantly higher agency scores, as measured by the Avatar Embodiment Questionnaire and additional agency measures.

H2. Users in conditions with higher control will self-report significantly higher embodiment scores, as measured by the Avatar Embodiment Questionnaire.

H3. Users with higher self-reported agency scores will perform better on the Stroop Interference Task.

H4. Users with higher self-reported embodiment scores will perform better on the Stroop Interference Task.

4.2 Study Design

This study investigated how the degree of self-avatar control affects embodiment while determining shortcomings in current agency measures. Towards this end, we conducted a between-subjects study, manipulating the degree of control users could exert over a seated self-avatar across three experimental conditions: (1) Low control (controlling only head movements of the avatar), (2) Medium control (controlling head and torso movements of the avatar), and (3) High control (controlling head, torso, and arm movements of the avatar) (see Section 3). Users in each condition were assigned an avatar that they embodied and performed a Stroop test over a total of 200 trials. Details about the Stroop test are described in Section 4.3.

4.3 Task

A Stroop test was employed to determine if performance on a cognitive task was affected by the degree of control users could exert over their self-avatar across the experimental conditions described in Section 4.2. Formally known as the 'Stroop Color and Word Test', the Stroop test is a widely used cognitive test that determines one's ability to inhibit cognitive interference, which occurs when the processing of one attribute of a stimulus affects the simultaneous processing of another attribute of the same stimulus [30, 61]. Typically, in Stroop tests, users are sequentially presented with a series of textual color names, each printed in a specific color. For instance, the word "blue" may be printed in red ink. The objective for users is to ignore the word (text) and instead name the color in which the word is printed. The Stroop test task employed in this study consisted of two types of trials: congruent and incongruent. Congruent trials featured the text 'XXXXX' printed in red, green, or blue. The rationale for presenting the congruent trials' text as 'XXXXX' rather than the name of the color in which the text was printed was to eliminate the inability to determine what the responses were based on (i.e., not knowing whether responses were based on the color or the text itself) [49]. Incongruent trials featured text reading one of the three aforementioned color names ('RED', 'GREEN', or 'BLUE') printed in a color different from what the text read or rather corresponds to. For example, an incongruent trial may have featured red-colored text that read 'BLUE', green-colored text that read 'RED', blue-colored text that read 'GREEN', or any incongruent combination of text and text color from the aforementioned three colors. The correct responses for trials of any type were the colors in which the text was written/printed rather than what the text literally read.

The responses for the Stroop test were obtained through the HTC Vive controllers held in participants' hands. The three colors (red, green, and blue) were mapped onto three button-pressing portions of the touchpad, allowing participants to select one color as a response through touchpad-based inputs. The Stroop test's stimuli were manifested on a black screen on a virtual desk. This desk was positioned in front of a virtual chair where users were seated during the experience. Two color palettes featuring the three colors (red, blue, and green) were displayed on the black screen to give participants a reference to the mapping of colors with the controller's touchpad. Participants were instructed to respond to the stimuli as quickly as possible. Users assigned to any of the three conditions described in section 4.2 performed this Stroop test across 200 trials. Twenty percent of these trials were congruent, and the remaining were incongruent. The order of the 200 trials was

Figure 3: Depicted are four of the avatars selectable by users. Users self-selected the avatar they felt best represented themselves to avoid embodiment effects from strongly dissimilar avatars. From left to right: Asian female, Black female, White male, Black male.

randomized to eliminate any order effects.

4.4 Measures

The following measures were used to investigate our hypothesis:

Embodiment Questionnaire - Users' level of embodiment towards their self-avatar representation was measured using Peck and Gonzalez-Franco's Avatar Embodiment Questionnaire [46]. This questionnaire comprises 16 items that load onto four interrelated sub-dimensions (Appearance, Response, Ownership, and Multi-Sensory), collectively producing a final overall embodiment score.

Agency Questionnaires - Perceived levels of agency associated with self-avatars were measured in the following two ways.

Agency A Six items, each sourced from prior literature measuring subjective agency [1, 6, 18, 26, 48, 53]. These six items do not appear in Peck & Gonzalez-Franco's original Embodiment Questionnaire and can be found in Table 1.

Agency B Peck & Gonzalez-Franco's Avatar Embodiment Questionnaire [46] proposed using the average of two historically used questions to measure agency. Agency B was measured as the average of these two questions. The design of the agency questionnaires in Peck & Gonzalez-Franco's work was influenced by questionnaires such as the ones used in *Agency A* [46].

Rationale for Agency A and B Agency B is an agency questionnaire that is listed in a validated embodiment questionnaire [46]. If no significant differences are found using Agency B, we can affirm that a validated - and currently used - measure may fail to capture agency effectively. Agency A is an agency questionnaire comprised of six items sourced from different studies that measure agency [1, 6, 18, 26, 48, 53]. The resultant dependent measure from Agency A is computed as the mean of the scores across these six items. While the items are subsets of those questionnaires, the inclusion of Agency A allows us to more confidently rule out the possibility that any effects detected in Agency B are incidental or specific to Agency B. In short, the inclusion of Agency A and B gives us eight items that measure agency for robustness.

Stroop Test - The *accuracy* and *latency* to respond to each of the trials of the Stroop test were recorded. Accuracy refers to the ratio of correctly answered trials (see Section 4.3) to the total number of trials. The latency to respond to each trial was computed as the time between the start of a trial and the time at which the user responded using the controller touchpad for that trial. A higher response time corresponds to worse performance on the Stroop test.

Rotational Data - Head-tracked and controller-tracked movement and rotation data was obtained and recorded. Since control over the *head* was the singular commonality between the levels of avatar control in our experimental conditions, we analyzed the rotational data of the participant's head movements. A P95 score, the number of principal components needed to account for 95% of the variance in movement, was calculated for each participant via principal component analysis (PCA) of each participant's head movement. This analysis is similar to the movement data proposed by [31, 47].

4.5 Participants

A total of 60 participants were recruited for this University of Florida Institutional Review Board-approved study, with 20 allotted per experimental condition. Data from one participant had to be excluded due to data logging errors, thus resulting in a total of data from 59 participants across all the conditions. This led to a total of 11800 Stroop test trials for analysis. Of the participants that completed the study, 22 of them identified as female, and the rest of them as male. Their ages ranged from 18 to 33 years (M = 22.71, SD = 2.74). Among the participants, 24% classified themselves as "Not experienced," 56% as "Somewhat experienced," 10% as "Experienced," and the remaining 10% as "Very experienced" in terms of their VR experience. All participants were recruited from the University of Florida, with 88% majoring in Science, Technology, Engineering, and Mathematics.

4.6 Procedure

Upon arriving at the laboratory, participants were greeted and asked to read and sign a consent form (informed consent). After consenting to participate, participants verified eligibility for the study (18 years or older, normal or corrected to normal vision, English-speaking, and having a full range of motion of arms and upper body). Participants were then randomly assigned to one of the three avatar control conditions (see Section 4.2). Following this assignment, participants were instructed to choose one of six avatar options that most accurately represented themselves in appearance (see Figure 3 for example). All participants selected an avatar that matched their gender identity at a minimum but could select any avatar they felt was their best representation (even if the racial appearance or skin tone was technically mismatched). All avatar options were clad in the same uniform and varied only in terms of race and gender (i.e., Black male, Black female, White male, White female, Asian male, Asian female). Users were not told what varied between avatar representations because we did not want to force race or gender as the criteria for identification. Upon selecting an appropriate self-avatar representation, participants were seated on a chair co-located with their virtual world counterpart. Users then donned the HMD and were provided with detailed instructions, both verbally and through the HMD, about the steps required to complete the study.

The study consisted of three sequential phases: training, embodiment, and Stroop test. The purpose of the training phase was to get participants acclimated with the Stroop test, effectively serving as a tutorial on how to use the controller to appropriately respond to the stimuli presented across trials of this task. Participants were first situated in front of the table and its screen. The screen was used to present the stimuli of the Stroop test. In the training phase, participants completed a total of 26 trials, six of which were congruent and the remaining 20 were either congruent or incongruent. Completing these practice trials marked the end of the training phase, following which the embodiment phase commenced. This phase, as routinely used in VR research on self-avatars [5, 41, 48, 49], was used to promote and foster a sense of embodiment towards participants' selected self-avatars. Upon the commencement of this phase, users were provided with their chosen

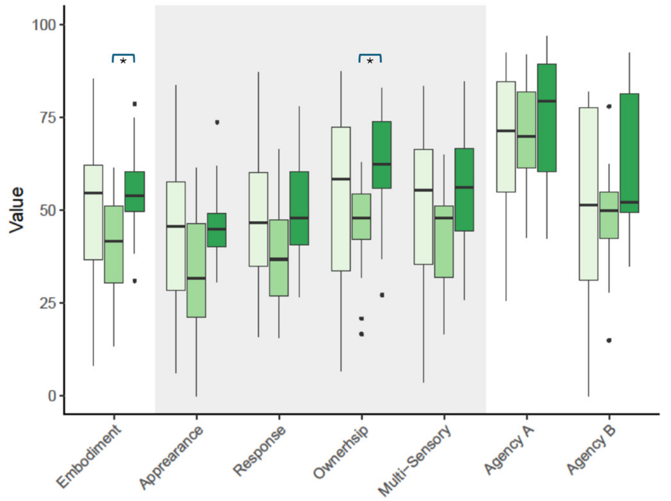

Figure 4: A boxplot of the subjective responses to the Embodiment Questionnaire and Agency Questionnaires A and B for each control condition, Low (light-green), Medium (medium-green), and High (dark-green). * indicate significance (p < 0.05)

self-avatar representation, and they could see themselves in a virtual mirror placed in front of the table. Similar to [49], the embodiment phase required participants to perform a number of actions to achieve the desired sense of embodiment towards their self-avatar. Users were required to look around and describe what they saw, move their self-avatars (in accordance to the condition to which they were assigned as described in Section 3) while looking into the virtual mirror, look down at their legs beneath their seats, and look in the up, down, and lateral directions. This embodiment phase lasted for five minutes after which the experiment phase commenced. The Stroop test consisted of the 200 Stroop task trials. Throughout this phase, participants' avatars remained visible and controllable to them as they performed the trials. Upon completing all the trials of the Stroop test, participants removed the HMDs. Following this, participants filled out the Avatar Embodiment Questionnaire [46] and the Agency Questionnaires (see Section 4.4 and Table 1). Participants also completed a demographics questionnaire and background survey regarding their experience with VR, virtual worlds, 3D environments, and video game experience. Users were then thanked and compensated for their participation in the form of course credit. On average it took approximately 40 minutes to complete the whole procedure.

5 Results

Analysis was performed with R version 4.1.1. During analysis, two participants were excluded due to the presence of numerous outlier data points in multiple (three of four) embodiment sub-measures. Outliers were defined as values 1.5 × the inter-quartile range (IQR) greater than the third quartile, or less than 1.5 × IQR below the first quartile.

Each of the four Embodiment Questionnaire submeasures, Appearance, Response, Ownership, and Multi-Sensory, as well as the proposed agency submeasure (Agency B) and the new Agency questionnaire (Agency A) were checked for reliability. The four Embodiment Questionnaire submeasures and the new Agency Questionnaire had high reliability with Chronbach's-alpha ranging from .75-.84. The Agency B submeasure had low-reliability (Spearman-Brown $r = .34$). For completeness, we report the results of Agency B, through results from this measure should be interpreted with caution.

The Embodiment and Agency measures did not pass Levene's Test for Homogeneity of variance and therefore robust statistical tests were used. Embodiment and Agency were analyzed with an 1-way robust ANOVA with trimmed means comparing 3-levels of Condition (Low, Medium, High). The Embodiment and Agency questionnaire data is presented in Figure 4.

5.1 Embodiment Questionnaire

A significant main effect of condition was found in the Embodiment measure, ($F(2,18.34) = 5.07$, $p = .02$, $CI = [.25, .69]$). Subjective Embodiment scores were significantly higher in the High control condition ($M = 54.06$, $SE = 1.90$) compared to the Medium control condition ($M = 39.96$, $SE = 2.38$) ($\hat{\psi} = -13.43$, $p = .02$, $CI = [-24.62, -2.24]$). No other pairs were significantly different. When breaking Embodiment into its submeasures, significant differences were found in the Ownership submeasure ($F(2,21.08) = 7.40$, $p = .004$, $CI = [.25, .65]$). Subjective Ownership scores were significantly higher in the High control condition ($M = 61.76$, $SE = 2.37$) compared to the Medium control condition ($M = 45.90$, $SE = 2.14$) ($\hat{\psi} = -15.07$, $p = .003$, $CI = [-25.04, -5.10]$). No other pairs were significantly different.

5.2 Agency Questionnaires

Agency A The main effect of agency was not significant between conditions ($F(2,21.97) = 1.01$, $p = .38$).
Agency B The main effect of agency was not significant between conditions ($F(2,21.05) = 1.39$, $p = .27$).

5.3 Stroop Test

Accuracy and Response Time were analyzed with linear mixed-effects 3 (Condition: Low, Medium, High) × 2 (Trial Type: Congruent, Incongruent) regressions with Condition as a between-participant variable and Trial Type as a within-participant variable. Covariates of Embodiment, Agency A, and Agency B were considered for the model. Agency B had a relatively high correlation with embodiment ($r = .74$) and was therefore not included in the mode. Assumptions for the Embodiment and Agency A covariates were met. Correlation coefficient of .45, tolerance of .79, and variance inflation factors ranged from $1.25 - 2.28$. Post-hoc analysis was performed pairwise with estimated marginal means with p-value adjustment using the Tukey method. Significance is reported at $p < .05$.

Accuracy: As expected with the Stroop Test, participants were significantly more accurate during the congruent trials ($M = 97.64\%$, $SD = 0.15\%$) compared to the incongruent trials ($M = 96.12\%$, $SD = 0.19\%$), ($F(1,51.48) = 6.55$, $p = .01$, $\eta^2 = .11$).

Latency: There were three significant main effects on latency, Trial Type, Condition, and Embodiment. The full model is reported in Table 2. Participants responded significantly slower during incongruent trials (M=1116.16ms, SE=11.50) compared to congruent trials (M=929.04ms, SE=5.12), ($F(1,52.03) = 142.03$, $p =< .001$, $\eta^2 = .73$). Additionally, there was a significant main effect between conditions, ($F(2,50.38) = 3.46$, $p = .04$, $\eta^2 = .12$). Participants in the High-Control condition responded significantly more quickly (M=901.78ms, SE=7.71, CI=[772, 990]) compared to the Medium-Control condition (M=1034.91ms, SE=8.64, CI=[1073, 1327]), ($z(37) = 2.63$, $p = .02$). See Figure 5.

	β	Std. Error	t value	Pr(>|t|)
(Intercept)	967.80	120.07	8.06	0.00
Embodiment	4.00	1.79	2.24	0.03
Agency	-0.61	1.69	-0.36	0.72
Congruent	-197.65	27.49	-7.19	0.00
Medium	110.66	80.38	1.38	0.17
High	-80.43	78.27	-1.03	0.31
Congruent:Medium	0.46	40.16	0.01	0.99
Congruent:High	5.76	39.58	0.15	0.88
$R^2 = .05$				

Table 2: Summary of the linear mixed-effects model for the latency to respond to the Stroop Test.

Finally, there was a significant main effect of subjective Embodiment on latency, ($F(1,49.04) = 5.02$, $p = .03$, $\eta^2 = .09$). The regression of latency to embodiment was statistically significant ($R^2 = .007$, $F(1,10598) = 73.26$, $p < .001$. It was found that embodiment significantly predicted latency ($\beta = 4.00$, $p = .03$). Participants with higher

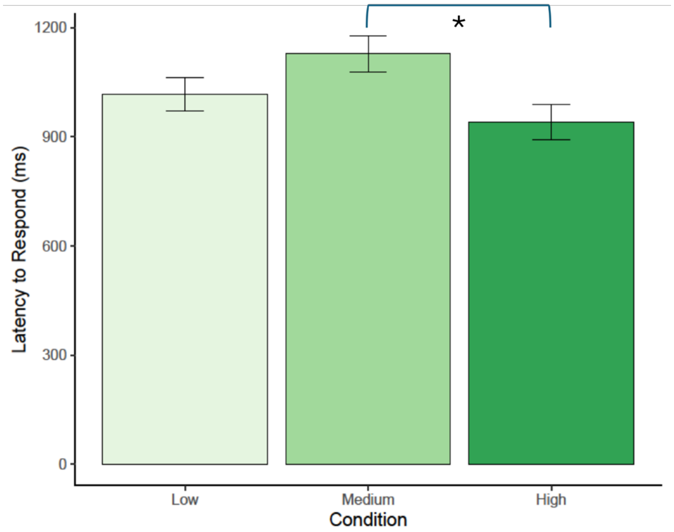

Figure 5: The average time to respond for each agency condition, Low (light-green), Medium (medium-green), and High (dark-green), with standard error bars. Medium Agency was significantly slower than High agency. * indicate significance (p < 0.05)

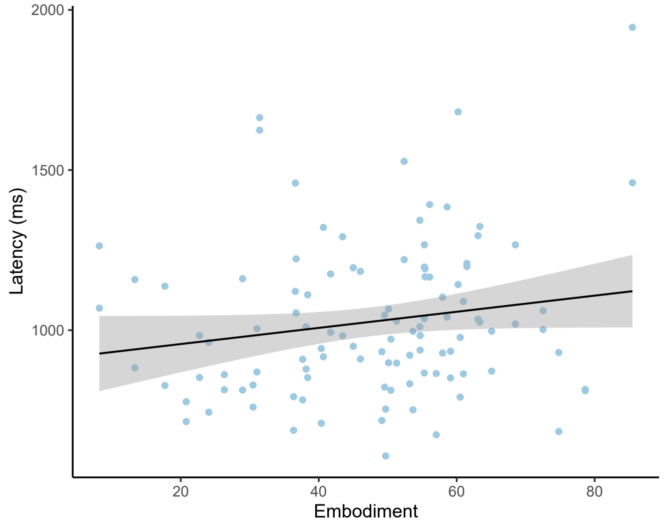

Figure 6: A scatter plot, with regression line and standard error region, of participant (y-axis) latency to respond during the Stroop interference test on both the congruent and incongruent trials, to (x-axis) subjective embodiment score. $F(1,10598) = 73.26$, $p < .001$, $R^2 = .007$. $Latency = 847.98 + 2.47 * Embodiment$.

embodiment scores had slower response times. See Figure 6 for a visual representation of the data.

5.4 Movement Data

A P95 score, the number of principal components needed to account for 95% of the variance in movement, was calculated for each participant via principal component analysis (PCA) of each participant's 6-dof head movement. The P95 movement data was analyzed with a linear mixed-effects regression with Condition, Agency, and Embodiment as predictor variables.

A significant main effect of Condition was found, ($F(2,37) = 3.96$, $p = .03$, $\eta^2 = .10$). See Figure 7 for a visual representation of the P95 data for each condition. This main effect was quantified by two higher-order interactions. A significant 2-way Condition × Agency interaction was found, ($F(2,37) = 3.55$, $p = .04$, $\eta^2 = .16$). Additionally, a significant 3-way Condition × Agency × Embodiment interaction was found, ($F(2,37) = 5.50$, $p = .008$, $\eta^2 = .23$). Post-hoc analysis of the highest-order interaction was performed using estimated marginal means of linear trends, with p-values adjusted using the Tukey method. The slopes of Agency at the first, second, and third quarterlies (Q1, Q2, Q3) of Embodiment were compared pairwise for each Control condition and are reported in Table 3. A significant difference in slopes was found between the Medium-Control and High-Control conditions in Q2 ($t(37) = 3.20$, $p = .008$, $d = 1.05$) and Q3 ($t(37) = 3.38$, $p = .005$, $d = 1.11$).

6 Discussion

This work aimed to determine if measures for agency would accurately capture the relationship between agency and embodiment. Our findings indicate that agency scores did not significantly increase in the conditions, and we could not support **H1**. Despite this, embodiment, as well as its submeasure, ownership, was significantly higher in the High control condition compared to the Medium control condition as in **H2**. Notably, the Low and High control conditions had no significant differences in embodiment or any of its components. Regarding **H3**, participants performed significantly better on the Stroop test in the High control condition compared to the Medium control condition, similar to the effect seen in embodiment scores. However, participants with higher embodiment scores performed slower in the Stroop test, contrary to our **H4**.

While our preliminary work led us to believe that agency metrics may be flawed, our hypotheses were written with the assumption that measures for agency *could* accurately capture sense of agency and demonstrate its effect on embodiment. Thus, our primary findings are: (1) the metric for agency *expectedly* did not demonstrate any significant change across conditions, and (2) the relationship between agency and embodiment may not necessarily be always positively correlated. These findings contribute to our understanding of embodiment by illustrating the problems in measuring agency through self-reported measures and improving our knowledge of control's role on agency and embodiment.

6.1 Agency and Embodiment

6.1.1 Agency

This work demonstrates potential challenges in measuring agency through self-reported scores. The amount of control a user was granted over their avatar only increased between conditions; thus, users *objectively* had higher control over their avatar. A proper metric for sense of agency was hypothesized to demonstrate significant differences in agency scores across control conditions (**H1**). Instead, no significant difference was found across conditions for both *Agency A* and *Agency B* measures. Our results indicate that embodiment significantly changed between conditions (**H2**), albeit different from our expectation. If there truly were no difference in the only manipulated variable, agency, we would not expect any significant differences in embodiment. We reason that this is evidence that improved control impacts embodiment, but self-reported agency measures fail to reflect that.

Prior work has also found conflicting results concerning agency. Peck et al.'s work with proximal hand placement had the same degree of agency across conditions, yet agency scores still varied across conditions [49]. Argelaguet et al. changed the visual representation of the avatar's hand but provided the same degree of agency to each condition [1]. Despite this, agency scores from self-reported measures illustrate significant differences between the visual representations. The results from such prior work indicate that self-reported agency measures may not accurately isolate and capture agency alone. While the senses of embodiment can inhibit or improve one another (e.g., Ownership was significantly higher in the High condition), we'd still expect that agency scores could be accurately captured when the condition is manipulated. Our findings indicate that agency questionnaires may not properly capture agency as once thought.

6.1.2 Embodiment

In this study, there was no significant difference between the High and Low control conditions in terms of agency scores and in turn, embod-

Condition	agency slope	SE	CI
Q1 embodiment = 36.72			
Low	0.0244	0.0123	[-0.0006, 0.0493]
Medium	0.0177	0.0116	[-0.0057, 0.0411]
High	-0.0090	0.0135	[-0.0362, 0.0183]
Q2 embodiment = 50.13			
Low	0.0251	0.0136	[-0.0024, 0.0526]
Medium	0.0636	0.0184	[0.0264, 0.1009]
High	-0.0044	0.0107	[-0.0260, 0.0172]
Q3 embodiment = 59.10			
Low	0.0255	0.0159	[-0.0067, 0.0577]
Medium	0.0944	0.0253	[0.0430, 0.1457]
High	-0.0014	0.0126	[-0.0269, 0.0242]

Confidence level used: 0.95

Contrast	estimate	t	p
Q1 embodiment = 36.72			
Low - Medium	0.0066	0.393	0.9186
Low - High	0.0333	1.825	0.1756
Medium - High	0.0267	1.503	0.3013
Q2 embodiment = 50.13			
Low - Medium	-0.0386	-1.688	0.2233
Low - High	0.0295	1.708	0.2159
Medium - High	0.0680	3.204	0.0077
Q3 embodiment = 59.10			
Low - Medium	-0.0688	-2.302	0.0680
Low - High	0.0269	1.327	0.3894
Medium - High	0.0957	3.384	0.0047

P value adjustment: tukey method for comparing a family of 3 estimates

Table 3: P95 estimated marginal means of linear trends post-hoc analysis. Top: The slope of agency at each Q1-Q3 embodiment score for each agency condition, with standard error (SE) and 95% confidence intervals (CI). Bottom: The Agency Condition contrasts, with estimate, t-value, and p-value.

iment scores (**H2**). The challenge in measuring agency is that there is both an objective and a subjective component to agency. Objectively, this study's participants were given greater control in the High condition compared to the Medium and Low conditions. Participants answer questionnaires for agency based on their perception and context associated with the avatar. We believe that the subjectivity of current agency metrics may encumber the interpretation of the data.

Participants may answer agency questionnaires based on the context instead of evaluating the total control of their avatar. For the purposes of this study, participants were provided *context* as to which body parts they could and could not control. For example, participants in the Low condition were instructed they could *only* control their head. If a user is told that the system can only provide movement to the head, their answers to the sense of agency questionnaires may have been answered based on the system's ability to allow head movement accurately. The agency questionnaires aim to measure control in its entirety but may have been answered with respect to only the controllable limbs in each condition. D'Alonzo et al. investigated embodiment using a rubber/virtual hand illusion with virtual, robotic, and real arms [14]. The authors suggest that embodiment may assess realness and an avatar's similarity to a human rather than the subjective belief that one is their avatar. Indeed, it can be challenging to measure more abstract concepts through questionnaires. According to Usoh et al., such responses are based on what a user deems sensible for the given question [65]. Famously, the authors described problems with presence questionnaires as "the sense of being there" is open to interpretation.

Worth noting is that participants in the Medium control condition often attempted to move their arms despite being instructed that they could only control their head and torso. This is likely because participants were given control over *part* of their arms (e.g., shoulders) when moving their torso. The visual mismatch of moving one's arms and not

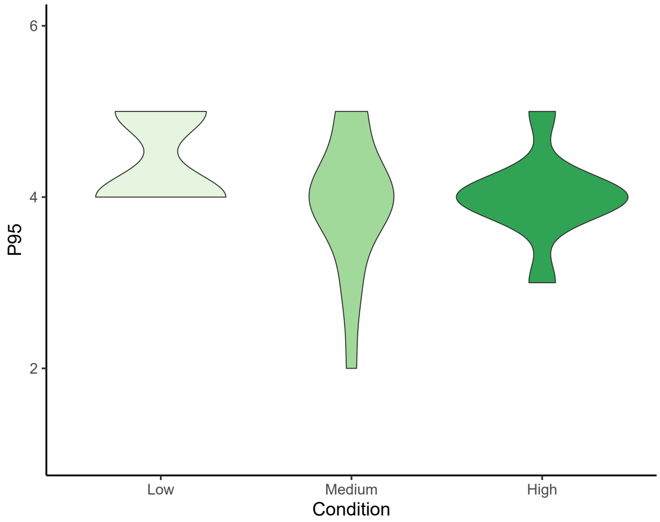

Figure 7: Violin-plots of the P95 scores, the number of principal components needed to explain 95% of head movement, for each agency condition, Low (light-green), Medium (medium-green), and High (dark-green).

seeing the avatar move may have impacted the overall perceived agency and embodiment, causing the significantly decreased result. Results may differ if participants were not told what degree of agency they were afforded, as participants may behave differently when unprompted. However, the primary aim of this study was to determine if there are flaws in the current metrics for agency in controlled research settings, which was evidenced in this work.

6.2 Effects of Control on Embodiment and Cognitive Performance

6.2.1 The Uncanny Valley of Control on Sense of Agency

Our results indicate it may be possible that when participants are afforded levels of control that only *somewhat* mimics realistic control over the body, the resulting embodiment may be negatively impacted (**H2**). Embodiment scores were significantly higher in the High control condition than the Medium control condition, but no differences were found for the Low control condition. Similar to the *Uncanny Valley* effect [44], control may only improve embodiment when in situations that are either largely similar or dissimilar to the agency one has over their real body. Prior work by Berger et al. has suggested the existence of an "uncanny valley" with VR haptics [7]. Greater fidelity of haptics does not necessarily improve the subjective impressions of realism. D'Alonzo et al.'s work also suggest that an uncanny valley exists within embodiment, where an object's resemblance to a human can increase emotional response if the resemblance is not uncanny [14]. If predictors of embodiment such as appearance, haptics, and vibrotactile stimulation can have an uncanny valley effect, we reason that the amount of control a user has over their avatar may produce similar effects.

This uncanny valley effect is also demonstrated in the user's performance of the Stroop test, a metric directly related to embodiment. Similar to embodiment scores, the Medium control condition had a worse performance (higher latency) than the High control condition (**H3**), and no significant difference was found between the High and Low Agency conditions. As evidenced in prior work, greater degrees of agency and embodiment *should* positively impact performance in cognitive tests [32, 35, 60]. Thus, the performance on the Stroop test also seems to indicate that this "uncanny" degree of control may impair one's ability to mitigate cognitive load.

6.2.2 Cognitive Performance

Contrary to **H4**, participants performed worse (i.e., quicker response times) on the Stroop test when they were highly embodied. The expectation was that higher embodiment would translate to lower cognitive load and improve performance. The worsened performance seen in the present work is unexpected compared to prior work. Typically, higher embodiment has translated to improved performance or no significant differences. Peck & Tutar found no difference in latency when manipulating the location of the avatar's hands [49]. However, accuracy improved when proximal hands were afforded. Steed et al. found no improvement in a mental rotation task when affording an avatar and gestures [60]. However, letter recall was improved with self-avatar and gestures. While the present findings on cognitive performance may be spurious, one possible explanation is that embodiment (supported by inverse kinematics) added mental load to the user and inhibited their performance. Some participants also noted that the hands were distracting in the High condition, as the hand positions were estimated via the tracked controllers. We leave this as an area for future work, and replication is needed.

6.3 Alternatives to Self-Reported Agency

While a definitive solution to measuring agency was not tested in this study, movement data may provide insight into the level of perceived agency. In each condition, participants were able to move their heads. Interestingly, users in the High control condition had greater variance in head movements than those in the Medium control condition. In other words, a noticeable change in behavior may be detected due to greater degrees of control. This may suggest that when users are afforded greater control over their avatar, they subconsciously perform more movement. Additionally, the 3-way interaction between movement, agency, and embodiment further points to the relationship between agency and embodiment. The slope of agency to the P95 score was significantly steeper in the Medium control condition than in the High control condition. This demonstrates that users in the Medium control condition with higher embodiment levels also had increasingly more complicated head movements (i.e., moved more). However, more complicated movements were unnecessary for higher embodiment scores in the High control condition. The findings on head movement suggest it may be possible to measure agency through movement-related inputs instead of, or in coordination with, subjective questionnaires.

Another possibility is that agency measurements depend on the avatar and/or context. If the avatar is humanoid, we'd expect "good agency" to be present when motor control is generally identical to real-life motor control [32]. In this case, an objective measurement of agency may be sensible. Agency may be measured as the visual similarity between the user's real-life actions and their avatar's actions. Conversely, if the avatar is non-humanoid (e.g., an animal, an alien, or an insect), it is difficult to objectively determine how similar the user's actions are to the avatar's actions. Oftentimes, it is impossible to accurately map such actions as well (e.g., if the avatar is a spider; how can we map motion to each of its eight limbs?). In this case, a subjective questionnaire may better reflect the user's sense of agency since there is no objective truth to how motor control should be portrayed. This has been demonstrated by Jiang et al., where agency over animal avatars was provided via hand motions [29]. Despite hand motions being dissimilar to the real movements of the animals in their study, agency was still rated quite highly among participants. In such cases, there is no definitive truth about what "good agency" may consist of; therefore, agency here is a subjective metric. Also, motor control over a humanoid avatar does not necessarily require the same movements from the real-life body (e.g., joysticks to control motion). If afforded more options of movement (e.g., more buttons enabled on the controller), agency might be measured both objectively (how many movement options) and subjectively (how much control the user feels they have). Thus, the embodiment and agency questionnaires may only be appropriate for certain avatar types.

6.4 Limitations

One notable limitation is the way motion was tracked and transmitted for this study. We used inverse kinematics for torso and arm movements instead of directly tracking those body parts. While inverse kinematics have been used in prior studies for embodiment [17, 49], it has flaws. It is possible that participants experienced slight inaccuracies from the inverse kinematic estimates based on the headset and controllers. This may also explain why embodiment scores in the Low and High control conditions were not significantly different. While objective control did increase, the extra visual mismatches in motion provided by inaccuracies in the inverse kinematics estimates may have dampened the improvements.

We urge readers to interpret our conclusions in light of the fact that agency metrics may not properly capture the intended effect. As a result, our discussions on agency and control are made based on our current understanding of the two and may be subject to change as we further unravel the role of control on agency and embodiment. Furthermore, there are also a few limitations in terms of generalizability and diversity that are worth mentioning. The gaps in age and the population of a university skew the generalizability of this work, and the designs of the avatars' race (e.g., black male's hairstyle) require improvement in future iterations. While avatars were designed to minimize differences in conditions, research has indicated a lack of consideration for designing avatars for non-white and typical populations [59]. Lastly, the amount of control granted to users is objective, but not all users may be readily equipped to utilize the full extent of control granted [59]. In this study, we specifically recruited those with a full range of motion in their upper bodies (lower body movement was unnecessary as the experiment was seated); however, this serves as a limitation when considering the full spectrum of users.

7 Conclusion and Future Works

In this article, we aimed to determine if standard agency metrics can properly differentiate between increasing levels of control. We tested this by assigning users to one of three conditions of avatar control: Low - head only, Medium - head and torso, and High - head, torso, and arms. Our results indicate that increasing the degree of control to users impacts and even improves embodiment. However, we also determined that self-reported scores for the sense of agency do not necessarily indicate the different levels of control as embodiment does. Higher control can positively affect performance on the Stroop Interference Task. Furthermore, we learned that control may not always positively correlate with embodiment. An uncanny valley effect on agency became evident in our conditions as perceived agency was actually inhibited in the Medium control condition but significantly improved in the High control condition and not significantly different in the Low control condition. While we did not directly explore other methodologies to measure agency, we suggest that objective data, such as the complexity or amount of movement, may better capture the sense of agency.

This research opens numerous pathways for future research. How should agency be measured in studies investigating embodiment and its effects? In this study, we identified that movement data may have a relation to one's sense of agency, but it was not formally investigated. It does seem that agency *may* be measured by a user's behavior in the virtual environment (e.g., cognitive tests or movement data). It's also worth noting that agency is not simply the manifestation of action but also the intent and portrayal of that action [32]. Some of the questionnaire items used for agency today seem to capture aspects of agency independently in their wording but fail to encapsulate what agency fully entails. Thus, future work may also explore other more objective wordings that encapsulate intent through actuality of agency in their questionnaires (e.g., "How much of what I commanded did my avatar actually perform in the way that I intended?"). Exploration of how levels of control, in all its forms, impact the sense of agency, embodiment, and cognitive performance will prove beneficial for future VR researchers.

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