A Sense of Urgency on the Sense of Agency: Challenges in Evaluating Agency and Embodiment of Self-Avatars

Category: Research

Figure 1: Agency conditions from left to right: Low - agency over head only, Medium - agency over head and torso, and High - agency over head, torso, and arms.

ABSTRACT

Agency over an avatar can improve the sense of embodiment. Yet, the relationship between agency and embodiment remains unclear. This work investigates the current metrics of agency and demonstrates its inability to capture this relationship properly. 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 agency (i.e., Low - head only, Medium - head and torso, or High - head, torso, and arms) and completed a Stroop test. Our results indicate that the degree of agency afforded to participants impacted embodiment but, as expected, could not be detected in the self-reported agency scores. Furthermore, our results elucidated further insights into the relationship between agency and embodiment, suggesting potential *uncanny valley*-like effects. Future work should consider these findings and determine how agency can be measured more effectively as a result.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

1 INTRODUCTION

Virtual reality (VR) enables users to explore and interact with entire other worlds by proxy of a virtual avatar. Virtual avatars serve as the user's form in their virtual environment and allow for interaction with the virtual environment. The sensation that one is their virtual avatar is referred to as embodiment. Kilteni et al. originally defined virtual embodiment as a combination of the senses of agency, self-location, and ownership [19]. When these senses are maximized, a full sense of embodiment is said to occur within the user. Other definitions of embodiment have been developed and expanded since [15, 26]; however, each definition captures properties of Kilteni et al.'s original three senses.

The impact and importance of the sense of agency on embodiment is unclear. Agency refers to the motor control that a user has over their virtual avatar [19]. Furthermore, it is clear that agency is an element of embodiment but determining how valuable it is and how it impacts other senses of embodiment has been a challenge since the seminal work. Peck and Gonzalez-Franco redefined embodiment *without* the sense of agency, and listed the components as Appearance, Response, Ownership, and Multi-Sensory [26]. These components encapsulate aspects of Kilteni et al.'s original three senses, but agency specifically was removed as a core sense due to its unreliability as a metric. Other prior work has shown mixed findings regarding agency's importance to embodiment [1, 6, 9, 28]. It is clear that greater agency is conducive to a greater sense of embodiment, often through the usage of additional visual-tactile stimulation and motion tracking of the physical and virtual bodies [21, 38]. We suggest that it is not agency itself that is not valuable to embodiment. Instead, we propose that how the sense of agency is *measured* may actually be negatively impacting the current understanding of embodiment. Agency is typically measured through self-reported responses to questionnaires, which are contingent on a user's expectations of how the VR system ought to behave. Because of this, properly distinguishing the degree of agency provided to the user can be difficult.

This work aims to improve the understanding of agency and embodiment by demonstrating drawbacks in how agency is measured. It is difficult to clearly quantify agency's value without being able to properly measure it. Therefore, a primary objective of this work is to determine if current agency metrics are effective and can differentiate between different degrees of agency afforded to a user. To determine this, we measured agency and embodiment in three conditions with increasing agency over the virtual avatar. If agency can be properly measured by standard metrics, we'd expect that agency and embodiment will increase across conditions. Our findings demonstrate that while agency does indeed impact embodiment, current agency metrics are not effective in demonstrating agency's impact on embodiment. 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.

2 RELATED WORKS

2.1 Embodiment

The sense of embodiment over an avatar refers to the feeling that the avatar and the self are one and the same. The senses of embodiment originally included ownership, self-location, and agency [19]. Ownership refers to the sensation that the avatar's body belongs to the user, self-location refers to the belief that the avatar's body is physically co-located with the user, and agency refers to the motor the user has over the avatar's body. Aspects such as tactile sensations [33], the external appearance of the avatar [34], and response to external stimuli [16] are known to impact the sense of embodiment as well [15]. Thus, later definitions of embodiment have been revised to account for such aspects. More recently, Peck et al.'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*) [26]. These four components attempt to retain the properties of embodiment defined previously while accounting for other factors of embodiment.

The relationship between the senses of embodiment and how they individually impact embodiment is complex [30, 38, 40]. Prior work has found that self-location may be the most dominant sense [4, 23]. On the other hand, literature has also argued against the need for the sense of ownership [7]. Kilteni et al. note that the relationship between the senses is largely unknown, and the effects of improvements on one sense may inhibit another sense. Other work has also found that other senses may co-exist with the original three [15,26,31]. Peck et al.'s recent work more concretely illustrates the correlation between Appearance, Response, Ownership, and Multi-Sensory [26].

Even without all senses present, embodiment may still be achieved. For instance, the famous rubber hand illusion showcases how users may feel ownership over another hand even if no agency or self-location is present [5, 37]. Kilteni et al. also note that embodiment is maximized when each sense is maximized, but embodiment can occur to a lesser degree when at least one sense is minimally present [19]. 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 [17, 22, 24].

2.2 Agency

Providing users with agency over their avatars enhances their sense of embodiment [19, 21, 38]. Agency is described as the global motor control over the avatar such that the avatar behaves as the user expects. [4, 19]. It is a subjective sense of how much control one has over the body's intention, actions, and 'conscious experience of will. [4]'. A clear distinction between subjective and objective agency should be made. Agency, as commonly utilized in VR research, is measured as the subjective sense of control the user *feels* they have [cites]. Yet, there is also an objective sense of agency, which measures the literal degree of control afforded to a user [cites].

By mapping a user's movements such that the avatar closely mimics the user, the user *may* achieve a full sense of agency [19]. However, accurately mapping a user's movements to the avatar may not always be possible. For instance, Jiang et al. embodied users in non-humanoid avatars (e.g., animals), which required mapping hand gestures to different motions associated with each avatar [17].

Achieving a sense of Agency in VR has been explored in a number of ways. Modern VR systems often 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 [9]. More robust systems even allow for fully tracked body suits that can more definitively map user movements to their avatar [35]. We assume that agency is maximized when a user's avatar mimics their real-life behavior, though this is not necessarily the case [12, 17]. Agency hinges upon a user's prediction for an action they take and the resulting action that actually takes place [12, 13]. In other words, a sense of agency can be achieved as long as the user has control over their own actions in a way that makes sense to the given context.

Despite agency's importance to embodiment, measurements of agency appear to conflict with the sense of embodiment. Agency was formally defined in Kilteni et al.'s work and included in one of the six components of embodiment founded by Gonzalez-Franco and Peck [15]. However, later work demonstrated that the questionnaires used for agency had low reliability and ultimately did not fit well with the other components of embodiment [26]. Agency was removed as a construct as a result. Prior work has also identified conflicting results with agency [10, 28]. Yet, the degree of agency the user has clearly plays a significant role in whether the user feels that they are embodying their avatar. We postulate that it is not necessarily agency itself that is conflicting but rather the way in which agency is being measured. The present work attempts to demonstrate this effect through the described user study in Section 3.

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).

2.3 Cognition in VR

Cognitive tests such as the Stroop test are utilized to assess one's short-term memory and cognitive function [18, 20]. 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 in order to succeed. Humans naturally tend to rely on gestures for such recall, and studies have shown that the inability to gesture directly inhibits recall [14, 36]. 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 a self-avatar. Peck et al. found that performance on Stroop tests was positively correlated to embodiment of a self-avatar (e.g., self-location) [28], suggesting that self-avatars may affect working memory. Steed et al. also investigated the effect of embodiment on cognitive tests and working memory [36]. 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, the performance on the cognitive test would correlate positively. The present work attempts to utilize cognitive tests to understand better how agency and embodiment relate.

3 Materials and Methods

Previous research has determined that agency is conducive to embodiment [19, 36, 38]. Assuming the subjective agency and embodiment measures are both related measures of body-ownership illusions, then we assume that the relationship between agency and embodiment is positively correlated; as agency increases, so too should embodiment. Additionally, we would expect that performance on a cognitive test should positively correlate with both embodiment and agency: as agency and embodiment increase, so too should performance. However, there is evidence that the subjective measures of agency currently employed may not be able to detect such changes [10, 26, 28]. We expect that agency metrics will not be able to differentiate the different degrees of agency between conditions. Because of this, we hypothesize that:

H1 Participants afforded higher agency will *not* report a higher level of agency.

We expect that improved agency still impacts embodiment positively though, whether detected via agency metrics or not. If embodiment is impacted by agency with regard to H1, it would suggest that

agency improves embodiment and cannot be shown in the agency metric. Because of this, we still hypothesize that:

H2 Participants afforded higher agency will report a higher level of embodiment.

H3 Participants afforded higher agency will perform better on the Stroop test.

H4 Participants with higher embodiment will perform better on the Stroop test.

To test these hypotheses, we performed a between-participants experiment with three conditions of increasing agency (Low, Medium, and High).

3.1 Study Design

This study aims to investigate how the degree of agency affects embodiment while demonstrating fallacies in current measures of agency. To determine this effect, three agency conditions were investigated:

- **Low Agency**: Participants could only control the avatar's head movements.
- **Medium Agency**: Participants could control the avatar's head and torso movements.
- **High Agency**: Participants could control the avatar's head, torso, and arm movements.

In each condition, participants were told what they could control (e.g., participants in the Medium Agency condition were instructed they could only move their head and torso and not their arms). As participants were seated for the duration of the experiment, no motor control was enabled for the lower body.

Participants completed the Stroop test during the experiment to assess the impact of embodiment. Formally known as the Stroop Color and Word Test, the Stroop test is a cognitive test that is used to determine one's ability to inhibit cognitive load [18]. The user's objective during the Stroop test is to click the button on the controller corresponding to the color (red, green, or blue) of a briefly displayed text as quickly as possible. The text displayed may vary depending on the trial: congruent or incongruent (see Fig. 2). A congruent trial will display a red, green, or blue "XXXXX" where users must click the button on the controller corresponding to the colored "XXXXX". An incongruent trial will also display colored text, but the displayed text instead is written as the literal word "RED", "GREEN", or "BLUE" and is colored a different color (e.g., red-colored text that says "BLUE" or green-colored text that says "RED"). Users must still click the button that corresponds to the *color* of the text rather than the literal text in an incongruent trial.

3.2 Experiment

We conducted a user study with participants (n = 59) at [Institution]. Participants completed a pre-survey to verify eligibility and to obtain informed consent. Participants were then asked to select an avatar (of six options) that best represented themselves. The avatars wore the same uniform and varied in terms of race and gender (i.e., Black male, Black female, White male, White female, Asian male, Asian female). Immediately after, participants were seated and situated into the HMD and provided instructions both verbally and through the HMD on steps to complete the experiment. The experiment consisted of three components: a *Tutorial* version of the Stroop test, *Embodiment Phase*, and the *200-trial Stroop Test*.

Tutorial. Participants were seated in their virtual and physical environments and situated in front of a virtual mirror and screen. The mirror was utilized to enhance embodiment, and the screen displayed the Stroop test. Participants were instructed on how to complete the Stroop test. Additionally, participants were required to complete a set of practice trials (n = 6 with no incongruent trials; n = 20 with incongruent trials).

Embodiment Phase. The *Embodiment Phase* is a five-minute phase used to attempt to achieve a sense of embodiment. Immediately following the tutorial, participants were assigned the avatar that they selected prior to the experiment. Participants could see their avatar in the mirror as well. Participants were also randomized into one of the three agency conditions. Participants were instructed to: (1) look around and describe what they see, (2) move their respective condition's avatar around and watch it move in the virtual mirror, (3) look down at their legs beneath their seat, and (4) look in the up, down, and lateral directions.

200-trial Stroop Test. Immediately following the *Embodiment Phase*, participants completed the 200-trial Stroop Test. Their avatars remained visible to them while they completed the test. On any given trial, there was a 20% chance that the trial would be an incongruent trial as opposed to a congruent trial (80%). Participants were removed from the HMD following the Stroop test.

Afterward, participants completed a post-survey and were granted course credit for completion of the study. All participants completed the study using an HTC Vive Virtual Reality System and were given two Vive controllers regardless of condition. The HTC Vive was connected to a Lenovo Legion 5 laptop equipped with an NVIDIA GeForce RTX 2060, Intel Core i7-10750H 2.6GHz, 16GB RAM, and 512 GB SSD

3.3 Participants

The [Institution] Institutional Review Board reviewed and approved this study. Before beginning the experimental procedures, all participants provided written informed consent. A total of 59 completed the study. Of the (n = 59) participants, the ages ranged from 18 to 33 (M = 22.71, SD = 2.74). Regarding racial identity, the participant composition included 61% Asian, 19% Caucasian, 10% Hispanic/Latino, 5% Black/African, and the remaining 5% identified as other/mixed-races. In terms of gender identity, 37% of participants identified as women (63% men). Additionally, participants' familiarity with VR was assessed, considering varying levels of knowledge and experience. Among the 59 participants, 24% classified themselves as "Not experienced," 56% as "Somewhat experienced," 10% as "Experienced," and the remaining 10% as "Very experienced." All participants were recruited from [Institution], with 88% majoring in Science, Technology, Engineering, and Mathematics.

3.4 Measures

The following measures were used to investigate our hypothesis:

Avatar Embodiment Questionnaire. We utilized the Avatar Embodiment Questionnaire [26] to assess embodiment. The Avatar Embodiment Questionnaire is composed of 16 questions measuring embodiment via four components: Appearance, Response, Ownership, and Multi-Sensory.

Agency Questionnaire. Six additional questions external to the Avatar Embodiment Questionnaire were included to measure agency. The six questions were extracted from prior surveys and can be found in the Appendix.

Stroop Test. User response time during the Stroop test was obtained and recorded.

Movement Data. Head-tracked and controller-tracked movement was obtained and recorded. Since agency over the *head* was the singular commonality between the levels of agency in our conditions, we analyzed the 6-dof movement of participants' heads for movement data.

4 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.

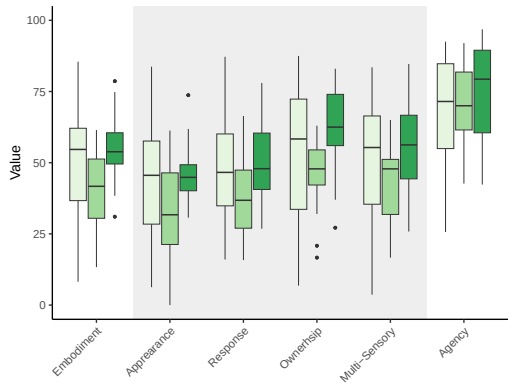

Figure 3: A boxplot of the subjective responses to the embodiment and agency questions for each agency condition, Low (light-green), Medium (medium-green), and High (dark-green), with standard error bars.

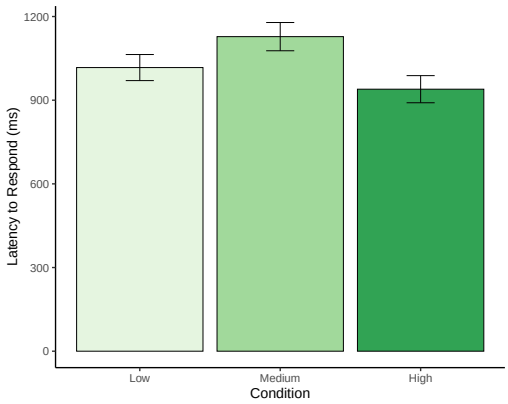

Figure 4: The Average time to respond for each agency condition, Low (light-green), Medium (medium-green), and High (dark-green), with standard error bars. Medium Agency was significantly slower than High agency.

4.1 Embodiment and Agency Questionnaires

Each of the four Embodiment submeasures and the Agency questionnaire had high reliability with Chronbach's-alpha ranging from .75-.84. Embodiment and Agency were analyzed with a 3 (Condition: Low, Medium, High) ANOVA with Condition as a between-participant variable. The Embodiment and Agency questionnaire data is presented in Figure 3.

A significant main effect of condition was found in the Embodiment measure, ($F(2,51) = 3.51$, $\eta^2 = .12$, $p = .04$). Subjective Embodiment scores were significantly higher in the high agency condition ($M = 54.06$, $SE = 1.90$) compared to the medium agency condition ($M = 39.96$, $SE = 2.38$). When breaking Embodiment into the submeasures, significant differences were found in both Ownership ($F(2,51) = 3.63$, $\eta^2 = .12$, $p = .03$) and Multi-Sensory ($F(2,51) = 3.37$, $\eta^2 = .12$, $p = .04$). For both submeasures the High Agency condition had significantly higher subjective scores compared to the Medium Agency condition.

The main effect of agency was not significant between conditions.

4.2 Stroop Test

Accuracy and Response Time were analyzed with linear mixed-effects 3 (Condition: Low, Medium, High) $\times$ 2 (Trial Type: Congruent, In-congruent) regressions with Condition and a between-participant variable and Trial Type as a within-participant variable. Covariates of Embodiment and Agency were added to the model. Assumptions for covariates were met. Correlation coefficients between independent variables were less than .46, tolerance of .79, and variance inflation factors ranged from $1.2 - 2.7$. 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: Participants were significantly more accurate during the congruent trials ($M = 97.64\%$, $SD = 0.15\%$) compared to the in-congruent trials ($M = 96.12\%$, $SD = 0.19\%$), ($F(1,51.84) = 6.55$, $p = .01$, $\eta^2 = .11$).

Latency: There were three significant main effects on latency, Trial Type, Condition, and Embodiment. Participants responded significantly slower during in-congruent trials (M=1116.16ms, SD=525.12) compared to congruent trials (M=929.04ms, SD=478.29), ($F(1,52.03) = 142.03$, $p =< .001$, $\eta^2 = .73$). Additionally, there was a significant main effect between conditions, ($F(2,50.38) = 3.46$, $p = .04$, $\eta^2 = .12$). Participants in the High-Agency condition responded significantly more quickly (M=901.78ms, SD=457.55, CI=[772,990]) compared to the Medium-Agency condition (M=1034.91ms, SD=503.09, CI=[1073,1327]), ($z(37) = 2.63$, $p = .02$). See Figure 4.

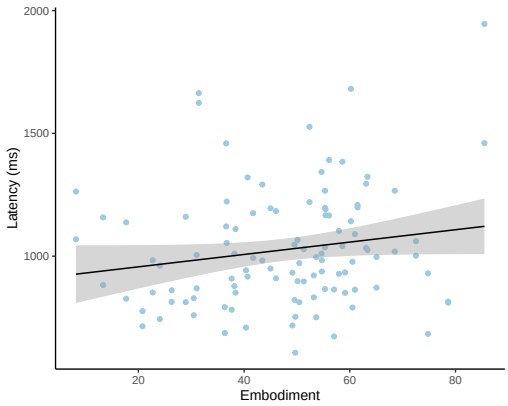

Figure 5: A scatter plot, with regression line and standard error region, of participant (y-axis) latency to respond during the Stroop interference test to (x-axis) subjective embodiment score.

Finally, there was a significant main effect of subjective Embodiment on latency, ($F(1,49.04) = 5.02$, $p = .03$, $\eta^2 = .09$). See Figure 5 for a visual representation of the data. Participants with higher embodiment scores had slower response times.

4.3 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 6 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 $\times$ Agency interaction was found, ($F(2,37) = 3.55$, $p = .04$, $\eta^2 = .16$). Additionally, a significant 3-way Condition $\times$ Agency $\times$ Embodiment interaction was found, ($F(2,37) = 5.50$, $p = .008$, $\eta^2 = .23$). Post-hoc analysis using estimated marginal means of linear trends

was performed 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 Agency condition and are reported in Table 1. A significant difference in slopes was found between the Medium-Agency and High-Agency conditions in Q2 ($t(37) = 3.20$, $p = .008$, $d = 1.05$) and Q3 ($t(37) = 3.38$, $p = .005$, $d = 1.11$).

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 1: 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.

5 Discussion

This work aimed to determine if the measures for agency would accurately capture the relationship between agency and embodiment. Two notable findings were found in this work: (1) the metric for agency *expectedly* did not demonstrate any significant change across conditions, and (2) embodiment did not sequentially increase across conditions. These findings contribute to our understanding of embodiment by illustrating the problems in measuring agency through self-reported measures and improving our understanding of agency's role in embodiment.

5.1 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 agency over their avatar. Because of this, we would expect to see a significant change in agency conditions. Notably, the absence of a significant difference does not necessarily indicate a flaw in the metric. However, since agency was the only manipulated variable, we would expect embodiment also to indicate no significant difference. Our results concurrently indicate that

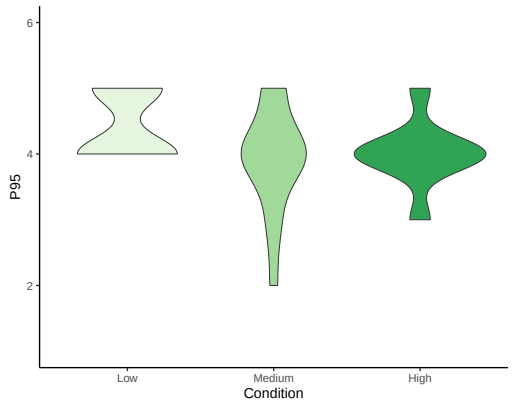

Figure 6: Violin-plots of the P95 scores, the number of principal components needed to explain 95% of head movement, for each agency condition, Low (light-green), Medium (medium-green), and High (dark-green).

embodiment did significantly change between conditions (though, not in the way expected). This would imply that agency did, in fact, have an impact on embodiment but simply may not be able to be detected from self-reported measures. 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 [28]. 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 be able to accurately isolate and capture agency alone. While the senses of embodiment can inhibit or improve one another, we'd still expect that agency scores could be accurately captured when the condition is manipulated. As our hypotheses suggested, our findings indicate that agency questionnaires may not properly capture agency as once thought.

While a definitive solution to measuring agency was not tested in this study, movement data may provide insight on the level of agency a user is experiencing. In each condition, participants were able to move their head at minimum. Interestingly, participants in the conditions with higher agency had greater variance in head movements than those in the lower agency conditions. In other words, a noticeable change in behavior may be detected as a result of greater degrees of agency. This may suggest that when participants 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 P95 score was significantly steeper in the Medium Agency condition than the High Agency condition. This demonstrates that participants in the Medium Agency condition with higher embodiment levels also had increasingly more complicated head movements (i.e., moved more). However, more complicated movements were unnecessary to obtain higher embodiment scores in the high-embodiment condition. The findings on head movement suggest it may be possible to measure agency through movement-related inputs of the user instead of, or in coordination with, subjective questionnaires.

5.2 Embodiment

A secondary finding in this study was found in the results for the embodiment scores. Embodiment scores were expected to increase from Low Agency to Medium Agency to High Agency conditions.

Instead, embodiment scores were significantly lower in the Medium Agency condition compared to the High Agency condition. Furthermore, we found no significant difference between the Low Agency and High Agency conditions. There are two potential explanations for this: (1) a flaw in the design of embodiment questionnaires or (2) uncanny valley effects when provided a near-full degree of agency.

5.2.1 Questionnaire Validity

One possibility is that embodiment questionnaires may not sufficiently capture embodiment. D'Alonzo et al. investigated embodiment using a rubber/virtual hand illusion with virtual, robotic, and real arms [8]. 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 [39]. Famously, the authors described problems with presence questionnaires as "the sense of being there" is open to interpretation. Embodiment questionnaire items such as "I felt out of my body" or "I felt as if my body had changed" may elicit similar responses from users. Slater adds how certain questionnaire concepts may not even exist in the mind of the user prior to the question being presented [32]. However, our results indicate that embodiment is related to performance on the Stroop test. Performance on the Stroop test was significantly lower in the Medium Agency condition compared to the High Agency condition. Furthermore, agency and embodiment were directly related to the head movement data. While it is possible that the metric is flawed, the supporting data suggests that the embodiment scores are generally accurate.

5.2.2 The Uncanny Valley of Agency

It is possible that when participants are afforded different levels of agency that only *somewhat* mimics real-life agency over their avatar, the resulting embodiment may be negatively impacted. Similar to the *Uncanny Valley* effect [25], agency may only improve embodiment when in situations that are either largely similar or dissimilar to the agency one has over their real body. In fact, prior work by Berger et al. has suggested the existence of an "uncanny valley" with VR haptics [3]. Greater fidelity of haptics does not necessarily improve the subjective impressions of realism. D'Alonzo et al.'s work also suggests that an uncanny valley exists within embodiment, where the resemblance of an object to a human can increase emotional response if the resemblance is not uncanny.

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 Agency condition had a worse performance (higher latency) than the High Agency condition, and no significant difference was found between the High and Low Agency conditions. As evidenced in prior work, greater degrees of agency *should* positively impact performance in cognitive tests [19, 21, 36]. Thus, the performance on the Stroop test seems to indicate that this "uncanny" degree of agency may impair one's ability to mitigate cognitive load.

Worth noting is that participants in the Medium Agency 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 seeing the avatar move may have impacted the overall embodiment and performance on the Stroop test. In the Low Agency condition, participants also could not move their arms. However, because the torso (e.g., shoulders) did not move at all in this condition, it may not have set an expectation that the arms could be controlled. Thus, if predictors of embodiment such as appearance, haptics, and vibrotactile stimulation can have an uncanny valley effect, we reason that the amount of agency a user has over their avatar may produce similar effects.

5.3 Subjective vs. Objective Agency

The challenge in measuring agency is that it is both objective and subjective. Objectively, this study's participants were given greater agency across conditions. Yet, if participants do not subjectively feel that they have adequate control over their avatar, their agency scores may not reflect this objective truth.

One possibility is that agency's measurements are dependent 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. In this case, an objective measurement of agency makes sense. Agency is simply 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. Often times, 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 in the work of Jiang et al., where agency over animal avatars was provided via hand motions [17]. 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 as to what "good agency" may consist of; therefore, agency here is a clearly subjective metric. Consider also that 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 had). Thus, the embodiment questionnaires and agency questionnaires may only be appropriate for certain avatar types.

6 Limitations & Future Works

Two notable limitations are present in this work. First, participants were provided *context* as to which body parts they could and could not control for the purposes of this study. Results may differ if participants were not told what degree of agency they were afforded as participants may behave differently when unprompted. Despite the provided context, participants still often attempted to move body parts that were clearly stated to be not controllable (e.g., arms in the Medium condition); thus, we reason that this may not impact the participant's behavior extensively. 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. Future work may examine how agency is reported in conditions without context to better mimic real-life situations.

A second limitation is in the way motion was tracked for this study. We opted to use 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 [10, 28], it is not without its flaws. It is possible that participants experienced slight inaccuracies from the inverse kinematic estimates based on the headset and controllers. In fact, this may also explain why embodiment scores in the Low Agency condition and High Agency condition were not significantly different. While objective agency did increase, the extra visual mismatches in motion provided by inaccuracies in the inverse kinematics estimates may have dampened the improvements.

Future work should investigate how agency can be measured beyond self-reported measures. While it seems apparent that agency could be measured in a user's behavior in the virtual environment

(e.g., cognitive tests or movement data), embodiment itself is ultimately a subjective sense. While subjective measures demonstrate flaws, using only objective measurements to quantify a subjective sense may not be a suitable solution.

7 Conclusion

This work aimed to improve the understanding of agency and its role in embodiment. Additionally, this work demonstrates the flaws in current measurements of agency. While agency is an essential component to one's sense of embodiment, the current measurements for agency do not accurately portray agency's significance. Agency's relationship to embodiment is complex, and it is possible that agency does not necessarily positively correlate with embodiment as once thought. This research opens numerous pathways for future research. Particularly, researchers should consider how agency *should* be measured and further explore how different forms of agency are perceived and impact embodiment.

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A Appendix

To measure embodiment, we utilized the Avatar Embodiment Questionnaire [26]. All items were scored on a sliding scale from 0 to 100. The Avatar Embodiment Questionnaire's items are listed below:

1. **R1** "I felt out of my body"
2. **R2** "I felt as if my (real) body were drifting toward the virtual body or as if the virtual body were drifting toward my (real) body"
3. **R3** "I felt as if the movements of the virtual body were influencing my own movements"
4. **R4** "It felt as if my (real) body were turning into an "avatar" body"
5. **R5** "At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw"
6. **R6** "I felt like I was wearing different clothes from when I came to the laboratory"
7. **R7** "I felt as if my body had changed"
8. **R8*** "I felt like I was sitting in a chair when I saw the body in the mirror sitting in a chair."
9. **R9*** "I felt concerned about getting the questions on the cognitive test wrong."
10. **R10** "I felt as if the virtual body was my body"
11. **R11** "At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features."
12. **R12** "I felt as if my body was located where I saw the virtual body"
13. **R13** "I felt like I could control the virtual body as if it was my own body"
14. **R14*** "It seemed as if I felt the touch of the floor in the location where I saw the virtual feet touched."
15. **R15*** "It seemed as if the touch I felt on my feet was caused by the floor touching the virtual feet."
16. **R16*** "It seemed as if my feet were touching the virtual floor"

* *These items were modified, as recommended by Peck et al. [1], to fit the context of our study.*

In addition to the items in the Avatar Embodiment Questionnaire, we measured agency via six additional questions previously used in other surveys. All items were scored on a sliding scale from 0 to 100. The Agency items (and the article they were extracted from) are listed below:

1. **A1** "I felt that the movements of the virtual body were caused by my own movements" [2]
2. **A2** "The movements of the virtual body responded to the movements of my real body" [11]
3. **A3** "The movements I saw the body in the mirror make seemed to be my movements" [16]
4. **A4** "I felt like I was able to interact with the environment the way I wanted to" [1]
5. **A5** "I liked being able to control the movements of the avatar" [27]
6. **A6** "I had the feeling that I had control over the virtual body" [29]