An embodiment paradigm in evaluation of human-in-the-loop control

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Abstract: This study introduces a novel approach for evaluating the quality of human-in-the-loop control using the psychological construct of embodiment in a haptic human-machine interaction task. Despite the fact that various forms of assistive control have been introduced, these methods mainly design semi-autonomous control to improve task-specific interaction performance. From a user perspective, however, the introduction of semi-autonomous control reduces controllability of the system, which could lead to negative user experience. Psychological research suggests sensory-motor factors dynamically modulate cognition of an external entity belonging to one's own body, i.e., embodiment. In our paradigm, we apply methods for evaluating embodiment in a virtual reality (VR) environment where the human users perform a reaching task with semi-autonomous haptic assistance to measure the degree to which the embodiment is effected by the quality of semi-autonomy. Our results with 8 participants show good persistence of subjective embodiment and subcomponents of presence within VR environment when a predictable assistive control is introduced while unpredictable assistance hindered the subjective embodiment. Results indicate embodiment can be exploited as a quantitative evaluation method of semi-autonomous controllers from a user-centric perspective.

Keywords: Embodiment, Shared-control, Human-in-the-loop control

1. INTRODUCTION

Semi-autonomy is a promising feature in applications such as teleoperation, mobility aids, and prosthetics. In teleoperation, for instance, the robot renders movement performed by a user. This can be highly beneficial in terms of safety in environments which are dangerous to humans or located at a far distance. However, teleoperation can be limited by communication delay and noise of input devices such as force sensors. The robotic system can compensate for such limitations with semi-autonomous control which solves some of sub-tasks locally (Dragan and Srinivasa, 2013). Furthermore, cognitive and physical load of the user can be reduced as the robotic system takes over some of the load (Crandall and Goodrich, 2002; Beckerle et al., 2017). However, semi-autonomous control might also have a negative influence on the quality of the human-machine interaction as controllability of a system can be reduced (Beckerle et al., 2017). Furthermore, this might lead to reduced performance, reduced comfortability, and reduced acceptance of the system. Existing methods evaluate task performance such as completed tasks, velocity, jerk, and maneuverability and its improvement (Salcudean et al., 1997; Son et al., 2011). Yet, an index for how the machine is integrated into the operator's control loop has not yet been established. In psychology, illusory experience of external objects or tools being part of own body has been reported, and generally referred to as embodiment (Botvinick and Cohen, 1998).

The present study is designed to investigate whether the embodiment experience is correlated with the quality of the semi-autonomous system. For a distinguishable comparison, we contrast the effect of a controller which behaves predictably or unpredictably. Furthermore, in order to show the sensitivity of embodiment in our experimental setup, we introduce a delay of visual feedback to the user's virtual arm in a factorial design as it is well-known to disturb the embodiment experience (Shimada et al., 2009). In this study, participants performed a reaching task in a virtual environment where the interaction performance of the semi-autonomous system is manipulated. The experience of embodiment on the virtual arm is then studied using a questionnaire which quantifies the strength of the embodiment. Widely, embodiment is assessed using a questionnaire which distinguishes three subcomponents: ownership as the feeling that the artificial limb is a part of the own body, location as the feeling to perceive the real and the artificial limb in the same place, and agency as the feeling to be able to control the artificial limb (Longo et al.,

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2008). Furthermore, the relationship between controllability of one's own body and his/her cognitive change has been studied as part of presence which measures whether the person is perceptually stimulated in a virtual environment as in real-life situations (Slater, 2003). Using these measures, we investigate how semi-autonomous control has an influence on the quality of the human-machine integration.

2. METHOD

2.1 Apparatus

The apparatus for the experiments includes a set of linear actuators for kinaesthetic rendering of a controller and the head-mounted VR display (see Fig. 1) for manipulating the visual feedback of the interaction.

Kinaesthetic rendering with linear actuators The semi-autonomous system virtual partner is rendered as a linear time-invariant mass-damper system reacting with a motion to the total input force $u \in \mathbb{R}^2$

$$u = M\ddot{v}_t + D\dot{v}_t, \tag{1}$$

where M and D are inertia and damping matrices, respectively and $v = [x, y]^T$ represents the two dimensional position. The device simulated the dynamics of a light object as

$$M = \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix} kg$$
$$D = \begin{bmatrix} 15 & 0 \\ 0 & 15 \end{bmatrix} Ns/m. \tag{2}$$

The current velocity is represented as $\dot{v}_t$ and the acceleration as $\ddot{v}_t$ at the current time instant t. The manipulandum consists of two linear axes actuated by a Thrusttube Module (Copley Controls, USA) linear motor. Each axis consists of a single rail stage and a linear servo-motor driven cart. Both axes are conjunct crosswise (see Fig. 1) such that the cart can move in two dimensional space

$$\left\{(x, y) \in \mathbb{R}^2 | x_{\min} \le x \le x_{\max}, y_{\min} \le y \le y_{\max}\right\} \tag{3}$$

where $x_{\min} = y_{\min} = -0.2\ m$ and $x_{\max} = y_{\max} = 0.2\ m$. A vertical handle is mounted on top of the servo-motor driven cart including a JR3-67M25 6-axis sensor (JR3 Inc., USA) at the base of the handle that measures the human force/torque inputs. The linear axes are controlled using Simulink executed on a Linux system with real-time kernel (Ubuntu 12.04, 3.2.23, rt37) and RT-Preempt Patch. A fixed step solver is used and the sampling time is set to $\Delta t = 1\ ms$.

Assistive control The force of the virtual partner was derived based on a minimum jerk trajectory (Fligge et al., 2012; Flash and Hogans, 1985) to resemble human-like motion such that

$$\dot{x}_{mj,t+\Delta t} = \sum_{k=1}^{5} k b_{xk} (\Delta t)^{k-1}$$
$$\ddot{x}_{mj,t+\Delta t} = \sum_{k=2}^{5} k(k-1) b_{xk} (\Delta t)^{k-2} \tag{4}$$

where b_{xk} is calculated on-line at every time instant t as

$$b_{x1} = \dot{x}_t$$
$$b_{x2} = \ddot{x}_t/2. \tag{5}$$

The coefficients b_{x3} to b_{x5} are computed as

$$\begin{bmatrix} b_{x3} \\ b_{x4} \\ b_{x5} \end{bmatrix} = \begin{bmatrix} T_r^3 & T_r^4 & T_r^5 \\ 3T_r^2 & 4T_r^3 & 5T_r^4 \\ 6T_r & 12T_r^2 & 20T_r^3 \end{bmatrix}^{-1} \begin{bmatrix} x_{tgt} \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

where T_r represents the remaining time to reach the target position x_{tgt} which is mapped to the normalized distance between the current handle position $v_t = [x_t, y_t]^T$ and target position $v_{tgt} = [x_{tgt}, y_{tgt}]^T$. The target acceleration and velocity are set to 0 on the target. The coefficients for minimum jerk trajectory for y coordinate were obtained analogously by using in equation (5) and (6) y_t instead of x_t and y_{tgt} instead of x_{tgt}. Given that $v_{mj} = [x_{mj}, y_{mj}]^T$ the assistance force $u_a \in \mathbb{R}^2$ equals to

$$u_a = M\ddot{v}_{mj} + D\dot{v}_{mj}. \tag{7}$$

In addition, a workspace constraint and obstacle was rendered as a force feedback u_{ws} with a position-based sigmoid function

$$u_{\text{ws}} = \frac{u_{\max}}{1 + e^{c\,d}} \tag{8}$$

where d equals

$$d = \sqrt{(x_c - x_t)^2 + (y_c - y_t)^2} \tag{9}$$

while x_t and y_t represent the current positions at the current time instant t. For the workspace constraint, the steepness of the sigmoid function was set to $c = 200$ and $(x_c,\ y_c)$ to $(x_{\max},\ y_{\max})$. The maximum force $u_{\max}$ was set to 40 N. The obstacle was introduced in the center of the workspace where $(x_c,\ y_c) = (0, 0)$ such that the participants could not move straight from one target to the other, thus creating a potential conflict point between the human user and the virtual agent. For the obstacle, the maximum force $u_{\max}$ was set to 15 N and the steepness of the sigmoid function was set to $c = 50$.

VR setup The virtual reality goggles HTC Vive Pro were used (see Fig. 1). The virtual environment was built in Unity 3D game engine with a constant refresh rate of 90 Hz. The virtual hand approximated the participant's right arm posture in a realistic way using the in-build inverse kinematics which used the head and the handle position as anchor points. The virtual workspace was manually calibrated to the size of the linear axis. The circular obstacle at the origin $(x,\ y) = (0,\ 0)$ with radius of 0.1 $meter$ and two targets at the top and the bottom of the workspace were displayed in the virtual environment. The area of the workspace border and origin obstacle force were represented in red and the targets were displayed as green circles (see Fig. 1).

2.2 Experimental design

In this study, a 2 x 2 within-subject design was used to investigate how experienced embodiment is influenced by behavior of semi-autonomous control in a human-machine interaction task. As the first factor, we manipulate the Synchronicity of the visual feedback such that virtual arm motion in the virtual environment was either synchronous to the real arm motion or asynchronous and delayed by 500 ms. The second factor was the Predictability of the controller in terms of two different control approaches of

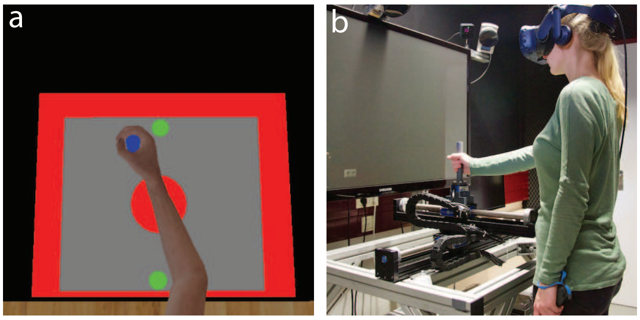

Fig. 1. (a) The virtual environment that is seen through the VR goggles. (b) Experimental setup: 2-DoF haptic device and a participant wearing the VR goggles.

which one aimed to be predictable while the other was unpredictable.

Predictability of the semi-autonomous system was realized in a shared control framework between a human user and a virtual agent. The force of the human user $u_h \in \mathbb{R}^2$ and the system u_a are lineally mapped to the total force u as

$$u = \alpha u_h + (1 - \alpha) u_a, \tag{10}$$

where the mapping weight, α is bounded by $0 \leq \alpha \leq 1$. For the predictable control, $\alpha = 0.5$ is used, whereas α of the unpredictable control randomly incremented as

$$\alpha_{t+1} = f(\alpha_t + w_t) \tag{11}$$

with $f(\zeta)$ defined as

$$f(\zeta) = \begin{cases} \zeta, \text{if} & 0 \leq \zeta \leq 1 \\ 0, \text{if} & \zeta < 0 \\ 1, \text{if} & \zeta > 1 \end{cases} \tag{12}$$

and w_t being independent identically distributed zero mean Gaussian noise

$$w_t \sim \mathcal{N}(\mu, \sigma^2) \tag{13}$$

such that α randomly drifts at every iteration Δt with a random value from the normal distribution function $\mathcal{N}$ with mean $\mu = 0$ and variance $\sigma^2 = 0.02$ to generate a slow drift and avoid immediate saturation at the boundaries. The controller was initialized at $\alpha_0 = 0.5$. All participants performed all four conditions in a randomized order using the Latin square design.

2.3 Measures

The present study employed the subjective measures which quantified the embodiment experience of the user, and the objective performance measures which describe how the users interacted with the virtual agent.

Subjective measures To assess the experience of embodiment, we used the questionnaire of Longo et al. (2008). The questions are reformulated to match the control-oriented task in the virtual environment (Table 1). As a subjective measure of presence, we use aspects of the presence questionnaire by Witmer and Singer (1998). From this questionnaire, we selected questions corresponding to the "control" and "sensory" factors as these items explicitly address a sense of controllability.

Both questionnaires were implemented in the virtual environment such that the participants could respond to the questions without removing the VR goggles. All items were provided with visual analogue scales. The scales of the embodiment questionnaire ranged from "strongly disagree" to "strongly agree". The presence-related aspects were directly adopted from Witmer and Singer (1998). The digital position of the virtual response tab on the visual analogue scale was extracted for analysis.

Table 1. Questionnaire items based on the Embodiment and Presence questionnaires.

Modified embodiment questionnaire (Longo et al., 2008)
Ownership. It seemed like...
... I was looking directly at my own hand, rather than at a virtual hand.
... the virtual hand began to resemble my real hand.
... the virtual hand belonged to me.
... the virtual hand was my hand.
... the virtual hand was part of my body.
Location. It seemed like...
... my hand was in the location where the virtual hand was.
... the virtual hand was in the location where my hand was.
... the touch I felt was caused by touching the virtual handle.
Agency. It seemed like...
... I could have moved the virtual hand if I had wanted.
... I was in control of the virtual hand.
Presence aspects from (Witmer and Singer, 1998)
Control Factors
How much were you able to control events?
How responsive was the environment to actions that you initiated (or performed)?
Were you able to anticipate what would happen next in response to the actions that you performed?
How much delay did you experience between your actions and expected outcomes?
How quickly did you adjust to the virtual environment experience?
How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
Control Factors and Sensory Factors
How completely were you able to actively survey or search the environment using visuion?

Objective measures To quantify the interaction performance, three measures were calculated: root mean square (RMS) jerk, mean scaler velocity, and compensation force. Jerk has been chosen as it represents the smoothness of a movement. Velocity is chosen as performance measure as it describes the general speed of the reaching motion which could influence RMS jerk. The compensation force represents the conflict of forces applied by the participant and the virtual agent. The mean square jerk is calculated from the third derivative of planar motion (x, y)

$$\frac{1}{T}\sum_{i=1}^{T}\sqrt{\dddot{x}^2(i\Delta t) + \dddot{y}^2(i\Delta t)} \tag{14}$$

whereas T is the total duration of each condition. The second performance measure is mean scalar velocity which is computed as

$$\frac{1}{T}\sum_{i=1}^{T}\sqrt{\dot{x}^2(i\Delta t) + \dot{y}^2(i\Delta t)}. \tag{15}$$

The third performance measure is compensation force $u_{comp} \in \mathbb{R}^2$ that is computed as

$$u_{comp} = \text{sgn}(u_h)(|u_h| + |u_a| - |u|). \tag{16}$$

where $\text{sgn}(u_h)$ returns the sign of u_h. The compensation force u_{comp} is the interaction force that does not result in motion of the cart.

To evaluate how the behavior of semi-autonomous control influences the subjective and objective measures, ANOVAs were calculated. For subjective measures, the average response to each subscale of the embodiment questionnaire and the overall embodiment score were analyzed. The presence aspects were evaluated considering the average of all items.

2.4 Procedure

The participants stood in front of the experimental setup and put on the VR goggles. When the participant felt comfortable with the VR goggles, the experimenter started a demonstration version of the experiment to explain the task and how to fill in the questionnaire. The demonstration was in the same virtual environment but the controller was deactivated. The task was to move the handle from one target to the other at a comfortable speed. As soon as one of the two targets was reached, the handle had to be moved to the other target. The participants were also asked not to exert excessive force and speed of motion for safety.

During the experiment, the participant interacted with the manipulandum which was controlled according to one of the four experimental conditions. After the interaction time of 5 *minutes*, a instruction message asked the participants to move the handle to the center where it was positioned during the questionnaire to ensure a comparable arm position across conditions and participants. This practice trial was performed as variable arm posture could influenced the questionnaire results. The questionnaire started automatically when the handle reached the center. To move the slider of the questionnaire, participants pointed with the VR pointer in their left hand to the questionnaire, hit the trigger button and moved the pointer such that the slider reached the desired position. The start position of the slider was set to the middle for all questions and only one question was presented at a time. To avoid biases induced by the experimenter, the experimenter stayed passive during the main experiment, as the entire workflow was automatically controlled by the computer (Beckerle et al., 2016).

2.5 Participant

Eight participants (2 female, 6 male, age $= 26.12 \pm 0.98$) took part in this study. All participants spoke English sufficiently to understanding the instructions and answering the questionnaire. The overall time for one experiment was approximately 1.5 hours. Before the experiment started, the participants were asked to read and sign the informed consent sheet. This study was approved by the ethical board of the Technical University of Munich.

3. RESULTS

The ANOVA on the embodiment score yielded significant main effects for Predictability $F(1,7) = 6.339$, $p = .04$ and Synchronicity $F(1,7) = 43.004$, $p < .001$ (Fig. 2). The embodiment score with the predictable control was significantly higher 0.76 ± 0.84 than with the unpredictable control 0.25 ± 1.13. Furthermore, the synchronous conditions 0.96 ± 0.97 yielded a higher embodiment score than the asynchronous conditions -0.45 ± 1.00. There was no interaction effect of the independent variables. Similar observations apply to all subscales of embodiment (Fig. 3). The statistical results of all the subjective measures are reported in Table 2. All subscales yielded consistent patterns and it is clearly visible that the predictable controller without delay yielded the highest score in all subscales of embodiment. In contrast, the lowest score was always reached by the asynchronous unpredictable controller.

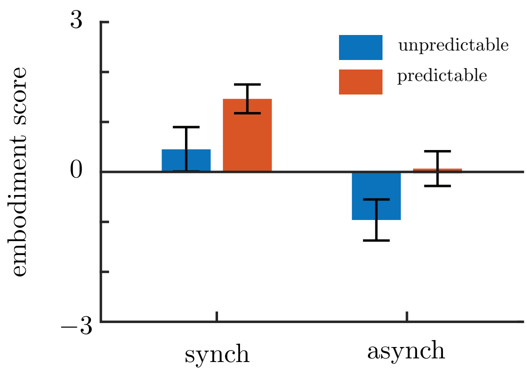

Fig. 2. Comparison of embodiment scores. The error bars indicate standard errors.

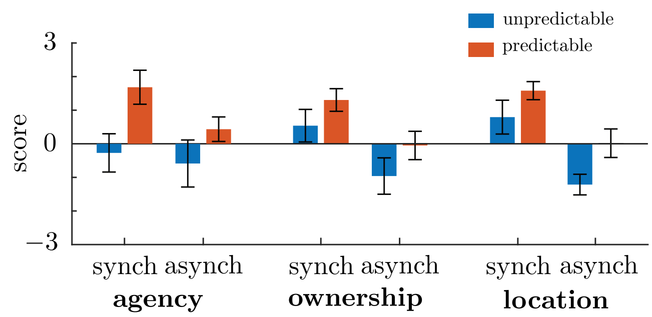

Fig. 3. Scores of the embodiment subscales

Table 2. ANOVA on subjective scores due to the experimental manipulations for embodiment, its subscales, and presence questionnaire.

Dependent variable	Synchronicity	Predictability	S * P
Embodiment	$p < .001$	$p = .040$	$p = .940$
Agency	$p = .086$	$p = .059$	$p = .275$
Ownership	$p = .002$	$p = .092$	$p = .786$
Location	$p = .002$	$p = .044$	$p = .496$
Presence	$p = .069$	$p = .031$	$p = .985$

The ANOVA for RMS jerk yielded a significant main effect for Predictability and Synchronicity (Table 3). RMS jerk was much higher with the unpredictabe controller than the with the predictabe controller and also higher when no delay was introduced (Fig. 4). The compensation force was not affected by the controller but was significantly lower in the synchronous conditions. The mean scalar velocity was

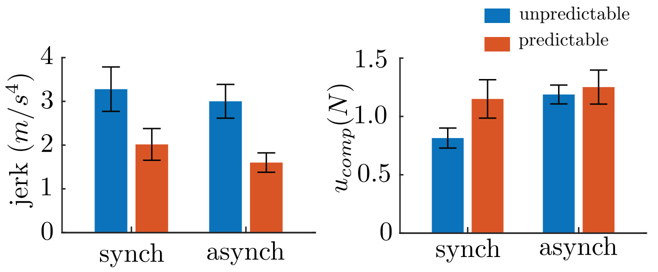

Fig. 4. Performance measure RMS Jerk and compensation force

also not affected by the controller but was significantly lower in the asynchronous conditions (Fig. 5).

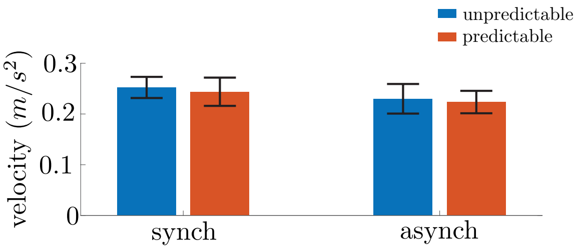

Fig. 5. Performance measure mean scalar velocity

Table 3. ANOVA on performance measures.

Variable	Synchronicity	Predictability	S * P
Jerk	$p = .050$	$p < .001$	$p = .700$
Velocity	$p = .046$	$p = .623$	$p = .927$
u_{comp}	$p = .030$	$p = .177$	$p = .143$

4. DISCUSSION

This study investigated whether and how the quality of semi-autonomous control influences the embodiment of the artificial hand by the user in a virtual environment. Results indicate predictable control can increase the subjective embodiment of the virtual hand and aspects of subjective presence experience in a virtual environment compared to unpredictable control. As embodiment composes of several different subjective components, a closer look to its subscales can provide a more detailed understanding of the effects. Embodiment and the subscale location as well as the aspects of presence showed significant effects on Predictability. The subscales agency and ownership showed a trend towards significance.

Under synchronous visual feedback, the predictable control resulted in the highest scores whereas asynchronous visual feedback and unpredictable control resulted in distinctly lower scores. Even though only a trend to statistically significant difference for the sense of agency was found, it still seems to be influenced by Predictability as the human force input u_h was perturbed by the unpredictable controller. These results support our initial expectation that the quality of semi-autonomous control influences embodiment, which decreases with reducing controllability.

Furthermore, delay also affected the sense of agency. As shown by the previous studies (Gallagher, 2000), this is caused by the large discrepancies between the visual feedback of the action and the internally predicted action outcome (Wolpert and Flanagan, 2001). In our experiment, learning of the semi-autonomous control patterns is persistently perturbed by the unpredictable control as the predicted movement did not result in intended motion. Caspar et al. (2015) investigated that agency was significantly lower when a robotic hand could be actively controlled, but reacted with delayed motions. Their findings are consistent with the results of this study as agency strongly decreased with a delayed visual feedback.

The sense of location was influenced by Predictability and by Synchronicity. Longo et al. (2008) report that somatic sensory experiences are tied to the sense of location. Such an somatic sensory experience is the applied force by the human to the system that has been reported in this paper as the compensation force which did not result in motion. This compensation force has been higher with the predictable controller and thus resulted in a higher sense of location in the predictable conditions. Furthermore, the sense of location describes the feeling that the real and artificial limb are in the same place which relates to spatial congruency between intended and observed action outcomes. The spatial congruency was corrupted by the unpredictable control when the expected movement and observed movement of the virtual hand was different which resulted in a displacement between the expected position and the actual position. Comparable findings have also been observed by Caspar et al. (2015) who reported a drop of embodiment for a mismatch of intended movement and observed movement. The subcomponent ownership was not significantly influenced by the factor Predictability even though the predictable control without delay yielded the highest ownership score. Nevertheless, Synchronicity yielded highly significant differences for ownership which can be attributed to distinct differences between the expected hand movement and position and the actual hand position and position in the asynchronous conditions. Kalckert and Ehrsson (2014) investigated the effect of distance between the artificial hand and real hand and report that ownership of the moving artificial hand decreased with increasing distance. This spatial incongruency decreased the sense of location as well as the sense of ownership in our experiments in the asynchronous conditions as the virtual hand was displaced to the real hand due to the delay. Overall, the sense of embodiment is a multifaceted construct which seems applicable to measure the quality of semi-autonomous control in a virtual environment.

For the control and sensory factors of the presence questionnaire, difference for Predictability was also statistically significant such that predictable control yielded higher presence than unpredictable control. The authors of the presence questionnaire reported a consistent positive relation between presence and task performance in virtual environments (Witmer and Singer, 1998). In our experiment, the performance measures RMS jerk and velocity were effected by Predictability such that predictable control yielded lower RMS jerk and higher velocity which represents higher performance. Therefore, the presence score was higher with higher performance which is in line with the results of Witmer and Singer (1998). The differences in performance can be explained by the behavior of the unpredictable controller that led to strong jittering and changes in acceleration and jerk whereas predictable control yielded to much smoother motion.

An explanation for the lower compensation force in the unpredictably control condition without delay could be compliance. Participants might have been more compliant to the movement of the controller when the handle was moving without being responsive to the human input force. Participants learned that producing a high amount of counter force does not result in the intended motion which caused a more compliant force input. This compliance has not been observed in the asynchronous unpredictable controller which might have been occurred as the participants kept on trying to reduce the incongruency between the seen and felt hand position.

The mean scalar velocity was not affected by Predictability but by Synchronicity as the overall velocity was significantly higher when no delay was applied to the visual feedback. When moving the cart with very slow speed, the experienced delay has been reduced to an almost synchronous level.

5. CONCLUSION

This study reported whether the quality of human-in-the-loop control can be evaluated using subjective measures such as embodiment and certain subscales of presence. Our results with 8 participants show significant higher scores of those measures within a virtual reality environment when predictable control is introduced whereas unpredictable control led to significantly lower scores in embodiment and presence. This implies that unpredictable control can have an influence on the quality of human-machine interaction, which seems to be due to reduced controllability and resulting incongruencies between intended and actual motions. Further studies with more participants are needed to gain a better understanding of how exactly embodiment and its subscales are influenced by the level of predictability of assistive control and its degree of autonomy. We conclude that embodiment and presence can be used as a quantitative evaluation method of semi-autonomous controllers from a user-centric perspective.

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