Sense of Embodiment Supports Motor Learning and Adaptation in Tele-Robotics

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In this article, we transition from the theoretical and experimental groundwork of manipulating and measuring Sense of Embodiment (SoE) to addressing a fundamental question: What is the purpose of optimizing the SoE in a teleoperation system? This exploration centers on investigating the potential positive effects of SoE on motor adaptation, the acceleration of motor learning, and the potential enhancement of task performance. The article delves into this investigation by focusing on two critical research questions: (1) what is the effect of SoE on task performance in a perceptual-motor task? (2) What is the effect of SoE on the asymptote of the learning curve in a perceptual-motor task? Drawing insights from the existing literature, the hypothesis emerges that enhancing SoE yields positive effects not only on task performance (H1) but also on the overall embodiment experience (H2). An additional layer of exploration is introduced through an exploratory research question: Are these results consistent across diverse scenarios and tasks? The study design encompasses two distinct user studies, each set in different applications and featuring various avatars, yet all anchored in similar tasks, specifically a modified peg-in-hole task: (1) in the first experiment, participants operated a robotic arm with a human-like hand as end-effector, and they were required to perform a classic peg-in-hole task; (2) in user study 2, the task is transformed into a variation that we called "peg-on-button," wherein participants use a robotic arm with a gripper as the end-effector to press a lit button. In both studies, a consistent pattern emerges: a setup that fosters embodiment has a positive impact on motor learning and adaptation, resulting in improved task performance. A supportive setup also reduces the perception of the surrogate as a mere mediator between the operator and the remote environment, especially when contrasted with a setup that suppresses embodiment. The positive effects on motor learning and task performance advocate for the incorporation of embodiment-supportive designs in teleoperational setups. However, the nuanced relationship between SoE and long-term task performance prompts a call for further exploration and consideration of various factors influencing teleoperation outcomes across diverse scenarios and tasks.

CCS Concepts: • **Human-centered computing → User studies**; **HCI theory, concepts and models**; **Interactive systems and tools**; **Interaction design process and methods**; **Interaction design theory, concepts and paradigms**; **Empirical studies in interaction design**;

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1 Introduction

We present two user studies aimed at better understanding the concept of **Sense of Embodiment (SoE)** and its effect on task performance and motor adaptation in two different tele-robotics setups. SoE has been defined as the sensations arising in conjunction with having (or even being) and controlling a surrogate, such as a robotic device or a virtual avatar [6, 11, 17]. We consider SoE as characterized by three components: (1) the sense of ownership, namely the feeling of self-attribution of an external object or device [17, 20]. (2) The sense of agency is defined as the feeling of having motor, action and intention control over the surrogate [17, 31]. (3) The sense of self-location refers to the volume of space where one feels located [1, 17]. Usually, self-location and body-space coincide so that one feels self-located inside a physical body [21]. SoE has been studied originally and extensively using the paradigm of the **Rubber Hand illusion (RHI)** [3]. The RHI is a perceptual phenomenon where individuals perceive a model hand as an integral part of their own body, generating a compelling sense of ownership. This illusion is achieved by the experimenter applying simultaneous tactile stimulation to both the real and fake hands. To disrupt the illusion, a threat, such as stabbing the fake hand or striking it with a hammer, is introduced, and participants' reactions are recorded. The occurrence of fear in response to the threat indicates the success of the illusion. This phenomenon underscores the significant impact of combined visual and tactile signals on the subjective experience of body ownership. Beyond its initial exploration with the RHI, subsequent studies have extended the concept to induce a strong SoE over both virtual and tangible extracorporeal objects. These objects range from artificial limbs, robotic hands, and arms to mannequins, virtual bodies, and even empty volumes of space and invisible bodies [5, 14, 19, 32]. Notably, these objects, unlike the original paradigm, can be actively controlled by the user, as observed in applications such as telerobotics.

One of the main reasons that brought to investigate SoE in teleoperation was to observe the effects of its manipulation on task performance. In the literature, we could not find studies approaching this effect in the teleoperation context, therefore, we decided to first understand how to manipulate it in a teleoperation setup [9] and then to observe the effects of this manipulation in different teleoperation scenarios. If high SoE can improve task performance, increase the learning rate, and decrease the motor adaptation time, then it becomes also relevant to optimize it in a teleoperation setup, and of give more importance to the design stage of a system. Our investigation was led by one main prediction that we tested: if SoE has a positive effect on motor adaptation—i.e., faster learning when SoE is higher, and it decreases the perception of the surrogate as mediator; as a consequence, it also has an effect on task performance. In other words, higher SoE leads to increase the learning speed compared to lower SoE, and the final performance plateau after learning is dependent on the level of embodiment. The optimization of the embodiment experience prompts the introduction of a crucial concept termed the *mediator*. This concept pertains to the level of perception associated with the setup or control pod, influencing the distance it creates between the operator and the avatar. This distance has a direct impact on reducing engagement and immersion.

In an ideal embodiment experience, the perception of the mediator should be null. This becomes particularly significant when exploring the SoE phenomenon in the context of teleoperation. This is due to the intricate interplay of multisensory integration and perceptual cues affected by the use of the setup to control the remote avatar. The components of the setup play a big role in determining the transparency in perceiving the remote environment. Operators, engaging in teleoperation, must get used to devices that mediate their senses and multisensory integration. Even if the setup excels in rendering the remote environment accurately, it remains an external apparatus that operators need to familiarize themselves with over time.

In this article, we present two user studies aimed at better understanding the concept of SoE and its effect on task performance and motor learning in two different teleoperation setups. We report how task performance and motor learning are affected by different levels of SoE. SoE levels are manipulated by varying perceptual cues known to affect SoE [9, 12, 26]. Perceptual cue manipulation consists of influencing the multisensory integration of external stimuli obtained by controlling an avatar in order to improve or degrade the level of embodiment of the operator. This can be obtained by changing the field or point of view of the camera used in the surrogate presented to the operator, by activating or deactivating the tactile feedback, and by choosing a certain haptic device rather than another. The experiment presented in [9] was realized as a benchmark to understand the importance of five selected perceptual cues and the effect of their potential interaction with SoE and task performance. Based on that, we designed the conditions and setup of all user studies. Here, we present data relative to task performance and motor adaptation and learning, where motor adaptation refers to flexibility in learning new movements but can also be used to determine whether some operators can generate a motor pattern to which they become used [35]. Repeated adaptation can lead to learning a new and more permanent motor calibration. This type of learning is likely to be an important method for making long-term improvements in operators' movement patterns. The conclusion on SoE and task performance would then depend on the moment of testing: during the learning phase, there may be a positive effect, but once learning is completed, this effect disappears. Therefore, we are interested in not only the (final) level of performance but also the motor adaptation process. For what concerns the supporting literature related to the relationship between motor adaptation and SoE, we are testing this assumption in the presented studies for the first time. However, there are studies suggesting and exploring explicit and implicit motor learning strategies and how they can affect motor adaptation in different tasks and motor conditions [23, 30]. Our plan encompasses the development of experimental methods to measure both the explicit and implicit components of the SoE phenomenon, employing approaches that encompass both empirical and subjective assessments. Studies have shown that implicit and explicit processes underlie human motor skill learning and each of them has its own peculiar properties and contributions. For example, implicit processes such as sensory prediction and reward prediction error-based learning seem invariant and stationary, while explicit processes such as awareness and strategy synthesis appear to be stationary. Furthermore, in [24], the authors developed techniques that isolate these processes and that could naturally be extended to common SoE paradigms. Second, we experiment with different contextual features that could affect SoE, such as visual and dynamic similarity with the human limb. In our physics engine, this was manipulated by proposing different tools/avatars with different kinematic properties. The main differences between the two user studies concern (1) the humanlikeness of the surrogate, (2) the level of immersion and participation of the embodiment experience, and (3) the way in which the SoE is manipulated. This allowed us to test the effect of SoE in different contexts of application. To make the task performance comparable, the studies have in common that the operators were required to manipulate a right arm, and they were asked to accomplish a similar task (variations of a peg-in-hole) with quantifiable performance metrics, i.e., a task that returns count data, and a similar level of difficulty.

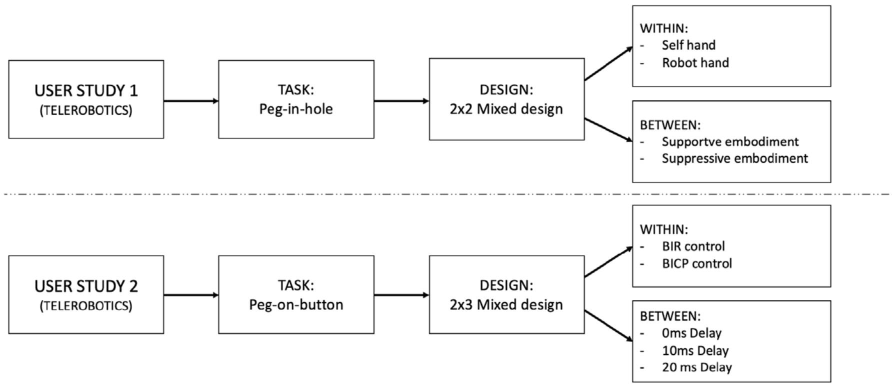


Fig. 1. The diagram summarizes, for each user study, the setup, the task, the design, and the conditions.

User study 1 involved a robotic arm with a mechanically complex, humanoid robotic hand attached to it (see Figure 2(a) and (b)), and operators had to perform a peg-in-hole task. In user study 2, operators controlled a robotic arm with a peg as an end-effector (see Figure 4(a)) and did a peg-on-buttons task, namely, they had to press the button that lighted up among the six buttons in the remote workspace. The diagrams represented in Figure 1 summarize the design of the two user studies.

Starting from the **research questions (RQs)**: (RQ1) What is the effect of SoE on motor adaptation in a perceptual-motor task? (RQ2) What is the effect of SoE on the asymptote of the learning curve (i.e., the performance level after the learning curve reached a plateau) in a perceptual motor task?—We hypothesize that (H1) SoE has a positive effect on task performance, i.e., faster learning when SoE is higher, and (H2) it improves the overall embodiment experience and decreases the perception of the surrogate as mediator. As a side issue, we also formulated an explorative research question: (RQE) Are these results robust over different tele-robotics contexts and tasks (i.e., the two experiments)? In both experiments, we found that task performance is not directly affected by SoE. However, we found that SoE has a positive effect on motor adaptation and in reducing the perception of the surrogate as mediator between the operator and the remote environment. These results indicate that a high SoE increases motor learning speed, but they do not confirm a correlation with task performance.

2 Prior Works

In teleoperation, some of the most investigated aspects are the effects of perceptual cues manipulation and time delay on SoE and task performance. In the two presented experiments we manipulated visuo-proprioceptive information, visuo-tactile information, point of view, and the visual-likeness of the surrogate.

More specifically, time delay is one of the main issues encountered and studied in teleoperation systems, particularly in telerobotics. For instance, [2, 9, 15, 33] investigated to what extent an operator can deal with and adapt to time delay and the impact of time delay on SoE. Overall, results show that time delay affects the integration of proprioceptive information and multisensory stimuli. As a consequence, the level of SoE decreases, and operators need some time to adapt to the situation. It is still unclear what the tolerance threshold is (if one exists) of adaption to delayed signals in a teleoperation scenario. This threshold should point to the maximum limit of delay that an operator can handle to be nevertheless capable of manipulating the surrogate. For what concerns the relation to task performance, studies demonstrated that it can be improved by conditions that support embodiment [22, 27, 28]. When the operator is strongly embodied with the surrogate, the perception of the surrogate as mediator is lower [4]. In other words, the operators do not perceive the surrogate as a third-party object or external tool that mediates the interaction between them and the remote environment, but they feel embodied and in full control of the surrogate as if it was part of their own body.

Starting from the literature, it is assumed that different levels of SoE through a surrogate, obtained by the manipulation of several perceptual cues, will have an effect on the task performance. In the case when operators feel strongly embodied, task performance would improve compared to situations in which the embodiment level is weak. However, these results cannot be generalized since they are mostly limited to **Virtual Reality (VR)** studies or they are conducted in the prosthetic field with participants who experienced an upper limb loss; another aspect is that they usually focus on cognitive load and not on motor performance [22, 27, 28, 34]. Moreover, there is still a debate if high SoE really leads to better performance. The effect of SoE on task performance has not been widely replicated, and there are also studies that found no effect or just different advantages in manipulating certain perceptual cues [7, 9, 13, 18]. An alternative explanation for the inconsistent results could be that SoE is not directly related to the final level of performance but results in faster learning and a steeper learning curve, and differences in motor adaptation. These differences can be due to the context of application (VR, social robotics, field robotics, industrial robotics, or others), the level of complexity and the kind of task, and the different kinds of avatars.

3 User Study 1

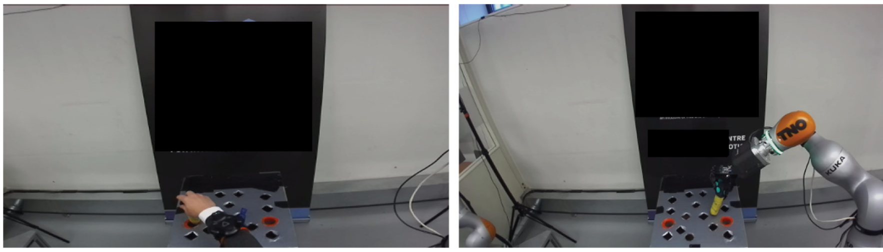
The design of this user study was previously presented in [10]. However, while in that article we presented the assessment of pupil dilation as an implicit measure of embodiment, here we present data relative to task performance and motor adaptation and learning.

3.1 Method

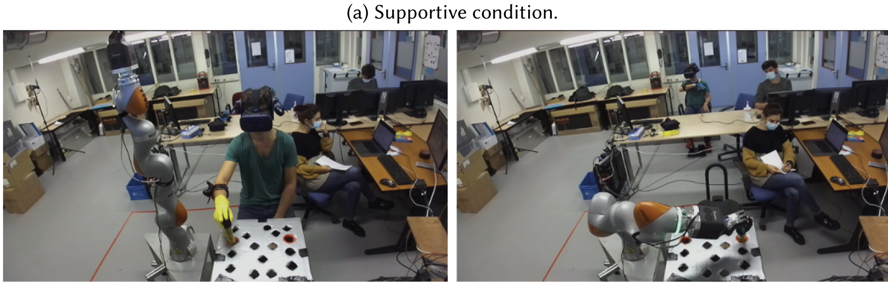
We explored the effect of SoE on task performance and motor adaptation with two independent variables: SoE level (supportive, suppressive), which was a between- subjects variable and *hand* (self, robot) which was a within-subject variable. Of the two SoE level groups, the “supportive” group experienced perceptual cues that support embodiment, while the “suppressive” group experienced perceptual cues that suppress embodiment. Each group did the task under two levels of Hand: (1) “self” using their own hand (either with or without the gloves), and (2) “robot” using a robotic surrogate. We set the perceptual cue such that strong (supportive) or weak (suppressive) SoE was expected based on previous studies [9]. Particularly, we manipulated the perspective (1PP for the supportive condition and 3PP for the suppressive one) haptic feedback (on for the supportive and off for the suppressive).

3.1.1 Participants. Twenty-eight right handed participants (16 females and 12 males, between 19 and 49 years old) were recruited from the TNO participant pool. Participants were paid 30€ and their travel costs were reimbursed. Participants were divided into two groups: 15 participants experienced the supportive condition, while 13 participants the suppressive one. The ethics committee of TNO approved user study 1 (RP 2020-012).

3.1.2 Setup and Materials. The teleoperation setup consisted of a telemanipulator, a haptic control interface and a visual telepresence system. The telemanipulator was the Shadow Hand Lite, equipped with 3D force sensors on its fingertips, mounted on the flange of a KUKA IIWA 7 serial link robot. The haptic control interface was realized by the haptic glove SenseGlove DK1, which tracks finger movements in 11 degrees of freedom and can provide passive force feedback on each finger. The movements of the operator’s wrist in space are recorded by an HTC VIVE tracker



(a) Supportive condition.



(b) Suppressive condition.

Fig. 2. Frames extracted from the ZED mini recordings during the supportive conditions. On the left, the participant's view during the human hand level. On the right, the participant's view during the robotic surrogate level.

mounted on the SenseGlove. The visual system consists of a ZED mini stereovision camera with a HTC VIVE Pro Eye relaying the visuals to the operator while also collecting eye gaze and pupil dilation. The HTC Vive offers a 110°field of view, a maximum refresh rate of 90 frames per second and a combined resolution of 2160×1200 pixels (1080×1200 pixels per eye). The setup was slightly different between the two conditions. For the supportive condition, the ZED mini was placed to provide a first person perspective, and the operators received the tactile feedback just in the moment in which they grasped and released the peg. In the suppressive condition, instead, the ZED mini was providing a third person perspective by facing the operators (i.e., a mirrored perspective of the workspace). The chosen third person perspective was challenging, but the purpose was to observe if the participants' performance while using their own hand and the surrogate hand would have been drastically affected in both conditions. Moreover, they had to wear two thick gloves during the task accomplishment with their own hand and, while accomplishing the task using the robotic surrogate, the tactile feedback was continuous from the moment in which they grasped the peg until they released it (see Figure 2(a) and (b) for an overview of the setup). In both conditions at both levels, participants had to wear the HMD during the experiment.

3.1.3 Design. We explored the effect of SoE on task performance and motor adaptation. We manipulated two embodiment conditions experienced by two groups: one group experienced perceptual cues that support embodiment, while the other group experienced perceptual cues that suppress embodiment. Each group had to face the experiment task at two levels: (1) one with their own hand and (2) another with a robotic surrogate. We set the perceptual cue such that strong (supportive) or weak (suppressive) SoE was expected, based on previous studies [9]. Particularly, we manipulated the perspective (first person perspective for the supportive condition and third person perspective for the suppressive one) and haptic feedback (on for the supportive and off for the suppressive).

3.1.4 Procedure. Participants were asked to fill out the consent form, and then they were given detailed instructions about the experiment and the tasks. Participants were also instructed that if they were unsure how the task worked they could ask the experimenter for help. The experiment lasted 45 minutes. Participants were asked to do a peg-in-hole task. The grid, used as workspace, had 16 holes. However, participants were required to focus just on two of them marked in red. The two holes had a distance of 32 cm on the horizontal ground. Participants had 90 seconds to place the peg in the holes as many times as they could. They had to repeat the task 6 times in total, three times by hand and three times by using the robotic surrogate. After each trial, they had to fill a customized version of the questionnaire on embodiment from [25]. Half of the participants accomplished the three trials using their own hand first, while the other half by using the robotic surrogate first (see Figure 2(a) and (b)). When participants accomplished the task with their own hand, they were sitting in front of the grid, and they could directly interact with it, but they were observing it through the HMD. When they were accomplishing the task using the robotic arm, they were sitting at a safety distance from the grid, and they used the robotic device to interact with it.

3.1.5 Measures. To measure SoE, we adopted a reduced version of the embodiment questionnaire from [25]. For the sense of ownership: (1) It felt as if my own body were turning into the surrogate body; (2) At some point it felt as if my own body was starting to take on the posture or shape of the surrogate body that I saw; (3) I felt as if the surrogate body was my body. For the sense of agency: (4) I felt as if the movements of the surrogate body were influencing my own movements; (5) I felt like I could control the surrogate body as if it was my own body; (6) It seemed as if my own body was touching the peg. For the sense of self-location: (7) It seemed as if I felt the touch of the peg in the location where I saw the surrogate body touched; (8) I felt as if my own body was drifting toward the surrogate body or as if the surrogate body was drifting toward my own body; (9) I felt as if my own body was located where I saw the surrogate body. Participants were asked to assess items on ownership, agency, and self-location using a Likert-Scale from 1 to 7 (where 1 is *completely disagree* and 7 is *completely agree*).

Moreover, motor adaptation was determined on the basis of task performance over trials.

3.1.6 Results. We implemented a 2×2 mixed-design ANOVA model, with one dependent variable within subjects (self and robot hand) and one dependent variable between subjects with two levels (supportive and suppressive embodiment). We observed the effect of this manipulation on four dependent variables: the SoE components (the sense of ownership, agency, self-location) and task performance. To determine the motor learning among trials we applied a two-way ANOVA. We found a significantly positive trend in the mean scores of task performance in the supportive conditions among trials (see Table 1) at both levels. However, we did not encounter the same results in the suppressive condition at both levels. Moreover, we observed a significantly different score for the self-level compared to the robot hand in both conditions and for almost all the evaluated items and task performance (see Figure 3). The self-level resulted in higher scores than the robot one.

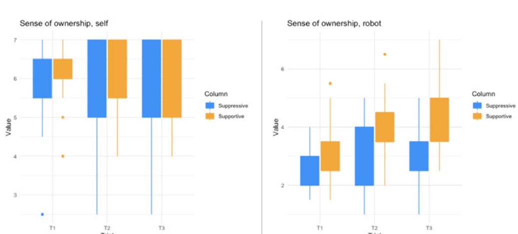
The Two-Way ANOVA detected a significant difference among trials in task performance for both the self-hand ($F = 3.67$, $p = 0.03$) and the robot hand ($F = 4.72$, $p = 0.01$) types in the supportive condition. We did not observe a significant difference in the suppressive condition for both hand types (see Table 1).

Post hoc analyses showed significant differences in agency (self-hand type) and ownership, agency, self-location, and task performance (robot-hand type) between subjects (suppressive-supportive conditions) (see Table 2).

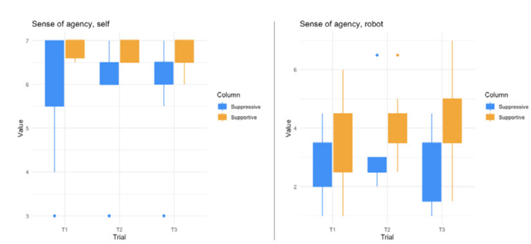
For each group (supportive-suppressive), post hoc analyses reported a significant difference in ownership, agency, self-location, and task performance within subjects (self-robot hand) (see Table 3).

Table 1. Overview of the Two-Way ANOVA Results of SoE Components and Task Performance Over Time (from Trial 1 to Trial 3) in Both Conditions and Levels

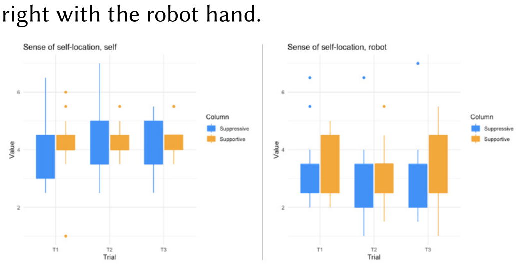
Value	**Level**	**Hand type**	**df**	**SD**	***F*-value**	***p*-value**
Ownership	Supportive	Self	42	1.06	0.30	0.74
Agency	Supportive	Self	42	0.41	0.30	0.74
Self-location	Supportive	Self	42	1.01	0.04	0.96
Task Performance	Supportive	Self	42	11.73	3.67	0.03
Ownership	Suppressive	Self	36	1.37	0.09	0.91
Agency	Suppressive	Self	36	1.22	0.120	0.89
Self-location	Suppressive	Self	36	1.10	0.59	0.56
Task Performance	Suppressive	Self	36	142.42	2.45	0.10
Ownership	Supportive	Robot	42	1.42	2.37	0.10
Agency	Supportive	Robot	42	1.44	1.37	0.27
Self-location	Supportive	Robot	42	1.19	0.06	0.94
Task Performance	Supportive	Robot	42	1.70	4.72	0.01
Ownership	Suppressive	Robot	36	1.10	0.77	0.47
Agency	Suppressive	Robot	36	1.11	0.10	0.91
Self-location	Suppressive	Robot	36	1.41	0.43	0.65
Task Performance	Suppressive	Robot	36	0.78	2.58	0.09



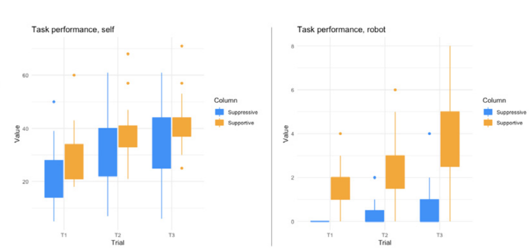
(a) The sense of ownership. On the left, participants were performing the task with their own hand, on the right with the robot hand.



(b) The sense of agency. On the left, participants were performing the task with their own hand, on the right with the robot hand.



(c) The sense of self-location. On the left, participants were performing the task with their own hand, on the right with the robot hand.



(d) The task performance. On the left, participants were performing the task with their own hand, on the right with the robot hand.

Fig. 3. Plots of the embodiment components scores and task performance over trials between the supportive and suppressive conditions.

Table 2. Overview of the Post Hoc Results of the SoE Components and Task Performance between Subjects (Suppressive- Supportive) for Both Hand Types (Self-Robot Hand)

Value	**Hand type**	**Suppressive**	**Supportive**	***df***	**SD**	***t*-value**	***p*-value**
Ownership	Self	5.70	5.89	26	1.07	0.45	0.65
Agency	Self	5.87	6.73	26	0.77	2.97	0.01
Self-location	Self	4.17	4.08	26	1.05	0.22	0.82
Task Performance	Self	36.11	2.62	26	12.63	1.60	0.12
Ownership	Robot	2.74	3.92	26	1.42	2.19	<0.001
Agency	Robot	3.06	3.69	26	1.18	1.40	<0.001
Self-location	Robot	3.17	3.11	26	1.31	0.11	0.02
Task Performance	Robot	2.62	0.36	26	0.90	6.62	<0.001

Table 3. Overview of the Post Hoc Results of the SoE Components and Task Performance Within Subjects (Self-Robot Hand) in Both Groups (Suppressive-Supportive)

Value	**Level**	**M Self**	**M Robot**	***df***	**SD**	***t*-value**	***p*-value**
Ownership	Supportive	5.89	3.99	14	1.71	4.44	<0.001
Agency	Supportive	6.73	3.69	14	1.18	9.95	<0.001
Self-location	Supportive	4.08	3.11	14	1.04	3.59	0.003
Task Performance	Supportive	36.11	2.62	14	11.21	11.57	<0.001
Ownership	Suppressive	5.70	2.74	12	1.41	7.55	<0.001
Agency	Suppressive	5.866	3.06	12	1.56	6.47	<0.001
Self-location	Suppressive	4.17	3.17	12	1.31	2.75	0.018
Task Performance	Suppressive	28.46	0.36	12	13.71	7.39	<0.001

In the supportive condition at the self-level, sense of ownership ($r = 0.61$, $df = 13$, $p = 0.016$) and sense of agency ($r = 0.62$, $df = 13$, $p = 0.01$) were found to be significantly correlated to task performance during the second trial. For the others trials we could just observe a positive, but not significant, trend. Finally, we found a significantly negative correlation between sense of self-location and task performance during the first trial ($r = -0.58$, $df = 13$, $p = 0.023$), the second trial ($r = -0.79$, $df = 13$, $p < 0.001$), and only a not significant trend during the third.

Moreover, we looked for correlation among the embodiment components. We found a weak correlation between sense of ownership and agency only during the third trial ($r = 0.57$, $df = 13$, $p = 0.02$). There was a correlation between sense of ownership and self-location during the first ($r = 0.57$, $df = 13$, $p = 0.02$) and the third ($r = 0.73$, $df = 13$, $p = 0.002$) trials. Finally, there was a correlation between sense of agency and self-location during the second ($r = 0.61$, $df = 13$, $p = 0.01$) and third ($r = 0.59$, $df = 13$, $p = 0.02$) trials.

In the suppressive condition at the self-level, we did not find a significant correlation between any SoE component and task performance. We only found a correlation between sense of agency and ownership during the first ($r = 0.62$, $df = 11$, $p = 0.02$) and third trials ($r = 0.69$, $df = 11$, $p = 0.009$).

In the supportive condition at the robot level, we did not find a significant correlation between any SoE component and task performance. We found a correlation between sense of ownership and agency during the first ($r = 0.78$, df = 13, $p < 0.001$), second ($r = 0.87$, $df = 13$, $p < 0.001$), and third ($r = 0.71$, $df = 13$, $p = 0.003$) trials; we also found a correlation between sense of ownership and self-location, but only during the third trial ($r = 0.61$, $df = 13$, $p = 0.02$).

In the suppressive condition at the robot level, we did not find a significant correlation or a trend between any SoE component and task performance. We found a correlation between sense of ownership and agency during the second ($r = 0.66$, $df = 11$, $p = 0.013$) and third ($r = 0.81$, $df = 11$, $p < 0.001$) trials. Moreover, we found a correlation between agency and self-location during the first ($r = 0.54$, $df = 11$, $p = 0.05$) and second ($r = 0.82$, $df = 11$, $p < 0.001$) trials, and a weak trend during the third one ($r = 0.51$, $df = 11$, $p = 0.07$).

To summarize, within-subjects, when participants were using their self hand, they evaluated the SoE components significantly higher compared to the robot hand type, and they also performed significantly better. However, among the three trials, we found a significant improvement only in task performance for both hand types and conditions but not for what concerns the evaluation of the embodiment components. Finally, between subjects, for the self hand, we found that participants attributed a significantly higher score only to the sense of agency while performing the task in the supportive condition than in the suppressive one. For the robot hand, instead, when participants were in the supportive condition, they evaluated the SoE components significantly higher compared to the suppressive condition, and also the task performance resulted significantly better.

4 User Study 2

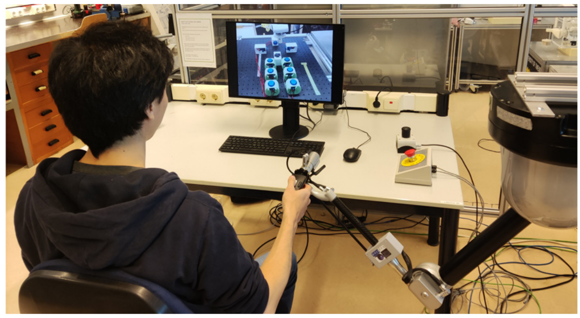
In the findings gleaned from user study 1, a noteworthy advancement in task performance was evident during trials where the embodiment was intentionally designed to be supportive. To further probe the dynamics of teleoperation, we aimed to determine whether the SoE could be manipulated not only through perceptual cues but also at the level of the control system architecture. In this instance, the experimental setting shifted to an industrial scenario context, featuring an avatar less visually human-like than in the previous experiment—a robotic arm with an attached peg serving as the end-effector.

To explore this, we introduced a **bi-directional impedance reflection (BIR)** control system strategically designed to address time delay challenges in teleoperation scenarios through the usage of EMG signals as a predictor. This was set in contrast to a **bilateral impedance control with a passivity layer (BICP)**, the prevailing system architecture in use in the literature. The significance of this study lies in its demonstration that embodiment can be intentionally shaped at various levels within the system setup and architecture. Furthermore, it contributes novel insights into the intricate relationship between SoE and task performance, underscoring the malleability of embodiment across different teleoperation configurations.

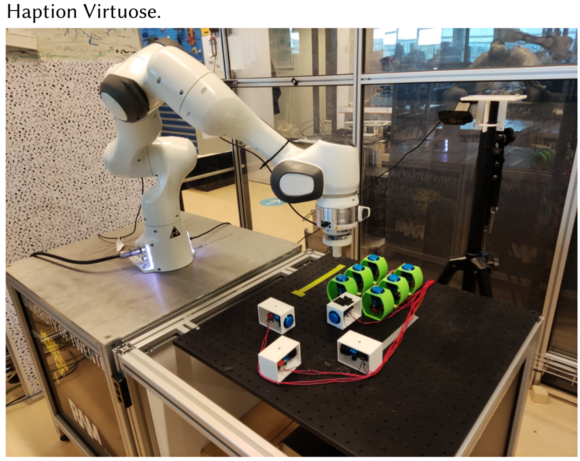
4.1 Method

4.1.1 Participants. Thirty right-handed participants were sampled from staff and students between 20 and 30 years old, 8 females and 22 males, and they were equally distributed in three groups. The ethics committee of the University of Twente approved user study 2 (RP 2021-110).

4.1.2 Setup and Materials. The operator side of the experimental setup can be seen in Figure 4(a). At the local side, there was a Haption Virtuose haptic device that could measure the positions of the operator and apply force feedback in 6 degrees of freedom. The operator could see the remote environment via a screen, through a webcam added on site in order to provide a first-person perspective on the environment. Participants had to operate the Franka Emika arm that was positioned on the right side of the interaction platform from the operator's perspective. The setup at the remote side can be seen in Figure 4(b). It consisted of a workspace with 6 green 3D printed blocks with a blue button on the top, equally distanced in rows, and 4 white 3D printed blocks with a blue button on the side facing each other. A led was attached to each button. These buttons and



(a) The operator's side of the experimental setup, via a screen the operator can see the remote site and control the robot using the Haption Virtuose.



(b) The remote side of the experimental setup, where the Franka Emika arm is controlled equipped with a force sensor.

Fig. 4. The operator and remote side of user study 2.

LED's were attached to an Arduino MEGA to manage the LEDs power on or off. At the operator and remote side, two computers were both running the control software. A local network was used to connect them. ROS was used as middleware, which also handled the communication between the two computers. The messages between the local and remote sites was differently delayed for each condition.

4.1.3 Design. Force feedback generally has a positive effect on the telemanipulation experience and SoE of the operator. However, systems with force feedback are vulnerable to time delays, reducing their transparency and stability. We implement a BIR controller. In this method, the impedances of the operator and the environment are estimated and reflected back to the remote robot and haptic interface, respectively. A trajectory predictor was added to compensate for the delayed motion, and we implemented a rigid impedance model. We then evaluated in a user study the effectiveness and SoE of the operators while using the system, comparing it to a system with a classical BICP. Three-time delay groups (0, 10, and 20 ms one-way delay) of 10 participants each executed the task with both controllers. The results show that the BIR controller performs significantly better in the 10 ms and 20 ms time delay groups in terms of task performance, user experience and SoE, showing that the transparency of the controller can also decrease the feeling of the setup as mediator between the operator and the remote environment.

4.1.4 Procedure. Participants were asked to fill out the consent form, and then they were given detailed instructions about the experiment and the tasks. Participants were also instructed that if they were unsure how the task worked, they could ask the experimenter for help. The experiment duration was approximately 30 minutes. We asked to accomplish a task that we called *Peg-on-button*: six green cubes with a button on the top were placed in the work-space in a grid. Participants had to press the button that lighted up. After they pressed the button, another random button highlighted. The task ended after two minutes. After the accomplishment of the task with one controller, participants were required to fill in the questionnaire. Finally, they were asked to repeat the same task with the other controller and to fill in the questionnaire again.

4.1.5 Measures. SoE components were measured through the evaluation of the items presented in a customized version of the embodiment questionnaire from [25], as presented in user study 1. To assess motor learning, we collected task performance.

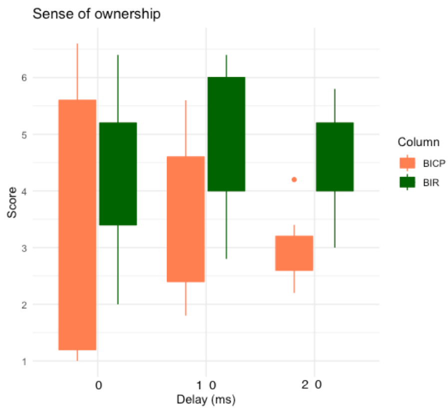
4.1.6 Results. We implemented a 2×3 mixed-design ANOVA model, with one independent variable within subjects (BIR and BICP controls) and one independent variable between subjects with three levels (0 ms, 10 ms and 20 ms delay). We observed the effect of this manipulation on four dependent variables: the SoE components (the sense of ownership, agency, self-location), and task performance. We found a significantly higher mean score of the BIR control over the BICP for the embodiment and for the task performance in the delayed conditions (see Figure 5 and Table 4). There was a significant difference between the two controls in ownership ($F(2, 25) = 40.77$, $p < 0.001$), agency ($F(2,25) = 5.61$, $p = 0.03$), self-location ($F(2, 25) = 20.61$, $p < 0.001$), and task performance ($F(2, 25) = 9.31$, $p = 0.005$), but not a significant difference across the three groups who experienced different time delay conditions. We also found a significant interaction between controls and delay ($F(2, 25) = 7.67$, $p = 0.003$) in task performance. Following up this interaction indicated that there was no significant difference between controls at the 0 delay condition, but the difference was significant in the other two conditions. The mean scores of the BICP decreased over time.

We did not find a significant correlation neither among SoE components nor between SoE components and task performance in none of the delay conditions.

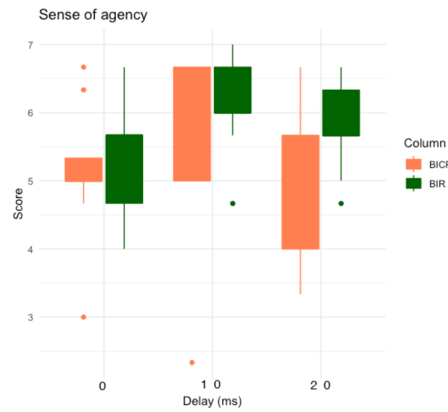
The results indicate that in case of delay, for almost all the evaluated items (i.e., the components of the embodiment and the performance of the task), the operators preferred the BIR over the BICP control and achieved a better performance in the peg-on-button task.

5 General Discussion

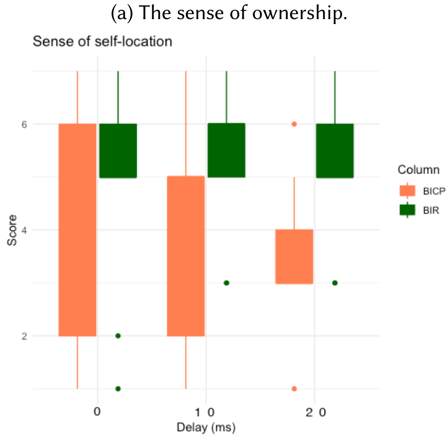
We hypothesized a positive effect of SoE on task performance (faster learning when SoE is higher) (H1). On the basis of the results, we accept H1. In study 1, Figure 3(d) and Table 1 show a better task performance in the condition in which the perceptual cues support a high SoE, i.e., when the level of embodiment is designed to be high, we observe a positive learning effect and a significant better performance over time. In the condition designed to provide a low level of SoE, instead, we observe a weak and non-significant learning effect over trials. Moreover, between subjects, we observed a significantly higher task performance of the supportive embodiment group compared to the suppressive one while performing the task with the robot hand. In study 2, we observed that by increasing the delay, participants perceived the proposed BIR control as providing higher SoE than the BICP control (see Figure 5). Moreover, we can also observe a significantly better performance by using the BIR in delayed conditions.



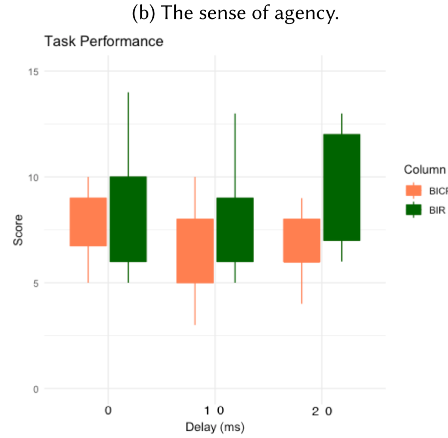
(a) The sense of ownership.



(b) The sense of agency.



(c) The sense of self-location.



(d) The task performance.

Fig. 5. Plots of the embodiment components scores and task performance in the three delay conditions (T1 = 0 ms, T2 = 10 ms, T3 = 20 ms) compared for both controllers (BICP and BIR).

Table 4. Overview of the Pairwise Comparison between the BIR and BICP Controllers for the SoE (Represented by the Sub-Scales: Ownership, Agency, and Self-Location), and the Task Performance (Peg-on-Button Was the Only Designed to Check and Compare Task Performance)

Measure	**Mean Square**	**Partial eta squared**	***F*-value**	***p*-value**
Ownership	18.55	0.62	40.77	<0.001
Agency	4.76	0.183	5.61	0.03
Self-location	20.61	0.42	18.17	<0.001
Task Performance	12.92	0.380	7.67	0.003

However, the interpretation of our results does not appear to be so straightforward. Particularly, in user study 1, the most significant correlations were found when perceptual cues support achieving a high SoE. We found significant positive correlations between SoE components and task performance, but no correlation was found when perceptual cues suppressed SoE. However, in case of a full dependency between SoE and task performance, we would have expected to find a negative correlation in the suppressive embodiment condition. In fact, in the suppressive condition, even if the learning effect is not significant over the three trials, we can observe a trend that suggests an increasing performance over time (see Figure 3(d)). Moreover, between subjects, we did not find a significant difference between the task performance of the supportive and suppressive groups while performing the task with the self-hand. One explanation could be that while using their own body, even if the perceptual cues are negatively affected, the learning rate is already so high that people reach the same plateau in task performance that they would reach in the most supportive condition (i.e., using their own body without any mediator). For what concerns the observations in the other user studies, in user study 2, we did not find a significant correlation between the scores of the embodiment components and task performance.

This brings us to H2, namely a positive effect of SoE on the overall operator's experience (i.e., an increasing evaluation of the embodiment components and a decreasing perception of the surrogate as a mediator). On the basis of our results, we can only partially accept H2. Starting from user study 1, we could not observe a significant difference among the scores attributed to the SoE components between subjects in the supportive and suppressive conditions at the self-hand level and neither at the robot hand level. The only exceptions are the sense of agency at the human level, which was scored significantly higher by the supportive condition group, and the sense of ownership at the self hand level, which was scored significantly higher by the supportive condition group. At the robotic hand level in the supportive group, we can also observe an increasing feeling of ownership and agency over the robot surrogate over trials within subjects (see Figure 3(a) and (b)), but the differences in scores are not significant. Another observation was that the correlation between self-location and task performance was negative, while participants performed the task in the self-hand condition. This is probably due to the setup: participants had to accomplish the task while experiencing the workspace through a teleoperation setup even when they were using their own hand. Therefore, while they could perceive their own body as usual, their visual perception and proprioception were affected by the setup. Over trials, they improved their task performance but they poorly scored sense of self-location items. As stated in the introduction, in the context of teleoperation, operators who engage in controlling remote systems or devices need to adapt to the tools that mediate their sensory experiences and facilitate multisensory integration. Even if the teleoperation setup is highly effective in accurately representing the remote environment, it still functions as an external apparatus. Over time, operators must become familiar with this external setup, understanding its nuances and intricacies through repeated use and practice. The process of familiarization is crucial for operators to achieve a high level of proficiency and comfort in effectively utilizing the teleoperation system. For what concerns user study 2, in the delayed conditions, namely in the conditions designed to test if our controller (BIR) could improve the SoE experience and task performance, we observe a significant higher score of the embodiment components while using the BIR than the BICP controller.

To answer the explorative RQ (Are these results robust over different scenarios and tasks?), SoE experience and task performance seem setup and task-dependent. However, there are some common observations, such as better task performance while using a setup designed to create a supportive embodiment experience compared to a suppressive embodiment one. Across experiments, through participants' feedback and our observations, we could conclude that the context of application and the setup play a role in the SoE experience. We learnt that also the task and the goal also have an effect on the operators' embodiment experience. There is evidence that there is a difference between a classic embodiment illusion, such as the RHI, in which the participants have a passive experience and focus all their attention on the perceived stimuli and the avatar, compared to an active experience, such as in a teleoperation setup in which a big part of the attention span is on the task accomplishment and in the motor learning experience. In those cases the priority is given to the task, and the SoE experience becomes secondary. This brought us to the conclusion that our manipulation, even if it had an effect on task performance, was not enough to affect the body schema—the unconscious and automatic representation of the body's spatial configuration and posture—and the body image—an individual's conscious and subjective perception of their own body, including thoughts, feelings, and attitudes toward their physical appearance—of the participants [6].

To summarize the contributions, we found that higher SoE, supported by perceptual cues, enhances task performance and learning over time, while lower SoE shows no significant correlation with task performance. Some SoE components, such as the sense of agency and ownership, improve in supportive conditions. The study highlights that the impact of SoE is context-dependent, with supportive conditions generally leading to better performance. However, the manipulation did not significantly change participants' body schema and body image, particularly in active tasks where the focus is on task accomplishment. By confirming previous related studies [8, 16, 29], these findings underscore the nuanced relationship between embodiment, task performance, and user experience.

6 Conclusions, Limitations, and Future Works

The findings suggest that SoE directly influences task performance, impacting motor learning and diminishing the perception of the avatar as a mediator. A supportive embodiment appears to enhance the operator's learning experience within a setup, potentially encouraging sustained usage over time. However, the intricate relationship between SoE, task performance, and motor learning in teleoperation necessitates further exploration. Notably, we observed a positive trend in task performance even in suppressive conditions of embodiment, even though it did not reach statistical significance. Extending the task duration and increasing the number of trials would yield more observations, providing a deeper understanding of how the manipulation of embodiment affects task performance. Crucially, this extended investigation could clarify whether operators in suppressive conditions can eventually attain the same level of performance as those in supportive conditions, given additional training and adaptation time.

Our findings and the previous studies suggest a default limitation of studies on embodiment, namely that different contexts, tasks, or setups can provide different outcomes. The lack of a common framework makes it difficult to comparison and a theoretical understanding of this phenomenon and its generalization. For example, when investigating SoE in teleoperation, it is important to consider the role of the mediator, namely the perception of the setup and how it affects the transparency between the operator and the remote environment. However, this concept does not apply to the classic RHI experiment. Another example relates to the tasks. We designed two variations of the same task, which is a very common task in tele-robotics. However, this makes it difficult to generalize these results to other tasks in the same or different contexts of application.

In future works, we aim to empirically examine the proposed explanation put forth in the discussion, i.e., the concept of the surrogate being perceived as a mediator, which introduces friction in the achievement of a completely immersive embodiment experience. Furthermore, we intend to investigate the impact of manipulating the SoE on operators' motor learning over an extended series of trials, continuing until operators reach a performance plateau. This exploration will be conducted across diverse contexts of application to discern any context-specific variations. Lastly, we aspire to delve deeper into the definition of SoE, considering both its subjective and objective dimensions to provide a more comprehensive understanding of this crucial aspect in our research domain.

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